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SOIL CREEP: AN ASSESSMENT OF CERTAIN CONTROLLING
FACTORS WITH SPECIAL REFERENCE TO UPPER WEARDALE,
ENGLAND

by

E.W. ANDERSON M.A. (Oxon) M.A. (Manch)

Part-time research student in the Department of
Geography, University of Durham

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ABSTRACT

Soil creep is important as a process affecting landform development, as a factor influencing slope stability and as an element of land wastage. Few definitive studies have been made of the process and work on variables controlling rates of soil creep is very limited.

Therefore, in the present study it was decided to monitor creep with a number of devices over different lengths of time so that variability over space and time could be determined. This involved investigations on three distinct scales: those of the laboratory, the plot and the drainage basin.

To measure rates of creep and to monitor probable controlling variables, new instruments were designed and established procedures were modified. All new instruments were validated and essential features at each stage of the work were replication and the measurement of local variability.

After initial tests on experimental plots a drainage basin was selected and instrumented for the pilot study, in which both creep rates and a number of basin variables were investigated. The experimental design for the main study was then constructed, using six main instruments: Anderson's Inclinator, Anderson's Tubes, aluminium pillars, dowelling pillars, Young's Pits and Cassidy's Tubes to monitor rates of creep on each of twenty measuring plots. The basin factors considered as probable controls were categorised as:

- (a) external or meteorological
- (b) surface, including slope angle and vegetation
- (c) internal, comprising the main soil variables

Annual rates of creep, shown to vary from 0.3mm to 2.4mm, were correlated with eighteen major basin factors. The results of graphical and statistical analysis showed that rates of creep are controlled by a number of 'force' factors, chiefly soil moisture, field capacity and plasticity index, together with 'resistance' factors, particularly bulk density and a number of shear stress measures. The importance of moisture and its related variables was reinforced by principal component analysis and confirmed in a model produced by stepwise multiple regression.

Laboratory experiments with soil troughs demonstrated the relationship between soil movement and meteorological cycles. The daily monitoring of creep for extended periods on an experimental plot allowed short term movement to be assessed.

Further developments indicated by these results include long term monitoring and the mapping of spatial variation of creep over a 'landscape' using the key variables identified.

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My Mother for all her work in typing the study and as sometime
field assistant, but particularly for her
encouragement.

When everything is moving at once, nothing appears to be moving.....

Nature constantly begins the same things over again, years, days, hours, spaces too. And numbers run end to end, one after another. This makes something in a way infinite and eternal.....

PASCAL: Pensées

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CHAPTER ONE

BACKGROUND TO THE STUDY

- 1.1. Introductory
- 1.2. The Model Approach
- 1.3. Examples of Models
- 1.4. The Measurement of Mass Movement
- 1.5. Soil Creep
- 1.6. Mechanism of Soil Creep
- 1.7. Possible Variables controlling Soil Creep
- 1.8. Aims of the Study



1. BACKGROUND TO THE STUDY

1.1. Introductory

In 1958 Wooldridge wrote 'geomorphology is primarily concerned with the interpretation of forms, not the study of processes'. Since that time the emphasis has been increasingly on experimentation and quantitative process studies (Chorley, 1966) so that King (1966) was able to describe the aim of geomorphology as 'to understand the shape of the earth and elucidate the processes at work on its surface'. Furthermore, Jennings (1973) in discussing the major strands of the new geomorphology considered that, in the last twenty years, the greatest advances in the subject had been in process study. However it remains largely true that the fundamental aspects of most processes are still poorly understood (Leopold, Wolman and Miller, 1964).

In the same sequence quantitative techniques have been applied to the measurement and interpretation of firstly form and then process. Process studies may be defined as those which involve an attempt to link system responses to controlling variables (Caine, 1971). Furthermore processes and their interactions vary in both space and time. Resulting from this two general problems have been identified by Clayton (1970); the multivariate nature of the relationships and the huge areal extent across which they operate. This is likely to produce therefore a complex system in which the component subsystems have evolved together and are not even obviously separable (Levins, 1970). Also, partly through difficulties of definition, the precise link between the process and the response may be obscure.

An understanding of any scientific system demands knowledge of:

- (a) the nature of the processes operative at any instant
- (b) the external variables which control these processes
- (c) the pattern of the resultant response of the system to the processes (Carson, 1969).

Only when these have been clarified can changes through time be introduced and the system be placed in its broader geomorphological setting. Therefore the position of studies concerned with the monitoring of processes and their controlling variables can be placed within the general framework of the subject. Indeed, in tracing the origins of schools in geomorphology Butzer (1973) has recognised four directions of primary research:

- (a) quantitative study of geomorphic processes
- (b) quantitative analysis of landforms
- (c) quantitative and qualitative study of sediments
- (d) systematic regional studies

It can be seen that while the present study fits clearly into category (a), aspects of the other three are also included.

However it must be stressed again that in this and related work in geomorphology and geology the problems are multivariate. It is rare for there to be a single phenomenon which can be isolated and attributed to a single simple cause. A number of possible explanations must usually be considered. 'If therefore there are any advantages in any field in being armed with a full panoply of working hypotheses and in habitually employing them, it is doubtless the field of the geologist' (Chamberlin, 1897).

Since most landscapes are composed of slopes, the study of slope processes must possess a general relevance in geomorphology. As Scheidegger (1970) has written: 'If it can be understood how slopes change under the influence of exogenic processes, then obviously it is possible to explain physical geography'. Ahnert (1971), in stating that geomorphology is by necessity mainly a study of slopes, has further stressed the point. A slope is a morphological surface that can be defined by the fact that it is inclined, and by the type of processes active on its surface (Jahn, 1968).

1.2. The Model Approach

With the complexity of the system, particularly when the heterogeneous nature of the soil component (Bear, 1964) is considered, the most likely way to achieve understanding is through the use of models. A model may be defined as a theoretical construction, a collection of objects and relations, some but not all of which correspond to components of the real system (Levins, 1970). Many other definitions are available (Chorley and Haggett, 1967) but this example seems as elegant yet as simple as any. Clearly the choice of model depends upon the aims of the study, but Levins goes on to warn that no model can simultaneously optimize generality, realism and precision. From the geomorphological standpoint this has been developed by Kirkby (1974) who poses the choice between explanations which stress the unique quality of individual forms and those which seek to generalise from the similarities between forms.

The contrast between the deductive and the inductive approach to the study of slope development has been discussed by Young (1963). On the one hand investigations have been of the operation of denudational processes and from these it was possible to make certain deductions about slope evolution; while on the other hand measurements have been made of the form of existing slopes and from the resulting profiles, evidence of past changes has been produced by inductive reasoning. Both approaches are still in evidence and both have become increasingly quantitative, acquiring greater precision. A development from them is the construction of a functional or process-response model. The stages in the formulation of such a model have been summarized by Carson (1969):

- (a) the determination of the process and its controlling variables
- (b) the evaluation of the nature of geometrical change due to the action of the process in an infinitely small period of time
- (c) the extrapolation of the geometrical change through time until the attainment of an equilibrium pattern of form

One of the earliest and most simple models is the balance equation of Jahn (1968). This illustrates particularly clearly the fundamental idea of process-response, since it only uses three variables:

- A the accumulation of slope material
- S the processes of slope wash and surface deflation
- M the processes of mass movement

When $A = S + M$, the slope is in equilibrium or 'equivalent' and the regolith layer remains of constant thickness

When A is less than $S + M$ the slope is in positive balance with a reduction in thickness of the regolith layer

When A is greater than $S + M$ the slope is in negative balance with an increase in the thickness of the regolith layer

Jahn then discusses changes with time and the feedback resulting from these last two denudational balances, but these are probably better considered in the context of the model proposed by Ahnert (1967) which includes additional variables.

1.3. Examples of Models

In attempting to use the equilibrium concept as a basis for the practical interpretation of landforms Ahnert developed a number of ideas relating form and process in the landscape. A fundamental aim was that such theory should be directly applicable since it could be verified by field measurement.

Two assumptions are made:

- (a) that the configuration of landforms results from the different rates at which rock waste is produced, transported and redeposited at different points on the surface
- (b) that the rate of waste production from bedrock on hill slopes decreases with increasing thickness of the overlying waste mantle

The rate of waste supply at any point depends upon the rate at which material is transported to that point from

upslope (A) and the rate of weathering at the point (W). The potential rate of waste material^{removal} (Rp) from the point is determined by the assemblage of site characteristics and the capacity of the denudational processes.

The balance between these two rates determines the waste mantle thickness (C) (Fig. 1.1 A)

$$C^1 = C + A + W - R_p$$

Where C is the mantle thickness at the beginning of a unit time period and C^1 is the thickness at the end of that period

If the system is in equilibrium $R_p = A + W$
and the thickness remains constant ($C^1 = C$)

If weathering is actually occurring then the equilibrium can be designated denudational since down wearing is taking place although the mantle thickness remains unchanged.

If there is no weathering ($R_p = A$), the point is in transport equilibrium since no actual erosion is occurring.

Unless they all change simultaneously and proportionately in the same direction, any change in the three variables, R_p , A and W will cause a change in the mantle thickness. Thus disequilibrium is indicated by alterations in a basic field measurement, depth of the waste mantle. If R_p is greater than $A + W$, the disequilibrium is said to be negative, while if it is less, a positive disequilibrium results. Since the second original assumption related weathering rates with the thickness of the overlying mantle, any thinning is likely to enhance rates while thickening will slow the process. Such feedback therefore tends towards the restoration of equilibrium. However, time lags are not taken into consideration and it is tacitly assumed that the weathering response will be in phase with the erosion stimulus.

This basic model can then be extrapolated from the scale of one point to that of a complete slope (Fig. 1.1 B). The slope is in undivided equilibrium if:

$$R_{pf} = A_s = W_s$$

where R_{pf} is the potential rate of waste removal at the slope foot,

A_s is the rate of waste arrival at the slope foot
 W_s is the rate of waste production on the slope

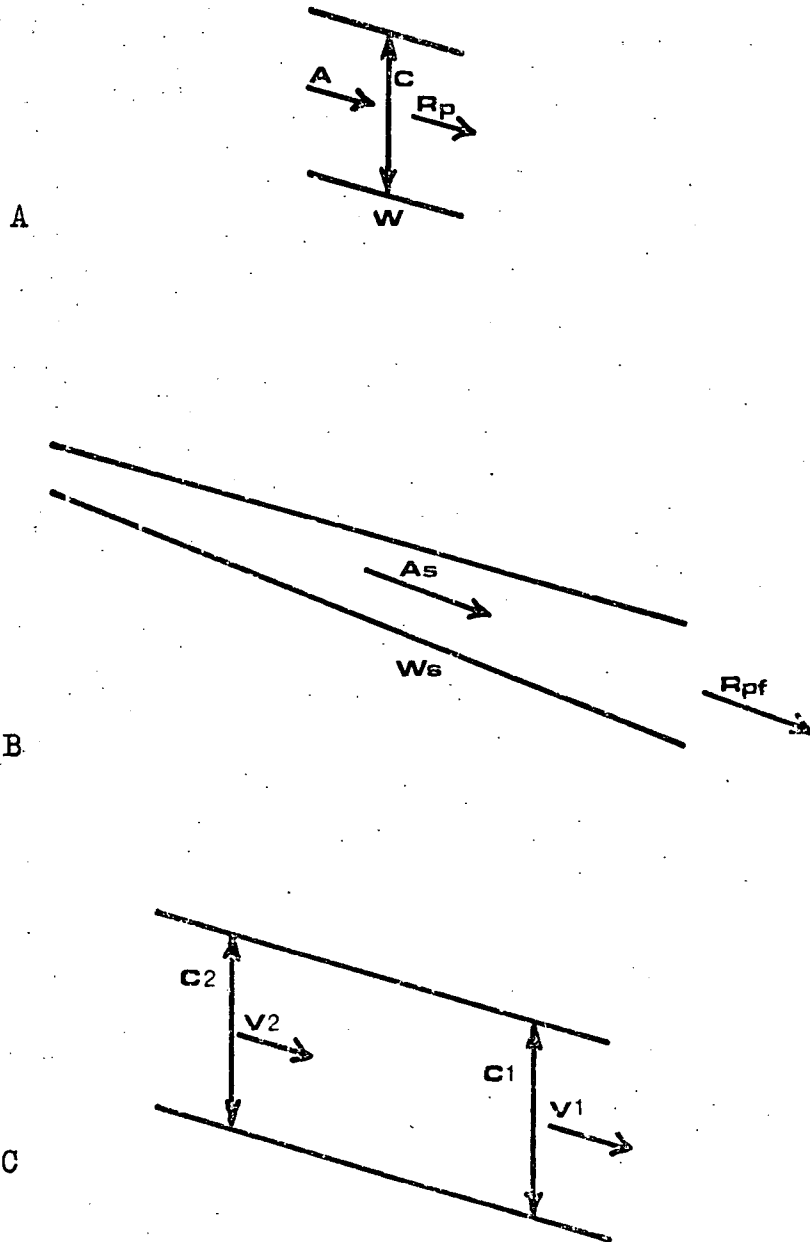


Fig. 1.1 Ahnert Model

- A Balance at a point
- B Balance on a slope
- C Form change measurements

If conditions at the slope base then change so that the removal rate is lower, material will still initially arrive at the original rate (A_s) and therefore waste will accumulate. This might occur for example, when a meander moves so that a slope is no longer undercut by the river. As the mantle deepens, the slope angle becomes smaller and the rate of arrival declines to a new equilibrium. The concave inflexion produced moves back upslope as the whole slope adjusts, as above it the original weathering rate is maintained until the mantle thickens.

Conversely, if the removal rate is enhanced by a change in conditions, the waste mantle thins and the slope angle increases. Again, the inflexion, in this instance convex, moves back upslope resulting in a decrease in the thickness of the waste cover and an increase in the weathering rate.

Thus both slopes are in external equilibrium but internal disequilibrium, in the first case positive and in the second case negative.

The form changes involved in this model can be monitored in the field by simple angular and depth measurements. However, changes are normally slow and to validate the complete system it is necessary to monitor process rates so that the relationship of form and process can be verified. The main processes are surface wash, mass movement and weathering, while the base of the slope may also be affected by erosion. These can be related in the framework already established.

Two points on a slope profile segment are selected, point 1 and above it point 2 (Fig. 1.1 C). The thickness of waste mantle at each point is respectively C_1 and C_2 and the mean velocity of mass movement V_1 and V_2 . Then, neglecting weathering and surface wash, $C_1 V_1 = C_2 V_2$

During movement from point 2 to point 1, weathering adds an amount U to the thickness of the mantle so that

$$(C_1 - U) V_1 = C_2 V_2$$

During the same period, surface wash removes depth S_1 and S_2 from the points. Thus

$$(C_1 + S_1 - U) V_1 = (C_2 + S_2) V_2$$

The components C , S and V can all be measured comparatively easily and therefore U can be calculated.

This model has been emphasised because it illustrates clearly the relevance of mass movement measurements to the practical study of slope development. Of the three components, most problems have been encountered in monitoring mass movement and therefore clarification in this area must facilitate the development of further models on increasing realism.

However despite its advantages in illustrating simply and directly the possible relationships between process and response, this model is limited. It has been tested in the field (Ahnert, 1970) but it is essentially discrete, and for general application the more sophisticated continuity model (e.g. Carson and Kirkby, 1972) must be cited. The foundation of the continuity model can be stated as:

$$\text{Change} = \sum \text{additions} - \sum \text{subtractions}$$

It is therefore tautologous but this is its strength since no extra assumptions are required. As the amount of energy performing geomorphological work in a hillslope system is probably a very small proportion of the total energy flux (Carson and Kirkby, 1972, Young, 1972) it is of little direct relevance and model construction is based on mass balance.

The boundaries of the slope system are defined and a soil block of unit width is considered (Fig. 1.2) where

y is the height above base level

x is the distance from the divide

S is the sediment flux

Then, in unit time, the magnitude of change in the sediment flux over unit width will equal the change in height

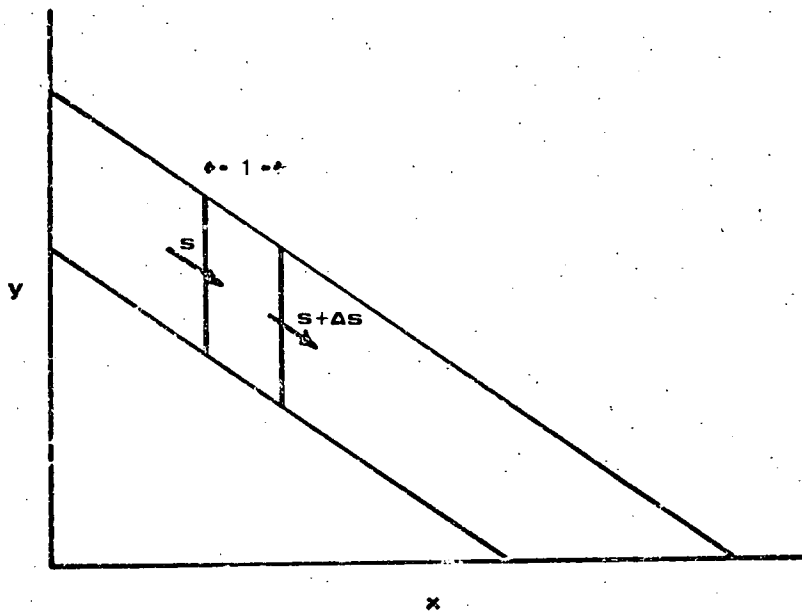
$$|\Delta S| = |\Delta y|$$

$$\text{as } \Delta x = 1 \text{ and } \Delta t = 1$$

$$\left| \frac{\Delta S}{\Delta x} \right| = \frac{\Delta y}{\Delta t}$$

$$\text{If } S > 0, \text{ then } \Delta y < 0$$

$$\frac{-\Delta S}{\Delta x} = \frac{\Delta y}{\Delta t}$$



y height above base level

x distance from divide

s sediment flux

Fig. 1.2 Continuity Model Framework

This is the discrete version of the continuity equation. In the limit the continuous version, a partial differential equation, results:

$$0 = \frac{\partial S}{\partial x} + \frac{\partial y}{\partial t}$$

This indicates that variation of form over time is related to variation of process over space. This is a fundamental concept of geomorphology. The model is constructed in profile and lateral sediment flux is not considered. Huggett (1973) includes a three-dimensional approach in his treatment of the continuity model. A further assumption is that negligible change occurs in mineral content on weathering.

The continuity model links the essentially field-based, specific model of Ahnert with the more general basic principles of geomorphology.

1.4. The Measurement of Mass Movement

It is clear that if the form of the landscape is to be understood then variations in the sediment flux must be known. The movement of material on slopes comes largely within the province of mass movement, a term subsuming a range of processes. Thus the measurement of processes is fundamental in studies of slope formation (Williams, 1970).

Furthermore it can be seen that a limited number of field measurements will suffice to allow an appraisal of the models discussed against real-world slopes. Of major importance therefore is the investigation of mass movement rates since the models cannot be functional unless they are known.

However the slow movement of soil-ground masses on slopes belongs to one of the least studied areas of geomorphology (Iveronova, 1964). The sum total of knowledge on the subject is therefore surprisingly small (Price and Alexander, 1971) partly because past measurements tend to give only relative indications of movement. Therefore in any process studies involving slopes, it can be appreciated that there is a particular requirement for the absolute measurement of slow mass movement and its controlling variables.

1.5. Soil Creep

Of the slow mass movement processes, soil creep has been largely neglected chiefly because of the problems of accurate monitoring. Kirkby (1967) has written: 'so few measurements of soil creep have been made that its role in slope evolution is largely a matter of speculation'. Leopold (1970) states that creep results are still meagre. Even in 1975 Troeh reports: 'soil creep is seldom mentioned and rarely measured yet its persistence makes it significant to sciences that deal with soils or landscapes'. It is only through measurements of soil creep that the relative rates of mass movement processes can be determined and the development of slopes deduced.

The various arguments which have been briefly examined show that knowledge of soil creep rates and variables controlling them is extremely limited. Furthermore they indicate that such knowledge is a pre-requisite to the understanding of slope development. Therefore to summarize, it is felt that the study of this topic fulfils a need in geomorphology and can be justified for these basic reasons. Firstly, it is a geomorphological process in its own right as a category of mass movement which is responsible for a variety of landforms. Since creep seems to occur on all debris covered slopes and constitute the basic element of landscapes, it is also intimately related to other processes of denudation.

Secondly, with the development of applied geomorphology and the links with soil mechanics, soil creep is a significant factor to be recognised in the safety of both natural and man-made slopes. As yet geomorphology rather than soil mechanics provides data on rate of movement, but civil engineering principles are being increasingly applied to considerations of mechanism.

Thirdly, while soil creep may be less spectacular than wind and water erosion, it is nevertheless a vital element in any study of land wastage and soil conservation.

Soil creep may be defined as the slow downslope movement of surficial material which results from the combined action of gravity and repeated applications of molecular stresses (Owens, 1969).

One of the earliest direct references to creep is attributed to Thomson (1877) who used the term in a description of rock glaciers, speculating on the slow downslope movement of soil and rock material. Since then a number of definitions have been advanced, many of them highlighting different aspects of the process. For example, Stamp (1963) emphasised the speed, stating that creep was not usually perceptible except through extended observation. Schiefferdecker (1959) stressed the continuous nature of the process which allows a contrast between certain other types of mass movement. This point is amplified by Nemčok, Pašek and Rybář (1972) who in their classification of the four types of slope process define creep as: 'a geologically long term movement of non-increasing velocity without well defined sliding surfaces'.

In considering the actual mechanics of creep to comprise miniature movements of all types, Parizek and Woodruff (1957) describe it as: 'a non-specific term for conveniently rationalising inexplicable downslope movements'. However, this is somewhat extreme and greater precision is possible if a number of distinctions are made. Among others Terzaghi (1950) has distinguished between seasonal creep, which occurs near the surface within the zone of seasonal changes of moisture and temperature, and continuous creep which takes place below this. Thus while the former results from the effects of expansion and contraction under the overall influence of gravity, the latter is produced by gravity alone. Continuous creep is therefore unaffected by the changing seasons and must be virtually constant. Since it is also extremely slow, from the point of view of geomorphology, it is justifiable to assume stability (Skempton, 1953). In his classification Hutchinson (1968) expands on this, listing three categories of creep:

- (a) Shallow, Predominantly Seasonal Creep; Mantle Creep. This type of creep is largely confined to the weathered surface zone of fluctuating ground temperature and moisture content. Viscous movements contribute little to the net downslope creep.

- (b) Deep-seated Continuous Creep; Mass Creep. This type of creep can be expected to occur in all soils and rocks which are subjected to shear stresses in excess of the critical. It is probably the result of viscous movements and has a much lower order of magnitude than the other forms of creep mentioned.
- (c) Progressive Creep. Creep movements of this type occur in slopes which are approaching failure. They are thus characterised by a stress level near to that at which failure takes place and by gradually increasing and relatively high rates of movement.

Kirkby (1967) argues that on hill slopes without recognisable landslide scars continuous creep cannot be more than locally active. However another contention is that continuous creep operates too slowly to break the soil cover. In geomorphology the accent has therefore been on seasonal creep since this is more likely to affect the interpretation of slope form.

1.6. Mechanism of Soil Creep

Discussion on the nature of soil creep centres on the definition of the mechanism, particularly on whether it is seen principally as a category of mass movement, with the soil particles moving closely together, or mainly as a diffusion process (Culling, 1963), with particles being displaced separately. Under the force of gravity, any disturbance may initiate a downslope movement. Systematic heaving (e.g. expansion and contraction resulting from wetting and drying) could activate either process, whereas agents producing less regular stresses (e.g. volume changes resulting from weathering) are more likely to give rise to diffusion. Mass movement of soil may itself result from shears at several layers, microshears (Kojan, 1967), or one major shear with possible rotation, giving in each case different rates of creep which may not even occur simultaneously. Hypothetical stages of creep deformation at the micro-mechanics level are discussed in detail by Kojan (1967). He also describes the effects of progressive failure, a topic developed by Skempton (1964). Of particular relevance to the experimental design for this study is his assertion that creep is activated not by soil expansion alone

but by expansion allied to shear failure on the particulate scale.

If variations in soil properties, particularly shear strength, are considered alongside this lack of clear definition, it is obvious that attempting to identify the process and the mechanism by which it operates is extremely difficult (Caine, 1971). However, the process must influence the choice of measurement technique including such factors as the angle and depth of insertion. For example, if the instrument is vertical, the effects of expansion and contraction need to be considered, but the effect of gravity will be largely neutralised. Similarly for mass movement as opposed to diffusion, the depth of measurement is more easily identified so that probe movement is not inhibited by the lower static layers but on the other hand bodily movement does not occur.

The actual mechanism of soil creep can be envisaged as a two phase action (Young, 1972) comprising firstly some 'triggering force' and then the constant factor of gravity which promotes downslope movement (Gilbert, 1909). The fundamental importance of gravitational stress is also emphasised by Sharpe (1938) and Strahler (1952). Therefore molecular stress in the upslope direction will be diminished, those acting downslope will be enhanced. Strahler also distinguishes superficial or seasonal creep as occurring on material with a high degree of internal friction which would not otherwise flow under the force of gravity alone. In his examination of frost creep, an overlapping process, Washburn (1967) produces a definition linked directly to the mechanism: 'the ratchet like downslope movement of particles as the result of frost heaving of the ground and subsequent settling upon thawing, the heaving being predominantly normal to the slope and the settling more nearly vertical'. As Benedict (1976) indicates, this differs from other forms of soil creep only in its dependence upon ice segregation as a motive force.

Culling (1963, 1965) as mentioned, considers soil creep results from the persistent effect of molecular and macro-molecular forces tending to displace the soil particles.

Thus within the constraints of the earth's gravitational field, a random displacement of particles will occur motivated by the smallest of stresses. In this theory, displacement will normally be determined principally by the distribution of pore space. This is therefore a particulate motion and can only marginally be included within the definition of mass movement.

The mechanics of soil creep as envisaged by Davison (1889) depend upon expansion normal to the surface and then contraction which under gravitational stress should be vertical. However this omits any considerations of soil cohesion which may be insufficient to prevent an amount of downhill movement during the expansion stage and is likely to prevent vertical resettlements. In fact Davison found that the effects of cohesion were to cause contraction in a direction intermediate between the normal and the vertical. Since the cyclical forces causing triggering of the movement are obviously more effective near the surface and since also the soil is likely to be more loosely packed in that layer, the downslope creep will be greatest at the surface declining approximately exponentially with depth. However Kirkby (1967) points out that Davison did not consider the weight of the soil overburden which is likely to distort the expansion downslope from the normal. Since there is no overburden at the surface, the soil cannot suffer a net shear and therefore the highest rate will not be recorded there. By Kirkby's reasoning, the zone of maximum velocity should occur somewhere just below the surface.

Kirkby supports this argument mathematically and the main phases can be summarized. Firstly the following assumptions are required:

- (a) that gravity acts solely through the weight of overburden
- (b) that cyclic forces are alternately exactly opposed in direction
- (c) that the cyclic force increases in each case until yield occurs
- (d) that at failure, movement is in the direction of maximum stress

It is realised that, owing to its heterogeneous nature, random variations in the soil are likely to affect the validity of all these assumptions. The following situation and reaction is supposed (Fig. 1.3 A). At a point P, located at a vertical depth Z, a cyclic stress Q_1 , acts in a direction inclined to the normal at an angle of β . In yielding, the soil unit at P of thickness δZ , expands by an amount δL , in the direction of the yield. This results in the yield differing from the direction of Q_1 by an angle of γ_1 in the downhill direction. If the triangle of forces is constructed (Fig. 1.3 B) it can be seen that:

$$\sin \gamma_1 = \frac{\rho_1 g Z}{f_1} \sin(\beta + \theta) \quad (\theta = \text{slope angle})$$

where f_1 is the yield strength of the soil in the direction of Q_1 and ρ_1 is the density of soil during expansion. Similarly in the contraction cycle in the downhill direction the angle can be calculated from

$$\sin \gamma_2 = \frac{\rho_2 g Z}{f_2} \sin(\beta + \theta)$$

These equations also show that the rate of creep should increase as the sine of the slope angle.

While a mechanism on this scale cannot be monitored in the field, the overall result is similar to the effect of laminar shear and this can be measured.

Therefore one aspect of this study is the measurement of net shear resulting from soil creep and the problems involved will be considered in the next chapter. The other aspect is the investigation of factors affecting the rate of creep, and these were selected using evidence from four sources:

- (a) a theoretical approach
- (b) practical studies reported
- (c) previous work (Anderson, 1971)
- (d) the pilot study at Rookhope

1.7. Possible Variables controlling Soil Creep

From the foregoing, theoretical appraisal alone, several controlling variables can be isolated as important: angle of

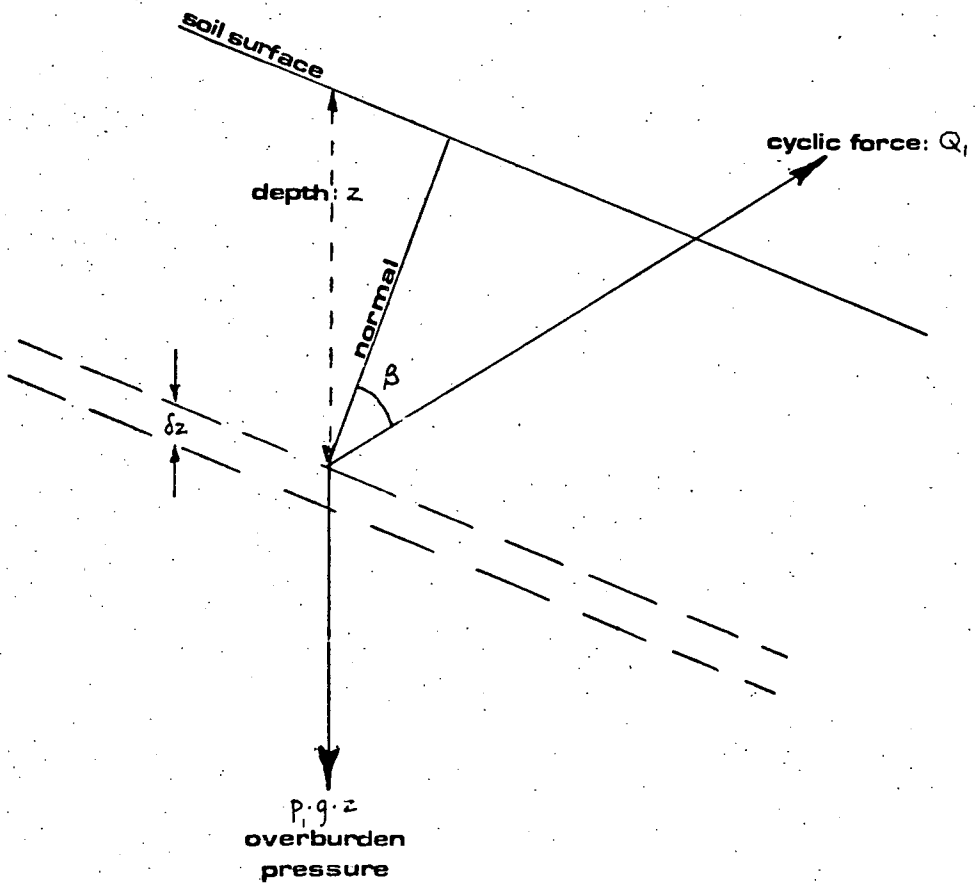


Fig. 1.3A Mechanics of Soil Creep (Kirkby 1967)

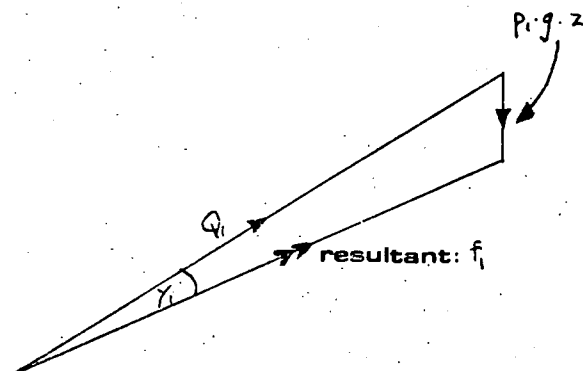


Fig. 1.3B Triangle of Forces (Kirkby 1967)

slope, cohesion, soil depth, soil density, yield strength and aspects of the cyclical forces. The models discussed earlier (Ahnert, 1967, Jahn, 1968) implied that creep rates are likely to be affected by slope angle and depth, while the models of Young (1963A) and Ahnert (1971) cite the sine of the slope angle together with distance from the watershed. Caine (1971) proposed a plot model for a range of responses including soil creep, which identified twenty-two boundary conditions. These can be summarized as: soil depth, soil shear strength, subsurface water flow characteristics, slope factors, aspect, climatic controls, plant cover, root factors and the effects of animals.

In a similar way Penck (1953) discussed a number of conditions applicable to all types of mass movement although his particular emphasis was almost entirely restricted to considerations of the effects of friction. For example, he related friction to the angularity of material, the soil depth and also to slope angle. Sharpe (1938) divided creep into five categories including besides soil creep. solifluction and rock glacier creep. His list of controls, compiled therefore for a range of mass movement processes, is similar in many ways to Caine's boundary conditions although there is a far stronger geological bias. His classification is given under the following headings: lithologic, stratigraphic, structural, topographic, climatic and organic.

For convenience, in many models it tends to be assumed that soil is homogeneous, but clearly as intimated by Caine, a number of soil characteristics are likely to affect movement. Particularly important would seem to be the changing soil moisture content and its effect upon the soil state. Also through its influence on the penetration of water and frost and through the root control it exercises, vegetation must be considered.

Results from the few studies which have attempted to relate creep rates and site variables can be rapidly summarized. The work of Davison (1888) and Gilbert (1909) has already been mentioned and both concentrated their explanations upon the expansion and contraction results from meteorological cycles, although Gilbert also discussed the possible effects of animals and plant roots.

From their observations in the Upper Ohio Valley, Sharpe and Dosch (1944) reported indications that water was a dominant control. Cumberland (1947) commented particularly on the effect of vegetation since he considered creep to be greatly accelerated once the plant cover and attendant root systems had been removed.

In the more recent work, Iveronova (1964) wrote convincingly of the need to consider soil mechanics methods, stressing especially the significance of soil plasticity. Similarly, Chandler and Pook (1971), in their research on long term creep movement in low gradient clay slopes, measured natural water content, plastic limit and liquid limit as significant variables. Everett (1963) in Southern Ohio, investigated the general relationship between soil moisture levels and soil movement. Young (1972) also produced strong evidence in support of the moisture variable but stressed that slope merited close attention. In what is probably the most complete analysis of controls, only part of which is empirically based, Kirkby (1967) attempted to grade the causes of creep in order of effectiveness. Measurements were made of the meteorological factors: soil moisture, freeze-thaw and temperature changes, while the others, burrowing animals and plant roots were estimated. Owens (1969) who monitored a small catchment area in the Southern Alps, New Zealand, concentrated upon accumulated soil moisture content and the number of freeze-thaw cycles. Harris (1973) also attempted to relate movement to cycles. Through their method of measurement, Niewenhuis and Kleindorst (1971) recognised implicitly the importance of soil density in creep. Several studies have included investigations of the relationship between creep and vegetation variables (Raup, 1969, Harris, 1972, Black and Hamilton, 1972, Williams, 1973). As Selby (1974) worked on friable pumiceous soils in North Island, New Zealand, his results provide a guide for comparison with other unconsolidated soils. Finally, Evans (1974) for his study of soil creep in the Upper Derwent Valley, chose as the variables to be investigated, soil moisture, freeze-thaw, soil texture and distance from the base level. However, apart from soil texture, few detailed measurements were made.

A number of laboratory programmes have also been completed using soil blocks and varying such factors as the slope angle and the incidence of meteorological cycles. These are discussed later (Chapter 5) but mention must be made here of laboratory simulations of creep (e.g. Komamura and Huang, 1974). In these, stresses are applied under controlled conditions so that rheological models of creep can be constructed.

In summarizing both the theoretical and the practical work, it is clear that a wide range of factors has been considered. However, in the majority of the field studies, the accent has been on the measurement of creep rate, and the monitoring of controls has been secondary. Consequently, while evidence on the rates is limited, there is even less on the governing factors and little has unambiguous support.

The factors to emerge from this brief survey can be classified broadly into three groups. These are the variables which, although they may affect it, are not part of the soil structure:

- (a) meteorological cycles
- (b) vegetation
- (c) animals
- (d) slope angle
- (e) aspect
- (f) distance from the watershed or base level

The remaining factors, basically internal to the soil system, can be further subdivided into those affecting forces which are likely to cause movement and those which tend to offer resistance to creep. In the former category are: soil moisture, plasticity, depth, while in the latter are various measures of shear strength, cohesion, texture and certainly initially, density. The general arguments of force and resistance apply when erosion and transport are discussed (Carson and Kirkby, 1972) and this division can be usefully retained.

Evidence from previous work and the pilot study indicated the likely controlling variables to be soil moisture,

aspects of vegetation, and probably slope angle. However, closely related to moisture absorption is organic content, and this led to the consideration of shrinkage, the two together appearing worthy of further investigation. Therefore, apart from the effects of animals, rated of low significance by Kirkby (1967) the experimental design was constructed so that all possible controls of creep rate monitored in this review would be measured.

1.8. Aims of the Study

It is apparent from this discussion that there are two broad problem areas which can be discerned in the study of soil creep:

- (a) there are comparatively few measurements of rates while there is virtually no standardisation of technique and little comparative work has been completed on instruments
- (b) evidence on causes and controls of creep is extremely limited, very few results have been systematically produced and much of the discussion rests on largely subjective judgments

Thus the main aims of this study can be listed:

- (a) to design new instruments and improve existing techniques for measuring creep
- (b) to compare results from a number of instruments
- (c) to measure the probable controlling variables and relate them to the creep rates
- (d) to monitor soil movement over the short term
- (e) to measure the direct effects of climatic cycles under controlled conditions

Besides these, it was hoped to examine the relevance of certain soil mechanics techniques by using them to investigate the controls and also to calculate overall losses from the basin resulting from soil creep.

These various aims can be basically summarized by the formulation of a working hypothesis: that rates of soil creep can be precisely and reliably measured and related to variations in a number of environmental factors.

To test the hypothesis a programme of fieldwork and laboratory experiments was completed and the major elements in this are listed in approximately chronological order. However certain parts overlapped in time and this can be clarified with a diagram (Fig. 1.4) but it obviously precludes thesis presentation in a strictly chronological order:

- (a) design and testing of instruments
- (b) initial measurement of certain variables
- (c) laboratory experiments
- (d) selection of main study drainage basin
- (e) pilot study in main study basin
- (f) instrumentation for main study
- (g) Durham area plot studies
- (h) subsidiary studies in the main study basin
- (i) main study

As stated, the area selected for the major part of the study was a small drainage basin. While the reasons for the choice of the particular site are discussed later, reasoning behind the selection of a drainage basin rather than any other landform can be discussed.

The problem of assessing rates of soil creep involves the interrelationship of many systems which cannot therefore be studied in isolation. The most appropriate landscape unit for such a study would seem to be the drainage basin, since within this the slopes are related to one another and all parts of the system are interdependent. Also for a small catchment, there is no variation of climate, measuring instruments can be close together and there is a common base level throughout the area.

Drainage basins have of course formed the basis for the Vigil Network scheme (Slaymaker and Chorley (1964) and since the study of soil creep necessitates the measurement of many of the same variables, their use for the present work would seem justified. ^(Slaymaker, 1972) However there are certain problems which must be noted at the outset, particularly those concerned with

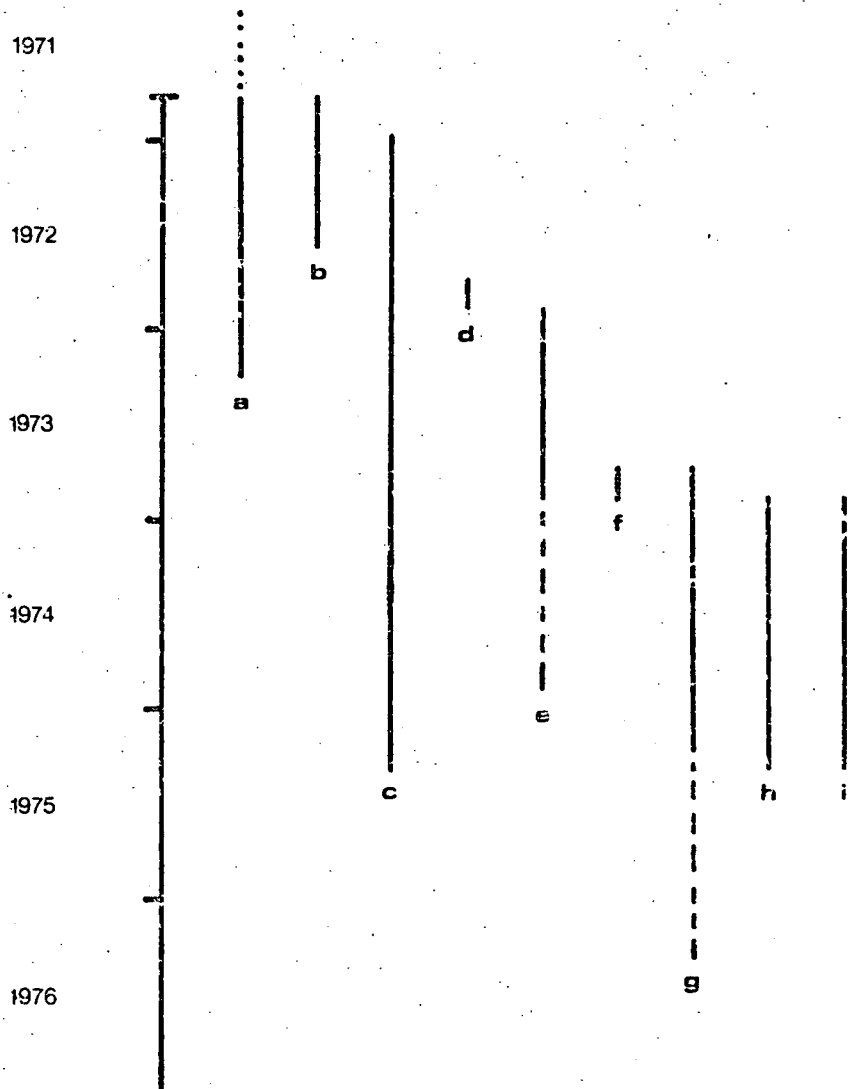


Fig. 1.4

Chronology of Study:

- (a) design and testing of instruments
- (b) initial measurement of certain variables
- (c) laboratory experiments
- (d) selection of main study drainage basin
- (e) pilot study in main study basin
- (f) instrumentation for main study
- (g) Durham area plot studies
- (h) subsidiary studies in the main study basin
- (i) main study

representativeness and control.

For the International Hydrological Decade (Ward, 1971) an attempt towards uniformity of terms was made by distinguishing representative basins as those which remain in the natural state while basins in which deliberate changes of, for example, vegetation or land use have been made, were designated experimental. The terms were interpreted more literally by the American Geophysical Union (1965) and the two were separated on the basis of purpose. Experimental basins were those selected for specifically studying the principles, relationships or predictions of hydrological phenomena, while representative watersheds are instrumented to produce readings which can be applied over a broader area.

For the present study, a middle position was adopted in that it was hoped to select a watershed in which relationships could be studied but it was also considered vital that results should be more broadly applicable.

Of more fundamental concern is the lack of control common to any observational science (Heath, 1970). In contrast to experiments in the laboratory, it is difficult to devise controls for those in the field except perhaps over limited areas. A degree of control may be achieved through deliberate site selection but such problems are probably best overcome by extensive replication. This is particularly important in studying a current process such as soil creep, as many of the measurements represent integrated values. It is only of course in the field that the relevant inter-relationships can be measured.

However if certain controls affecting soil creep are to be isolated and evaluated, it is important that other factors are, as far as possible, controlled. Therefore the sites within the basin, during the second stage of instrumentation, were selected as unit sources (Amerman, 1965) or plots. Readings were also complemented by results from other plot and laboratory experiments, both of which approaches provided a better opportunity to study the mechanics of the basic processes involved. Anderson (1967) suggested in fact that small plots should be used for test purposes before the watershed is instrumented. Further removed from reality is the laboratory tank in which the

soil block is treated as an isolated unit on which a number of experiments can be conducted. Finally, various intuitive models can be constructed and later refined in the light of results obtained.

While it is considered that the main landscape unit for the study must be a drainage basin in which the major factors affecting current rates of soil creep are operative, it is realised that there are limitations in such a design. Therefore plots, laboratory tanks and intuitive models have all been employed in an attempt to clarify the problem and to overcome the difficulties inherent in the use of watersheds.

The elements in the outline programme are reflected in the structure of the thesis, the remainder of which falls broadly into five sections:

- (a) A discussion of the instruments for measuring creep and the controlling variables.
- (b) The collection and analysis of results from the subsidiary and laboratory studies.
- (c) The selection and instrumentation of the main study basin.
- (d) The collection and analysis of data from the main study basin.
- (e) Summary and prospect.

CHAPTER TWO

TECHNIQUES FOR MEASURING SOIL CREEP

- 2.1. Classification of Techniques
- 2.2. Instruments which measure extremely accurately
 - 2.2.1. General
 - 2.2.2. The S.G.I. Rod Inclinator
 - 2.2.3. Linear Motion Transducers
 - 2.2.4. Strain Gauges
 - 2.2.5. Strain Gauge Inclinator
 - 2.2.6. Finlayson's Helix Tube
 - 2.2.7. Discussion
- 2.3. Instruments which measure in the long term
 - 2.3.1. General
 - 2.3.2. Pillars
 - 2.3.3. Bore Holes
 - 2.3.4. Cassidy's Tubes
 - 2.3.5. Hydrofluoric Acid Cylinders
 - 2.3.6. Young's Pits
 - 2.3.7. Selby's Cones
 - 2.3.8. Painted Rocks or Markers
 - 2.3.9. Vegetation
 - 2.3.10. Discussion
- 2.4. Instruments which magnify and measure the changes
 - 2.4.1. General
 - 2.4.2. Kirkby's 'T' Pegs
 - 2.4.3. Evans' 'T' Bar
 - 2.4.4. Discussion
- 2.5. Conclusions

2. TECHNIQUES FOR MEASURING SOIL CREEP

2.1. Classification of techniques

The emphasis on a quantitative approach in geomorphology has been of special significance in the study of processes and the rates at which they operate. The collection of data necessary for such studies has been promoted by, and has encouraged the development of, new techniques and instruments (Reynolds, 1968, 1975A). As a result, a basic problem often arises as to the selection of appropriate techniques for particular pieces of work. Clearly decisions are facilitated if a suitable series of classifications can be evolved.

For measuring rates of seasonal soil creep, a large variety of devices has been constructed and tested, each with its own inbuilt advantages and limitations. The basic problem in design is the rate of soil creep considered in relation to the limits of experimental accuracy. Furthermore, as movement varies seasonally and with depth and as the demands of different research programmes will themselves vary, no one instrument is likely to emerge as wholly suitable for all occasions. It is proposed to examine briefly the various possible classifications before considering the instruments themselves.

With such small movements, in most cases a few millimetres annually, instruments can be classified by mode of operation.

1. Mode of operation

- (a) Instruments which measure extremely accurately
- (b) Instruments which measure in the long term
- (c) Instruments which magnify and measure the changes

However, while this offers the most complete classification and is therefore adopted as the basis for subsequent discussion of the techniques, for selection of actual

instruments it is rather general. Similarly, a division into broad morphological classes such as that commonly quoted and listed below is of limited value.

2. Basic type of instrument

- (a) Pillars (e.g. Leopold, Wolman and Miller, 1964)
- (b) Tubes (e.g. Iveronova, 1964)
- (c) Angular measuring devices (e.g. Kirkby, 1963)
- (d) Others (e.g. Young, 1960)

For practical decision making, a series of broad, overlapping categories based on the constraints imposed by particular groups of instruments is proposed (Anderson and Finlayson, 1975).

3. Short term and long term measurement

- (a) Instruments which can be read when required
- (b) Instruments which need to be left for a long period for rates to be measurable

Clearly if an attempt is to be made to correlate rates with other site variables, selection would be from group (a) whereas group (b) instruments might be used as a long term check or for calculating overall rates of soil loss. Similar points might be advanced about category 4.

4. Regular and once only measurement

- (a) Instruments which can be read any number of times
- (b) Instruments which need to be excavated totally and from which only one measurement can be obtained

Depending on the experimental design, a decision must also be made as to whether a depth profile is required or whether an average or surface rate will suffice.

5. Surface and depth measurement

- (a) Instruments which only measure surface soil creep or net shear
- (b) Instruments which allow a profile of movement with depth to be obtained

Finally, as soils are notoriously heterogeneous materials (Bear, 1964), there is the problem of replication, closely allied to costs.

6. Complex and simple instruments

- (a) Instruments which are costly and require specialized manufacture
- (b) Instruments which are simple in design and therefore more easily replicated

It is essential then to define the problem carefully as, depending on this, a certain instrument will be more or less suitable (Fig. 2.1). Many difficulties emerge when measuring such small changes and it may even be debatable as to what exactly is being measured by a particular instrument. The apparatus used therefore imposes limitations on the interpretation of results. Furthermore, with such a delicate system, a rigorous experimental design must be employed and disturbance resulting from instrumentation minimized. It can be concluded that for most research programmes, more than one instrument is likely to be required.

Using the classification based on mode of operation, the main instruments which have been employed for measuring rates of soil creep will be described and assessed with particular regard to their advantages and limitations.

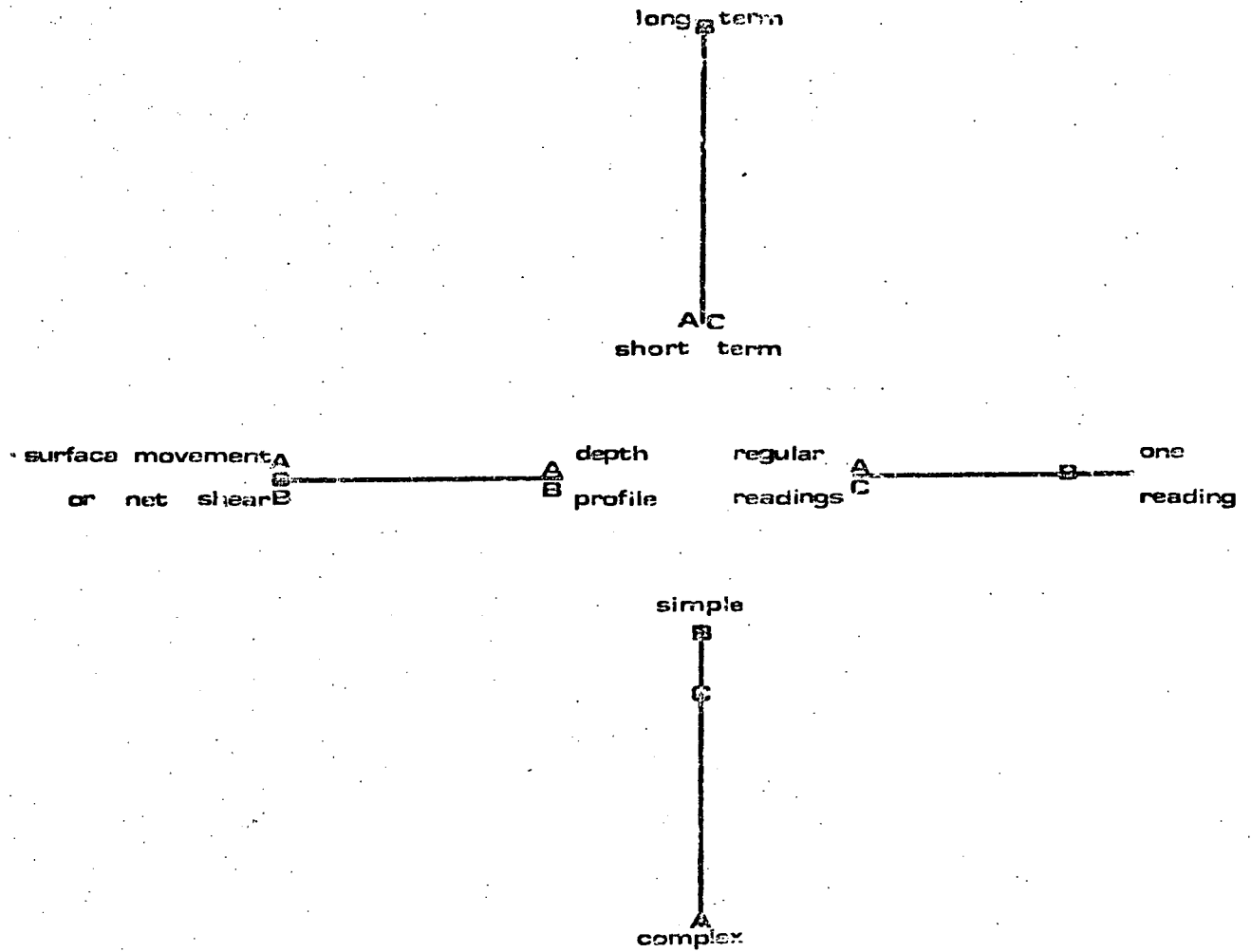
2.2. Instruments which measure extremely accurately

2.2.1. General

The use of extremely accurate measuring instruments which are sophisticated and expensive to construct, must be justified by the experimental design. The accuracy required or even possible may not warrant the use of such equipment. Furthermore if the device itself needs to be left in the field, the degree of replication will be severely limited. Many such instruments are also delicate and the soil may be greatly disturbed during insertion. However, if the limits of experimental accuracy are considered suitable, measurement of soil creep can be made at short time intervals allowing possible correlations with other features such as rainfall.

2.2.2. The S.G.I. Rod Inclinometer

This purely mechanical instrument was developed at



INSTRUMENTS

A very accurate

B long term

C magnify movement

Fig. 2.1 Measuring Instrument Classification

the Swedish Geotechnical Institute (Kallstenius and Bergau, 1961) to measure movement to depths of 4m. It consists of a flexible smooth-walled tube having an internal diameter of 4 to 11cm into which is inserted a straight rod carrying the measuring device. A flexible guide on the end of the rod allows it to follow the irregularities of the tube while a spherical guide centres it in the top of the tube. It can be held at any depth by a lock nut on the spherical guide and the inclination and length of rod between the two guides then determines the position of the centre of the lower guide in relation to the centre of the top of the tube (Fig. 2.2).

Measurements of the rod position are made by the measuring device mounted on it above the surface. This consists of a diopter tangentially fitted on a scale disc and below it a 'T' piece spirit level on a turnable beam. The disc is set in a chosen horizontal zero direction by means of the diopter and locked to the rod. The two readings are then obtained:

- (a) The turnable beam is moved until the tangentially placed spirit level indicates a horizontal position. This is the inclination plane of the rod and the horizontal angle between it and the zero direction can be read from the index at the opposite end of the beam
- (b) The radially placed spirit level is adjusted by the set screw to the level position and the reading on this screw therefore gives the inclination of the rod.

Three sets of measurements are made at each depth and the rod is turned through 120° between each reading. The observed scatter is then averaged and plotted as a coordinate on a graph.

The main advantages of this method are that each tube can be measured at any number of depths as frequently as required, while as only one inclinometer is needed, the tubes can be cheaply replicated. There is unlikely to be damage or interference since there are no above ground parts permanently in position. Furthermore as the initial tube profile is measured, there is no need for great accuracy during insertion. The major limitation

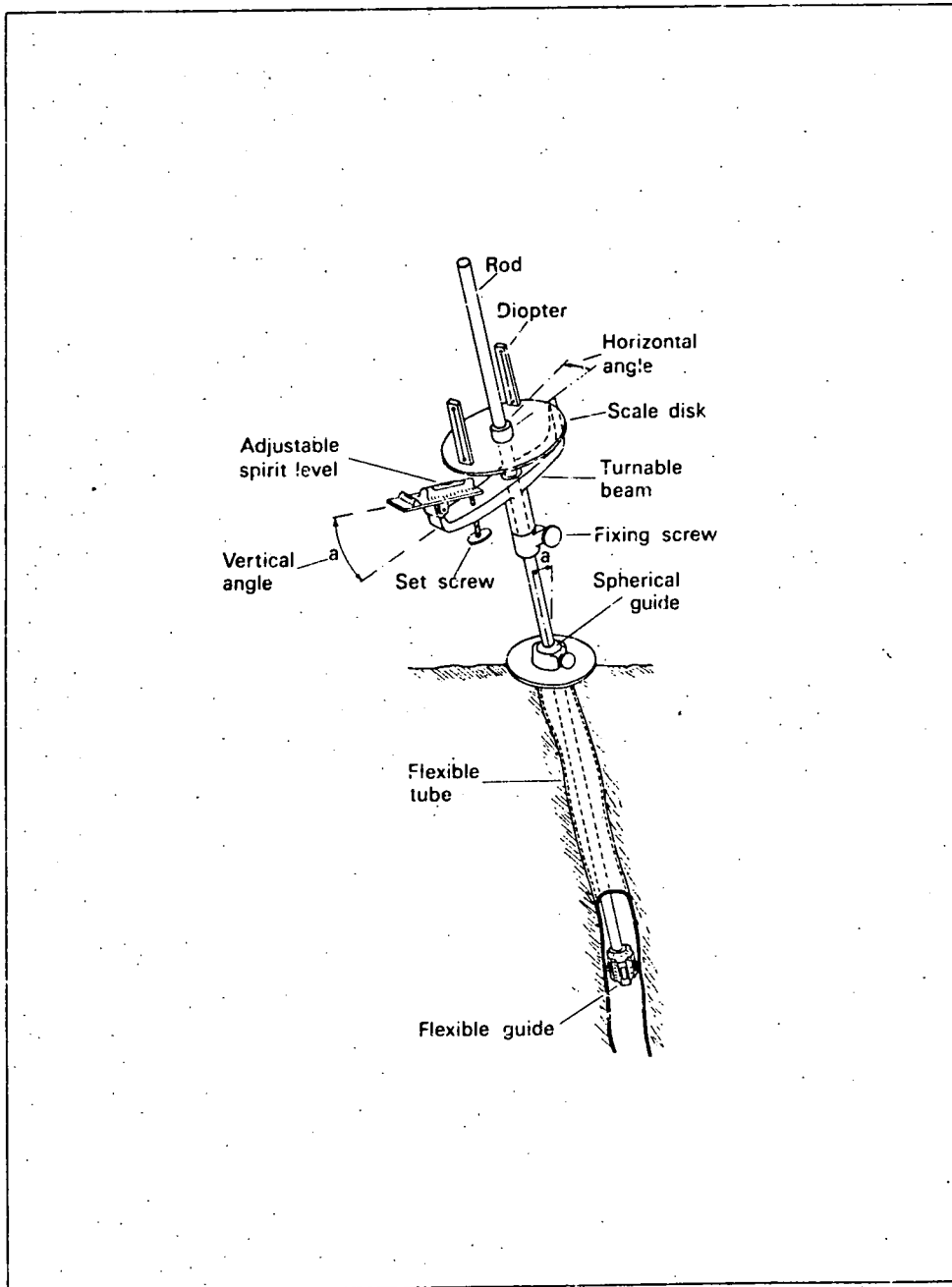


Fig. 2.2

S.G.I. Rod Inclinator

is that the passage of the rod down the tube is liable to cause disturbance to the surrounding soil and limit the reliability of readings. Also the instrument does not measure absolute or bodily movement of the tube. To obtain this the position of the tube top must be fixed by survey. Further, it has been found that the scatter of the three readings, for example, 0.35mm at 1m down, is such that it may be difficult to discern creep movements over the very short term.

2.2.3. Linear Motion Transducers

A linear motion transducer consists of a shaft which may move into or out of a coil of wire respectively increasing or decreasing the electrical resistance. With the coil rigidly anchored and the shaft attached to a movement plate buried in the soil upslope from it, creep rates can be measured. The soil movement against the plate causes the shaft to move in the coil, altering the resistance. The device needs to be calibrated initially so that resistances in ohms can be converted to movement in mm.

Everett (1963) used a plate of 0.05cm thick aluminium sheet with a diameter of 15cm for his work in the Neotoma Valley, Ohio, but for later research in Alaska, preferred a square plate with sides of between 5 and 8cm. His transducer unit is jointed to allow easy vertical and rotational adjustment so that the instrument can be fixed for different directions and depths (Fig. 2.3). The anchor pipe is cemented 20 to 30cm into the bedrock within a pit some 1m in diameter and the pit is supported on all sides by a concrete lining. The movement plate is inserted upslope from the unit and the soil replaced carefully round it as near the field density as possible (Fig. 2.4).

A significant advantage of this instrument is that continuous readings can be obtained and can therefore be interpreted in relation to other continuous recorded variables. The plots produced by Everett (1963) for Ogoturuk Creek, Alaska, show soil movement, together with moisture and soil temperature changes (Fig. 2.5). Also,

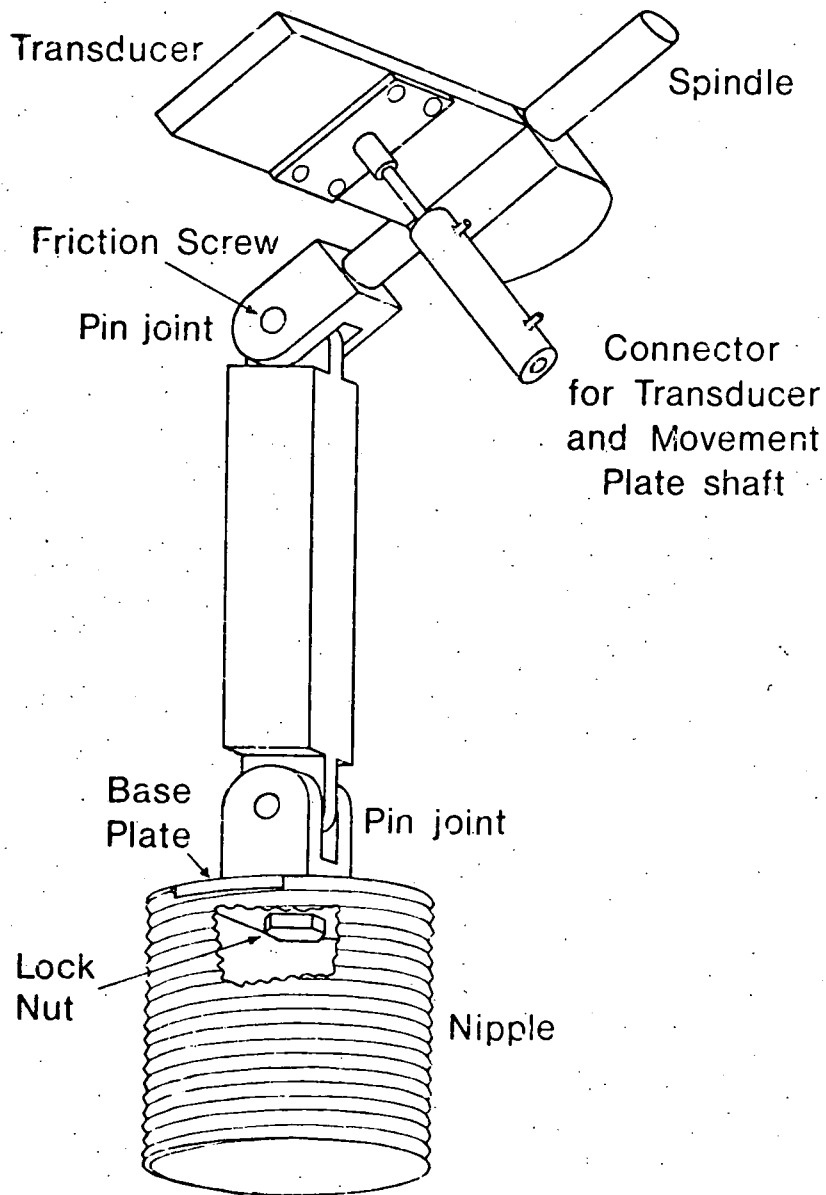


Fig. 2.3 Linear Motion Transducer

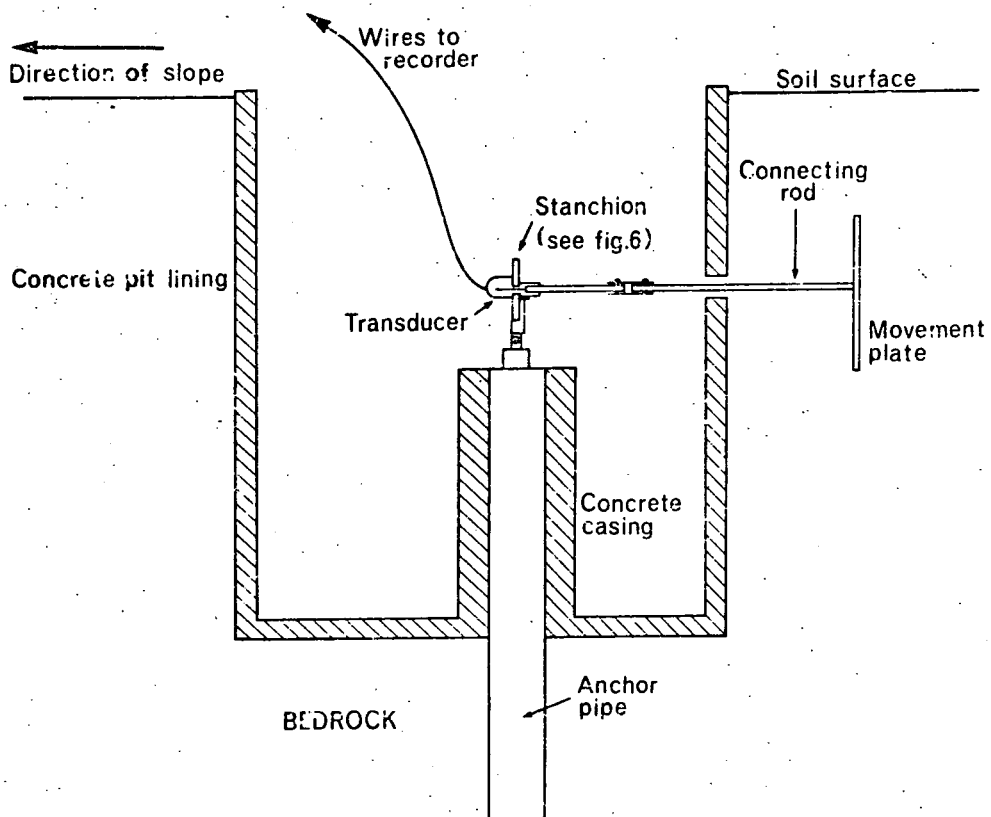


Fig. 2.4 Pit for Transducer Unit

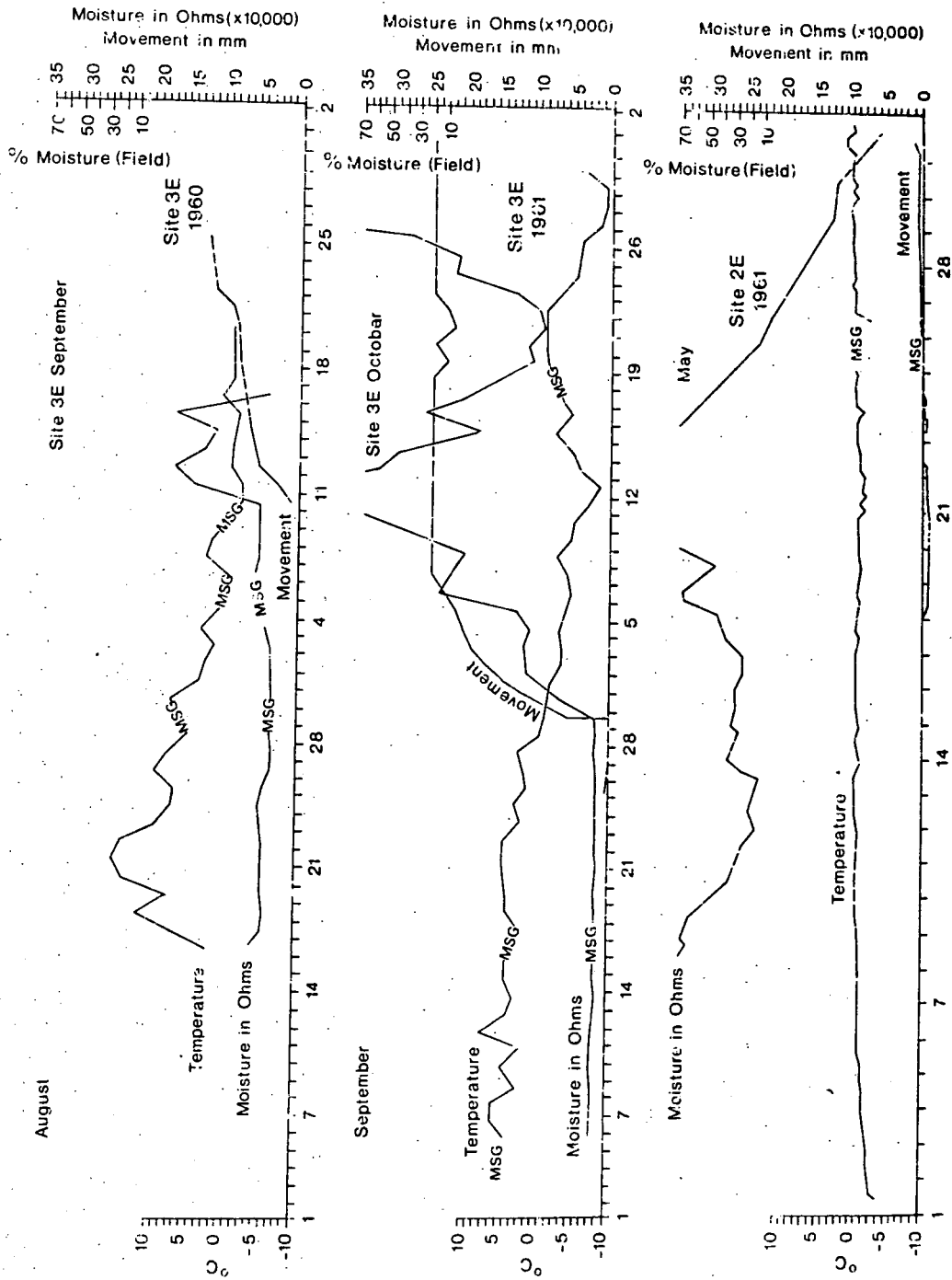


Fig. 2.5 Linear Motion Transducer Results

in theory, movements as small as 0.001mm can be detected, but Everett reports that, owing to recording limitations, only those greater than 0.2mm can be reliably measured. There are however major limitations in the use of linear motion transducers, particularly concerning the considerable soil disturbance involved at all stages of installation. In the design described by Everett, the concrete pit lining immediately downslope of the plate must itself influence creep rates, and also, movement is only recorded for one depth. However it would seem possible that the transducer unit could be installed in a simple tube and that the anchor post could be modified to support a number of transducers and plates thereby allowing a profile of movement to be measured. Another difficulty is common to all electrical devices which, in a field situation, are liable to interference and breakdown. The provision of sufficient insulation and a housing to cover the instruments adds to the problems and makes possible damage more likely. When the expense is considered, it must be concluded that replication possibilities are limited.

2.2.4. Strain Gauges

There are many different types of strain gauge but those normally used for the measurement of soil creep are made to be read electrically and consist of a thin wire or foil wound back on itself several times and bonded to a suitable backing. When a gauge is stretched in the direction of the windings, there is a small change in the resistance of the wire or foil which can be detected using a Wheatstone bridge arrangement. If gauges are attached to a flexible rod which is inserted into the soil, bending at various points caused by creep can be measured.

Williams (1957A and 1957B) developed a spring-steel probe 2cm wide, 1mm thick and 1 to 2m long with two or three gauges per metre, the whole device being sheathed in cold setting Araldite-type plastic. It was found that with these dimensions, the probe did not strengthen the soil or reduce shear, and twisting did not occur. Probe curvature of the order of 1mm in 1m, equivalent to 4 microstrain, could be measured.

The accuracy of field readings depends largely on the careful arrangement and insulation of the gauges and their leads. The probe itself needs to be cleaned, degreased and slightly roughened, while any internal stresses in the metal can be released by annealing. The gauges for any one probe should be taken from the same batch to ensure comparability of drift and temperature sensitivity. They should be mounted on opposite faces of the probe in pairs so that with bending, one pair is in tension and the other in compression (Fig. 2.6). The four gauges at each point form the arms of a Wheatstone bridge so that when a known voltage is supplied, changes in offset voltages may be measured when required.

Before installation, the instrument must be calibrated so that sensitivity can be converted to amounts of linear movement. However this may need to be repeated, as Williams has stated that changes may occur with time. When calibrated, the probe is inserted into the soil using a bore hole, and the sides of the hole around it are carefully packed with fine sand or mud. If movements are to be continuously recorded, the above ground measuring apparatus needs to be carefully protected and special precautions must be taken to ensure a stable supply voltage.

A modified system resembling the S.G.I. Inclinator, has been evolved by Williams (1962) in which the strain gauges are mounted on a steel strip inside a probe of epoxy resin. This is inserted into a plastic tube of 1.5cm internal diameter and 1.5mm wall thickness, buried perpendicular to the ground surface, and measurements can be taken at successive depths giving a profile of movement. This overcomes inaccuracies associated with packing the bore hole and soil disturbance during installation. Leopold, Wolman and Miller (1964) report that a 90cm probe with four attached strain gauges was used at Bethesda, Maryland, in 1961 and readings were taken weekly. Iveronova (1964) mentions that Zhigarev (1960) has been using a similar technique in the north eastern U.S.S.R.

A further modified model has been employed by Ellis (1973) and Sugden (1973) on a mobile tip in Somerset.

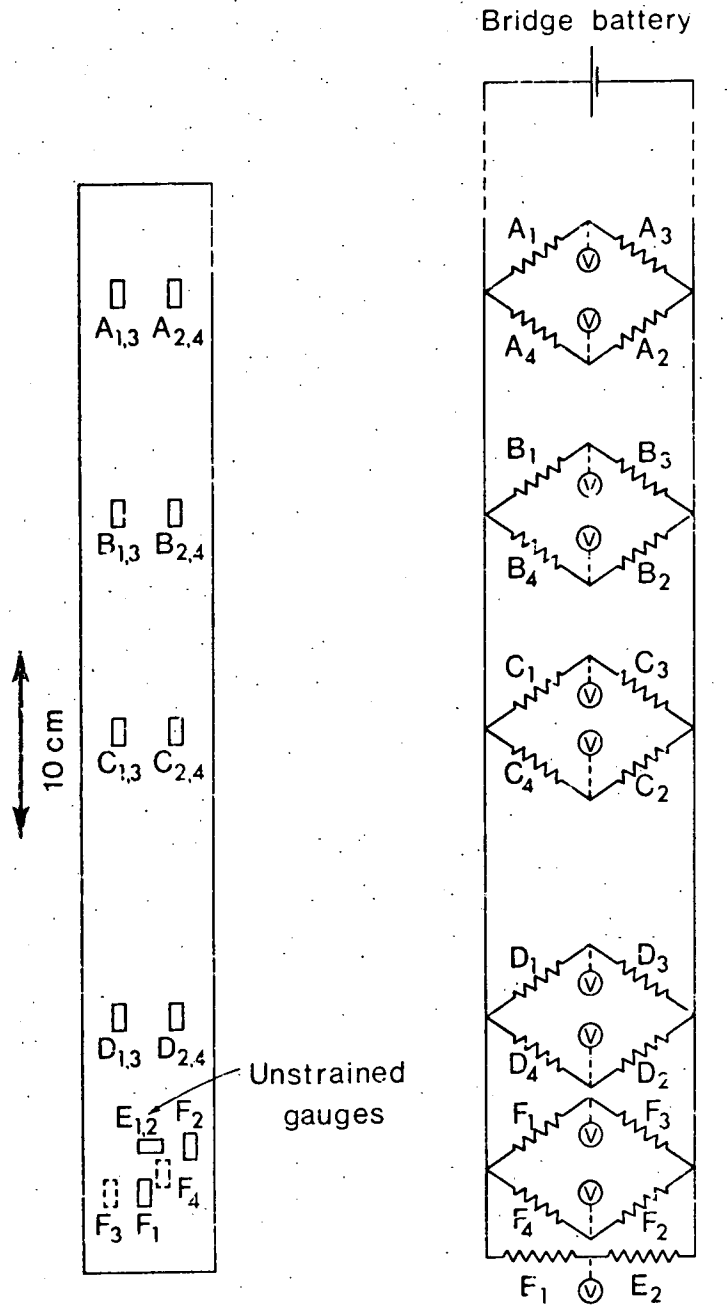


Fig. 2.6

Gauge Arrangement and Bridge Network

They found it possible to detect movements of 0.03mm over a 10cm length of probe, but the work only continued for a five day test period. The major innovation in their method is the provision of an aluminium rod 10 to 12cm long, fixed vertically to the top of the probe. A measuring device using an engineers level vial is slid over this rod so that the angle of tilt of the probe at the ground surface can be read (Fig. 2.7).

Strain gauges are very sensitive to soil movement and are therefore particularly suitable for short term and continuous measurements. They are also quick and easy to read, and on completion of an experiment, the probe can be excavated and its curvature checked against the results obtained. A further advantage is that unless continuous readings are required, there need be little of the instrument exposed above ground and liable to damage. The major limitations of this technique concern the provision of an electricity supply on site and the difficulties and costs of construction, calibration and continued operation. There are numerous points in any of these processes where serious errors could be introduced and the services of an electronics technician required. During installation there may be comparatively little soil disturbance, but changes in soil texture produced by packing the bore hole must lead to inaccuracy. If the Wheatstone bridge is to be left with the strain gauge leads permanently attached, an insulated housing must be provided and a wide sample area cannot be covered without extensive wiring. In this case replication is limited and there is a great danger of interference.

2.2.5. Strain Gauge Inclinator

This technique developed by Hutchinson (1970) measures the profile of a flexible tube inserted vertically into a soil profile by means of a strain gauge mounted between a pair of bogies. The instrument is lowered down the tube and the curvature of the tube at various depths measured by means of the strain gauge.

A similar instrument has been used by Plantema (1953) and by Kojan (1967) who gives the following description:

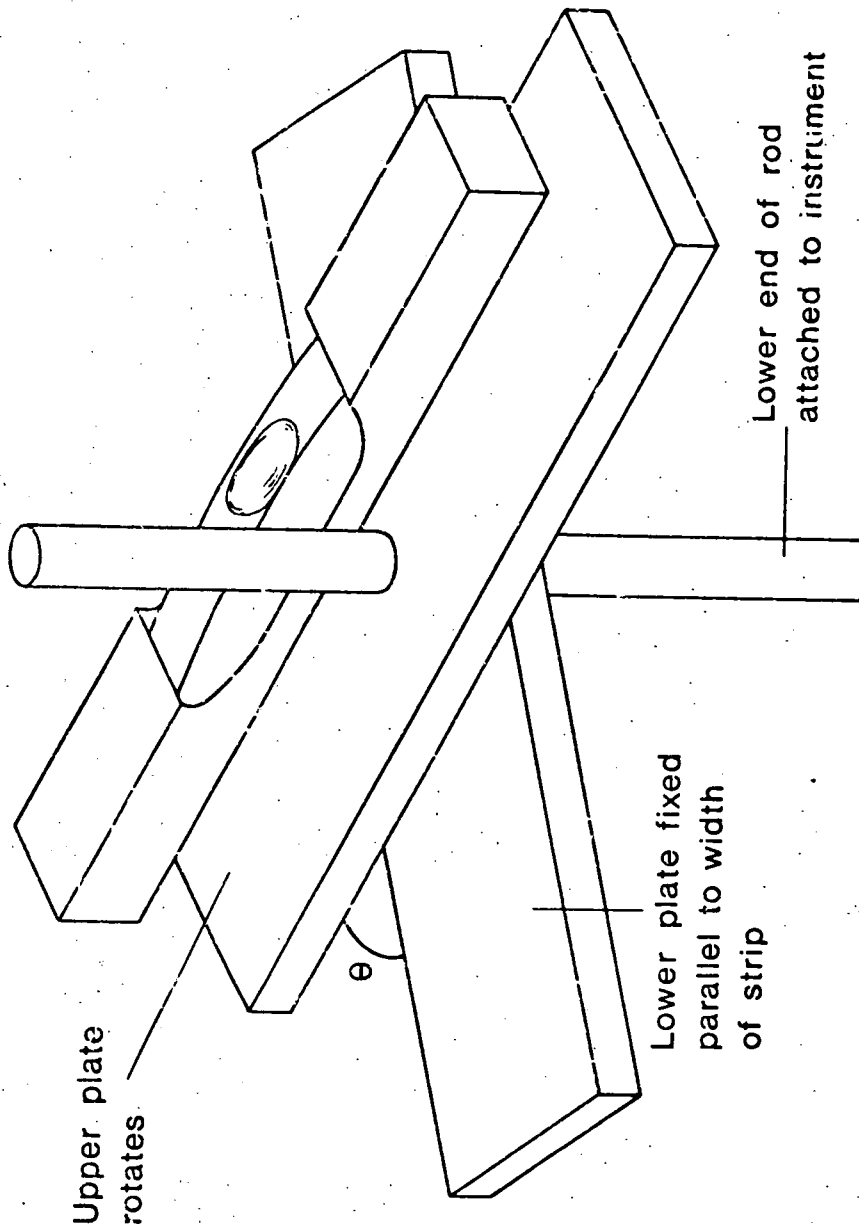


Fig. 2.7 Inclinometer for Strain Gauge Technique

'An S.G.I. Inclinator (Kallstenius and Bergau, 1961) was improved by the installation of modern, high-resolution strain gauges. The readout is via a Baldwin-Lima-Hamilton Model 120 Strain Indicator. Periodic calibration of the instrument is provided by a high precision sine plate, gauge blocks, and a granite surface plate. By means of appropriate calibration and measurement techniques, the simple and reliable system has a resolution of about 5 seconds of arc and a reproducibility to within less than 15 seconds of arc, giving the capacity to measure as little as 1mm of lateral creep in a 10m deep hole. The performance of this instrument system is remarkably stable between calibrations. Periodically, the three-dimensional configuration of smooth-walled P.V.C. pipe installed through the soil and well into bedrock (up to 18m in depth) is determined. Projections are made both in the plane of maximum displacement and in a horizontal plane. Comparison of successive surveys indicates direction pattern and rate of creep.'

2.2.6. Finlayson's Helix Tube

This is a sophisticated bore hole technique being developed by Osmaston and Finlayson (Department of Geography, University of Bristol) in the Mendip Hills, Somerset (personal communication 1974). The basic device is a flexible plastic tube with a wire helix, four sets of cross wires at required depths and a sealed light source at the base. Using a travelling telescope and the light source, the higher crosses can be aligned against the lowest and movement measured at any depth. The measuring instrument comprises a modified theodolite telescope mounted on micrometers giving movement in X and Y directions set on a portable tripod and capable of fine adjustment for level. The micrometers have a resolution of .001mm. The system has the great advantages of easy and cheap replication and little soil disturbance during installation, while readings can be obtained at any time interval although not continuously. There is little likelihood of damage but there may be some disturbance while taking readings. The main limitation is that no measurement of

bodily movement can be obtained without a separate survey. However it is not yet possible to draw any conclusions about this instrument or compare it with those already described since it is still in the experimental stage and no readings have yet been published.

2.2.7. Discussion

Comparing these first three instruments, it can be seen that all are expensive to construct and all are capable of giving extremely accurate readings. Beyond that, they vary considerably but the linear motion transducer as described by Everett shows most limitations. A great deal of disturbance is caused during its installation, it cannot be used to obtain a depth profile and it is too costly to replicate freely. Furthermore the exposed parts are very vulnerable to interference. On the other hand, it does give a reading of bodily movement for the section of the soil profile being tested and can be employed for continuous measurement.

With the S.G.I. Rod Inclinator there is little disturbance during insertion and the tube can clearly be easily replicated.!it may be advantageous to install relatively inexpensive materials at a large number of sites and combine these installations with a single relatively expensive and sophisticated device which is able to record the movement at each installation in turn' (Carson and Kirkby, 1972). The instrument would seem to fit the pattern suggested well, although it cannot be used for continuous recording and does not indicate bodily movement.

Strain gauges as normally used probably come between the foregoing two instruments on a utility scale. They are comparatively costly to replicate and possess the disadvantages inherent in electrical devices, but they cause little soil disturbance during insertion, yield a movement profile and can be used for continuous measurement. The modifications developed by Williams (1962) largely overcome the problems but at the expense of continuous measurement.

'These methods of measuring creep using a flexible tube insert in combination with strain gauge carriage-mounted measuring devices come close to the ideal in many ways' (Carson and Kirkby, 1972).

The S.G.I. Inclinator and the modified strain gauge instrument therefore seem to exhibit most advantages; the measurements are sensitive and can be repeated frequently; the tubes are inexpensive to replicate and only the single probe is relatively costly. However the level of accuracy is in some cases disputed and anyway needs to be justified in the particular fieldwork design, continuous recordings cannot be made and the method has to be combined with another survey to provide evidence of bodily movement.

2.3. Instruments which measure in the long term

2.3.1. General

For measuring the low rates of movement typical of soil creep, these instruments could not be used in the short term as the limits of their accuracy are of the same order as the readings required. However, in the long term, they can allow overall erosion losses to be calculated and also provide a check on and complement to, other techniques. The major advantage of this group of these instruments is that they are mostly very inexpensive to construct and therefore replication is easy, allowing for example, comparisons of rates within a plot as well as between plots.

2.3.2. Pillars

A series of stakes or pegs is placed vertically in the soil in a predetermined line, usually along a contour or orthogonal to it. Any movement of the stakes is measured with a steel tape, or more normally, a theodolite from monumented fixed points. A large variety of rods, pipes or pins made of wood, iron or other suitable material has been reported for this type of measurement. The length of each rod is usually between 15 and 50cm, but

again there is great variation. For example, Leopold, Wolman and Miller (1964) used rods 21cm long, Emmett (1965) 25.4cm, Schumm (1967) between 60 and 90cm and Gerlach (1967) specified oakwood stakes of 50cm. Similarly a range of diameters is quoted, generally between 0.13 and 1.3cm, but Emmett (1965) considered that this dimension was not critical. There are also differences in the length of rod left protruding above the soil although most are between 1.3 and 5cm. Miller and Leopold (1963) left 1.3 to 2.5cm upstanding and Emmett (1965) 5cm. To aid sighting, the tops of rods may be notched (Miller and Leopold, 1963), in some way inscribed, as for example by the crosses cut in solder used by Kirkby (1963), or be capped by inverted cones (Washburn 1960). Measurement is commonly by a transit theodolite which fits over a monumented fixed point (Miller and Leopold, 1963, Emmett, 1965) but a steel tape has also been used (Rapp, 1960). The fixed points may be long stakes driven deeply into the soil or baserock, natural rock outcrops (Young, 1960), or even bolts in large trees.

This technique, used by a large number of workers, was first reported in detail by Miller and Leopold (1963) as a result of their research in semi-arid New Mexico. The stakes were iron rods or pipes, 17.5 to 30cm in length, driven as vertically as possible into the soil, leaving 1.3 to 2.5cm protruding. They were spaced at 1.5 to 3m intervals along the contours in series extending up to a maximum of 30m, thereby minimizing surveying errors. The fixed points comprised stakes 1.2 to 1.5m in length driven into the soil at each end of the line to a depth assumed to be unaffected by creep. One such stake was designed to allow the transit theodolite to be placed over it. An indelible notch was filed in the top of each stake along the line of sight and the amount of movement could then be measured by any angular displacement from this line of sight. For resurveying, Emmett had a scale held with the zero marking placed accurately at the centre of the stake so that movement from the original line of sight could be read to this.

This technique is recommended by Miller and Leopold (1961)

and Emmett (1965) as part of the Vigil Network scheme in the U.S.A. and by Slaymaker (1965) and Slaymaker and Chorley (1964) for the similar scheme in Britain. In fact an accuracy of 0.25mm is claimed for this method.

The main advantage of this system is that it is simple and readings can be taken rapidly at any time interval required, several from the same fixed position. The stakes are inexpensive and an experimental area can be fully instrumented. However the rate of creep measured is that at or near the surface and there are no indications of the velocity profile. Furthermore it would seem to be very difficult to distinguish between tilt and absolute or bodily movement. Another problem is the difficulty of establishing fixed points with a theodolite platform that ensures stability. If a tape is used for measurement, especially over long distances, there may be problems in keeping it at the correct tension. Finally, since the stakes protrude above the soil, they are vulnerable to disturbance.

2.3.3. Bore Holes

Flexible columns of material are inserted vertically into the soil so that a profile of movement with depth can be obtained. The bore hole can be made with an auger or hollow tube, and for example, Rudberg (1962 and 1964) and Iveronova (1964) used an iron pipe while Hadley (1967) employed hollow steel tubing 90cm long, with an external diameter of 1.2cm and a wall thickness of 0.85mm. For insertion, a solid steel rod was placed in the tube and the two were driven into the soil. Since nothing protrudes above the surface, the exact position of the bore hole is marked with a short wooden stake or painted bench marks.

A number of different materials have been installed in the bore hole but most commonly, wire and cylinders. Williams (1957A) used varying lengths of 8mm diameter lead cable, while brass and copper wire have also been reported. Rudberg (1962 and 1964) and Rapp (1967) inserted columns of plastic or wooden cylinders, each measuring 2cm by 2cm while Iveronova employed wooden cylinders from 5 to 10cm long. For their columns Everett (1963) used cylinders

of modelling clay frozen in dry ice, Schumm (1964) used glass beads, Hadley (1967) specified glass beads or coloured sand grains of approximately the same median diameter as that of the local soil and, besides lead cable, Williams (1957A) also employed iron nails 15cm long.

As it is important for the columns to be as vertical as possible, installation is guided by a plumb line. In each case, soil or mud is gently pressed into place to fill the sides of the hole. To obtain readings, the column is extremely carefully excavated and movements from the vertical are measured by plumb line, assuming that the lowest cylinder or part of the wire has remained static.

As with the pillars, the technique is simple and inexpensive so that large scale replication is facilitated, but unlike pillars, there are no protruding parts to be disturbed. The other major advantage is that a profile of movement can be established and, if the lowest cylinder has remained fixed, bodily movement can also be measured. The visual impact of seeing the effects of relative and probably absolute movement should be mentioned. Further, with sand grains and small discrete particles, an assessment of diffusion as a possible creep process can be made (Carson and Kirkby, 1972). The main limitation of the technique is that normally only one reading can be taken as the soil is greatly disturbed during excavation. Another problem is that in packing the bore hole, the soil structure will be altered. Also a space is likely to remain between parts of the column and the bore hole and there may well be a discrepancy in measurements as a result of this. Iveronova (1964) states that 1mm must be allowed for this, but it is very possible to reduce such a figure which would tend to nullify the technique.

2.3.4. Cassidy's Tubes

A number of workers (Owens, 1969, Rudberg, 1958 and 1962) have used flexible plastic tubes installed vertically in the soil in what is a special category of bore hole techniques. Caine (1965) inserted 30cm lengths of 9.4mm diameter P.V.C. tubing into low angle scree. When it

is intended to measure the deformation of the tube only, the method of Cassidy (reported in Kirkby, 1963 and Selby, 1966) would seem to be the most reliable. Lengths of smooth-walled P.V.C. tubing of the order of 1.3cm internal diameter are sealed at the lower end and lowered into a vertical auger hole in the soil. A rod can be placed inside the tube and used to push it gently in as a tight fit with minimum disturbance is required. A cap can then be placed on the tube. When the reading is required, the tube is filled with quick setting cement and, as with other bore hole techniques, extremely carefully excavated so that the profile can be measured in the soil. The velocity profile is obtained with a theodolite, a photograph and a plumb line or a plumb line and a steel tape. The calculations of movement depend on the fact that initially the tube was vertical.

As with all bore hole techniques, this method has the advantages of being simple, inexpensive and easy to replicate, with no protruding parts which can be damaged. However it gives only one long term reading of the profile and its accuracy depends on the validity of the assumption that the tube was originally vertical.

2.3.5. Hydrofluoric Acid Cylinders

This is a more sophisticated bore hole method in that, although long term, it is not limited to one reading only. A small glass cylinder partly filled with hydrofluoric acid is lowered down a flexible tube, inserted vertically into the soil (Fig. 2.8). It is held at the required depth while the acid etches an ellipse on the glass from which the angle of inclination, and with several readings, the profile of the tube can be obtained (reported in Dury, 1966).

The necessary length of P.V.C. tubing, bound with a wire helix to retain its cross section while flexing, is fitted with a stopper at the upper end and sealed with encapsulating resin at the lower. The resin plug should have a diameter slightly greater than that of the tube (Fig. 2.9). A vertical auger hole is made and the tube installed by a special insertion tube made of thin-walled metal with three indentations moulded in it

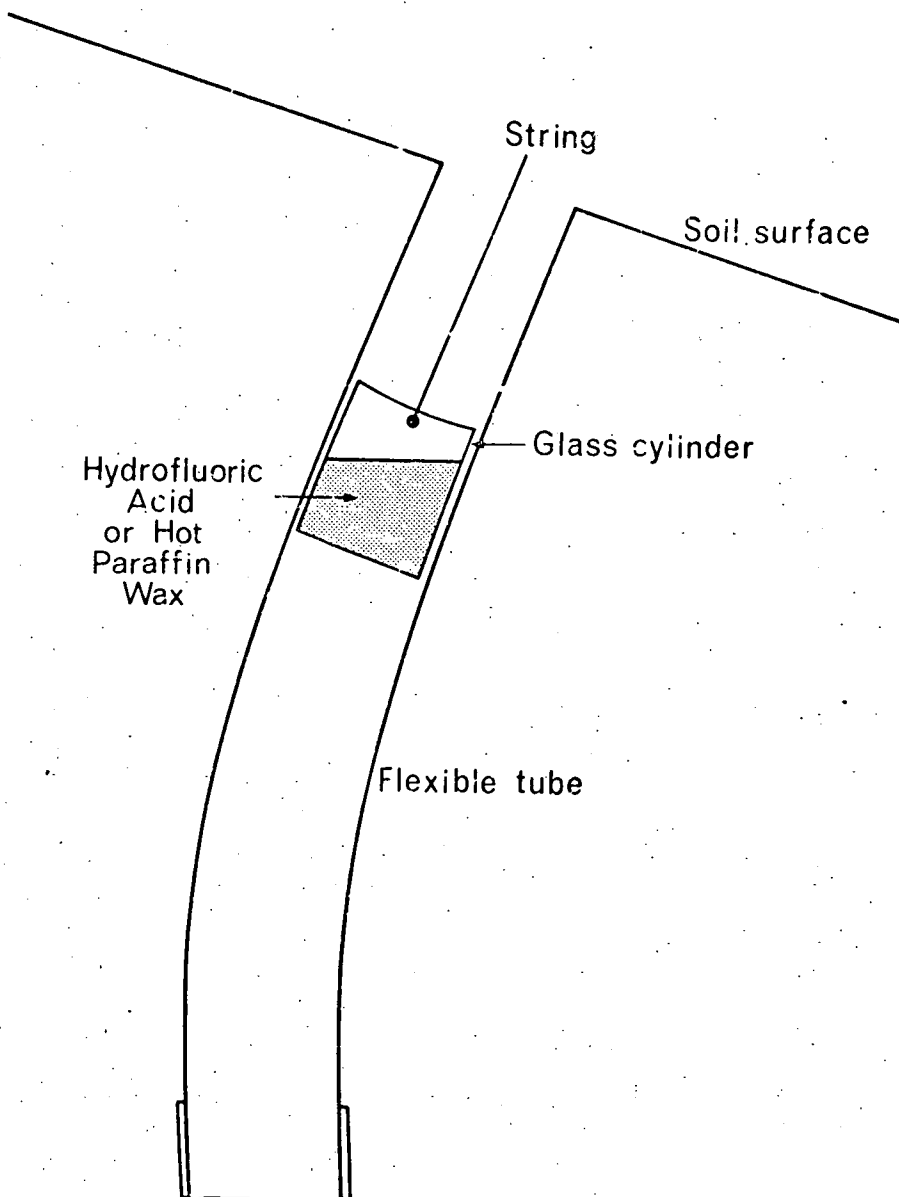


Fig. 2.8 Hydrofluoric Acid Technique: Insertion of Cylinder

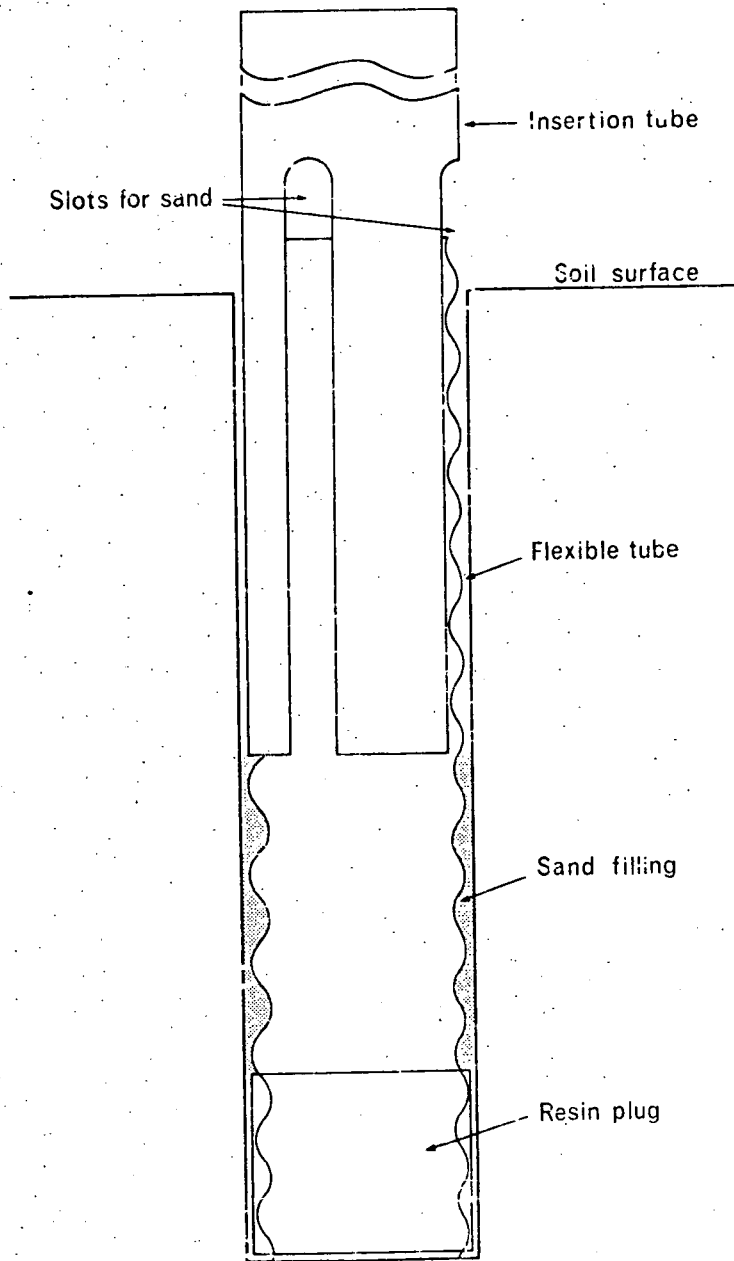


Fig. 2.9 Hydrofluoric Acid Technique: Installation of Tube

for a length slightly greater than that of the P.V.C. tube. When the instrument is in place, dry sand is poured down these indentations and while the insertion tube is slowly withdrawn it is used to pack the sand. After a period has been allowed for settlement, readings may be taken with the acid at successive depths to determine the initial profile with which all subsequent measurements are compared.

This technique exhibits all the advantages of the other bore hole methods with the important addition that readings can be obtained when required. It is not sufficiently sensitive to record short term movements and its accuracy is limited by the precision with which the ellipse angle can be measured. There are other limitations in that there is no record of bodily movement unless the top of the tube is fixed by accurate survey and also great care must be exercised in handling hydrofluoric acid, especially under field conditions.

2.3.6. Young's Pits

This technique was devised by Young (1958) to measure both the vertical and the horizontal movements of soil down the profile, and several variations have been reported. The basic idea is to record the movement of a column of thin metal rods, each 10 to 20cm long, inserted horizontally into the soil. A range of rod diameters has been employed, Emmett (1965) using 1.6cm and Young (1960) 2mm, while a further refinement with soft aluminium strips each 2.5cm long and 0.8mm in width has been developed (Emmett and Leopold, 1967).

In the original version of the method, a narrow pit approximately 90cm long was excavated to bedrock in a downslope direction (Fig. 2.10B). Six metal skewers were firmly driven into the bedrock joints, three at the upslope end of the pit and three at the downslope. Midway between the skewers, a column of 12.5cm long thin metal rods was inserted into the side wall of the pit perpendicular to the angle of slope, leaving in each case 6.2mm projecting. The position of each rod was then fixed from the skewers by metal tape and for this, an accuracy of 0.8mm was claimed. For protection, the

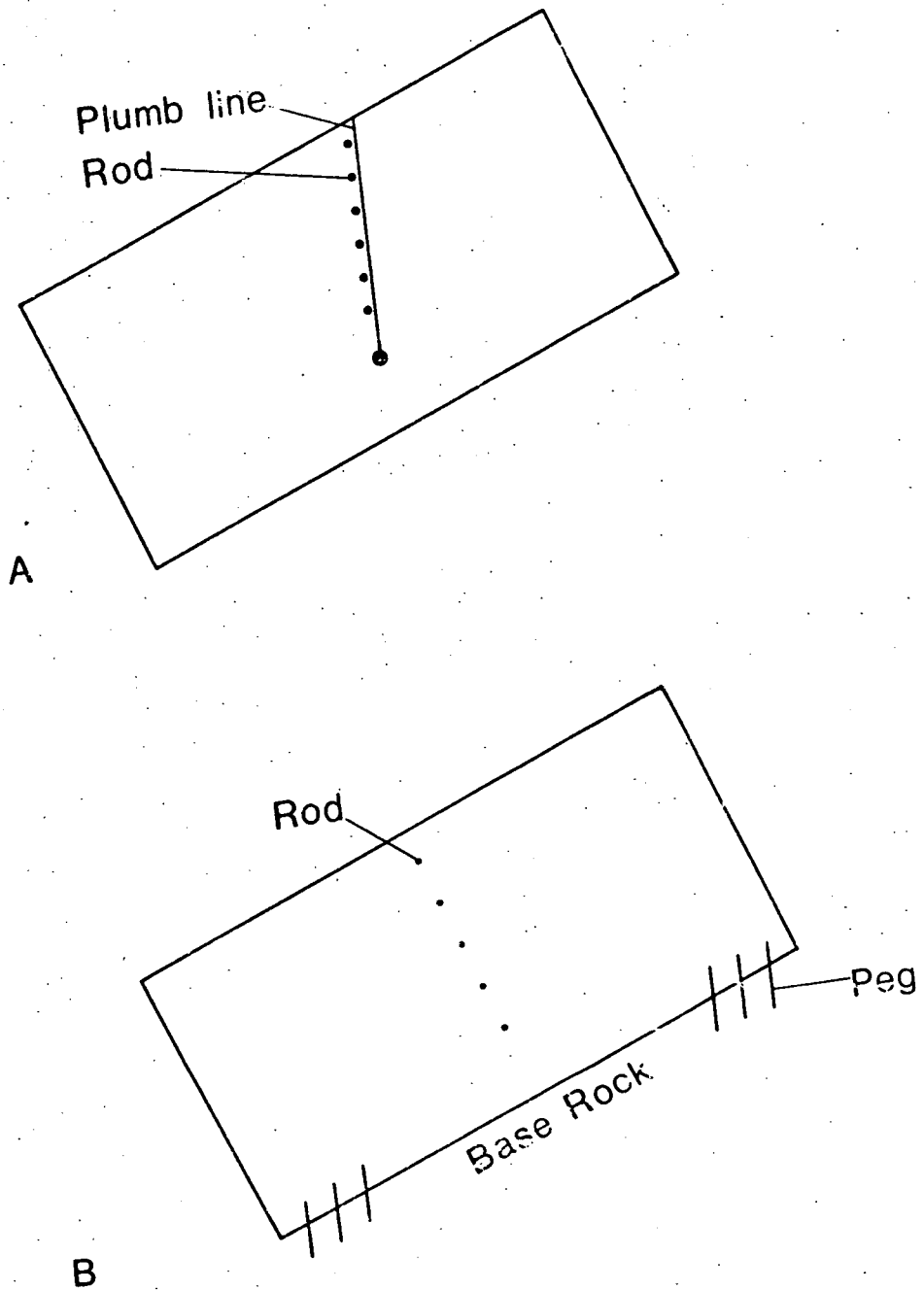


Fig. 2.10

Young's Pits

skewers were then covered with metal tins and paper was spread over the rod ends before the pit was carefully infilled.

In the later modification, a pit of similar dimensions but approximately 45cm deep (Emmett, 1965), is dug and the first rod inserted near the midpoint of the side wall at its base. This rod, because of its depth, is assumed to be stationary and acts as a control. A plumb line is suspended centred on it, and using this, the remaining rods are driven in at measured intervals in a vertical column so that all are flush with the pit wall (Fig. 2.10A). The rod ends are covered with plastic sheeting to help later excavation and act as a marker, and the pit is carefully refilled. To obtain readings, the pit is uncovered, the plumb line is suspended over the lowest rod and the distance the other rods have moved from this line is measured. This method allows a more accurate indication of the horizontal component of movement, but only an approximation can be made of vertical movement. An accuracy of 0.25mm is claimed for this approach. Emmett (1965) introduced further refinements, as in the opposite wall to the rods he placed a line of soft aluminium strips in a prepared notch. Each strip was cut into segments 2.5cm long, joined together by adhesive tape which, on refilling the pit, quickly decomposed leaving the segments free to move and leaving soil shear unaffected. For measurement he used a transit theodolite and monumented fixed points consisting of 1.2m steel bars sited some 2.4m on either side of the pit along the contour. The rods and strips were inserted with reference to this line of sight and the pit was relocated from stakes placed upslope and downslope from it. Young (oral communication) has developed the technique further using acrylic rods in place of the metal rods and cementing the skewers to the bedrock.

With this method it is possible to obtain direct measurements of both horizontal and vertical movements in the soil profile and if the pit is re-excavated carefully it can be re-used. Replication is inexpensive

and also, since they are buried, the rods cannot be disturbed and can therefore be left over long periods. However there are several disadvantages, particularly concerning the disturbance to the soil system during excavation and refilling, even though the rods themselves are not directly affected. It is also thought that a concentration of moisture could occur in the reconstituted soil, and as moisture is postulated as a major cause of creep, this could lead to serious errors. Furthermore it seems improbable that the pits can be re-excavated more than a limited number of times without disturbing the rods.

Finally, there is the problem common to any such technique in which measurement depends on a plumb line, in that except in the very long term, the reading error may exceed the actual movement.

2.3.7. Selby's Cones

Aluminium cones buried in the soil are attached by wires to a fixed post or pipe and downslope movement is found by measuring changes in the length of each wire at the fixed position. The cones are 4.5cm high and 6cm wide at the base, with a 9cm long rod welded inside the apex by which they are attached to the required length of 1mm diameter piano wire (Fig. 2.11C). To install them, a narrow pit is excavated normal to the slope and each cone is pressed into the downslope face of this at a known depth. The wires can then be led either in a horizontal direction back to a fixed pipe (Fig. 2.11A) or in a vertical direction up to a fixed post (Fig. 2.11B). The pipe or post is precisely located by survey and its angle of inclination recorded. The wires are fixed at the upper end, but in the case of the pipe they have to first pass in through holes lower down.

Washburn (1960) describes a similar technique which he used in North-East Greenland to measure rates of solifluction. In this method, the cones are replaced by bricks, measuring 4cm by 5cm by 9cm, and the wires pass to dial gauges mounted within a transparent weatherproof hood at the top of the fixed tube. The

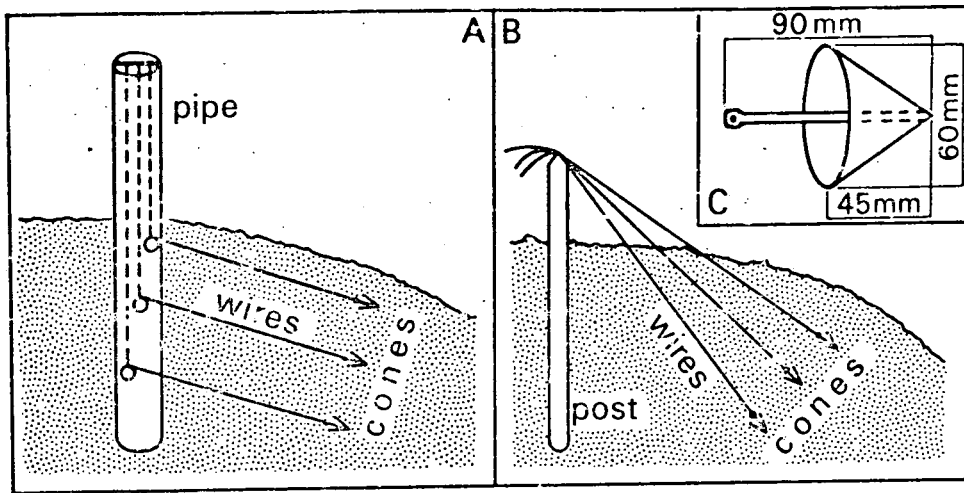


Fig. 2.11

Selby's Cones

gauges register movement in degrees of arc, being calibrated so that 18 degrees in one model and 23 degrees in the second is equivalent to a change of 1cm in the length of the wire.

The device is simple to construct and cheap to replicate, and if the fixed pipe is used there need be no protruding parts. The other great advantage is that absolute movement and the velocity profile can be measured at any selected time interval. However, unless sensitive dial gauges are used, it is still a long term technique. The major limitations are the amounts of disturbance to the soil during installation and disturbance to the cones when tension is applied to the wires during measurement. Also, Washburn (1960) has stated that it is impossible to differentiate between downslope movement and heaving, as the same result will be indicated for both. This problem, which can only be solved by excavation to determine the final position of the cones, may not be so significant outside periglacial areas.

2.3.8. Painted Rocks or Markers

These methods have been most frequently used in areas where surface creep is relatively rapid and it can be assumed that the movement of surface markers will reasonably accurately reflect that of the surface layer of the soil. For example, they have been reported by Michaud (1950), Schmid (1955) and Washburn (1960) in periglacial conditions and by Schumm (1964) and Emmett (1965) in semi-arid environments. Measurements from fixed positions are taken of the movement of markers or painted rocks, the latter being either in their original positions or arranged in a particular pattern. Schumm used a variety of markers including metal washers 3.4cm in diameter, wooden discs 3.3cm in diameter and 1.9cm thick, and wooden blocks 5.1cm square and 1.9cm thick, besides painted rocks of different sizes. Jahn, reported by Dumanowski (1967) employed wooden boards measuring 5cm by 5cm and boulders marked with varnish. Barnett (1966) inserted wooden pegs into the boulders and Rudberg (1967) applied a small patch of paint to each rock along the line of sight by means of a taut line and plumb bob.

(1967B)
 Rudberg^A also reports that a guide to the depth and direction of movement can be obtained from observations of the preferred stone orientation on the surface and in depth. Various other patterns have also been detailed (Leopold and Dunne, 1971). Fixed positions are established by painting bench marks on suitable rock outcrops or large boulders, (Rudberg, 1967), or by cementing steel tubes into the rock (Demek, 1967) and measurement can be made by transit theodolite, tachometer (Demek, 1967) or steel tape.

This technique is significant mainly because a very large number of readings can be quickly and easily obtained once the problem of finding a fixed position has been overcome. The obvious limitation is that the movement of the markers may not accurately reflect even surface creep rates as a result, for example, of vegetation effects. There is also no indication of a velocity profile and the markers are extremely vulnerable to interference which will seriously affect results if it is not detected.

2.3.9 Vegetation

A crude measure of soil movement may be obtained from plant roots (Schumm, 1967) as, on unstable slopes, the roots may provide an anchorage but the plant will be carried downslope. A marked bend in the roots indicated movement, and rates can be inferred if measurements are made on annual plants. Evidence of stem and root curvature in trees and shrubs is available for some locations but must be treated circumspectly (Carson and Kirkby, 1972).

2.3.10. Discussion

All the techniques described within this category lack sensitivity, although in some cases, as for example Selby's Cones, modifications can be introduced to allow short term measurement. They are all simple, inexpensive to construct and allow large scale replication. They are therefore extremely valuable in providing the detailed instrumentation required if creep rates are to be accurately measured over a site of any size. They can possibly be used to complement the results obtained from a few more sophisticated instruments. A comparison can be made

between the two major classes; pillars can be read when required but provide no velocity profile, whereas bore hole devices give a measurement of movement with depth but can normally be used only once. Young's Pits and hydrofluoric acid cylinders present something of a compromise although the former, together with Selby's Cones can be criticised on the grounds of soil disturbance.

2.4. Instruments which magnify and measure the changes

2.4.1. General

This category comprises angular measuring devices of simpler design than the S.G.I. Inclinator and the strain gauge techniques. They consist essentially of a blade inserted into the soil the angle of which, when tilted by creep can be read usually by a separate measuring instrument. They therefore convert the soil shear rate into an angular measure which itself can be converted into a linear measure. They are relatively sensitive and can be read when required while being sufficiently inexpensive to bear extensive replication. However there are many problems of a general nature associated with their use (Reynolds, 1968) and they do not give a velocity profile.

2.4.2. Kirkby's 'T' Pegs

The peg consists of a steel blade 22.5cm or 37.5cm long and 6mm in cross section to which is attached a cross piece 15cm long, constructed from a flattened 'U' shaped spring steel bar measuring 3mm by 2.5cm. The cross piece, fixed centrally over the blade with the arms of the 'U' shape perpendicular to it, has welded on its upper surface 12.5cm apart, two brass or stainless steel 90 degree 'V' notches, each 1.6cm high, for carrying the measuring device. The open downslope end of the cross piece is held under compression by an adjustable brass screw and lock nut. Tilt is measured by an engineers level vial fixed parallel to a 15cm stainless steel rod, 1.3cm in diameter and true to $\frac{1}{10,000}$ in. The level vial itself is graduated in 10-second intervals and has a total range of ± 50 seconds of arc (Fig. 2.12). For movements

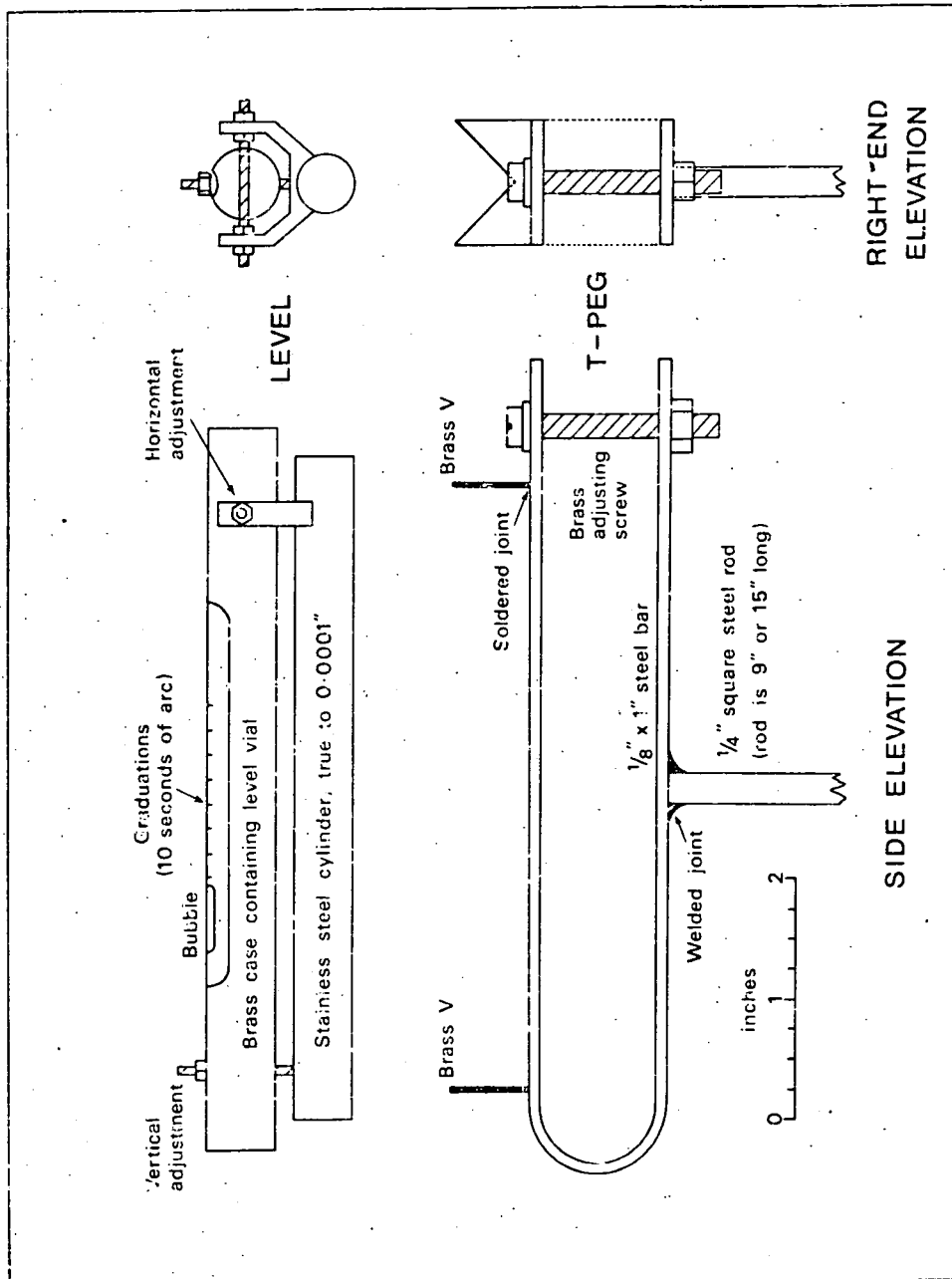


Fig. 2.12

Kirkby's 'T' Peg

in excess of 50 seconds of arc, the capability of the level vial, the adjustable brass screw can be used with somewhat less accuracy. Since this screw has a 1mm pitch and the effective length of the cross piece is 15cm, rotation through 17° alters the level of the bubble by 1 minute of arc.

The 'T' pegs are installed in the soil vertically in pairs, one 37.5cm long and one 22.5cm long, so that 7.5cm can protrude in each case and the long axis of the cross piece is parallel to the direction of maximum slope. If they are vertical the weight of the cross piece exerts as little disturbing effect as possible. The design of the instrument is such that the 37.5cm peg has a sensitivity of 4×10^{-4} mm and the 22.5cm peg a sensitivity of 8×10^{-4} mm, thus allowing meaningful measurements over periods as short as three days. Readings are recorded as positive for downslope tilt and negative for upslope, and results are more commonly used for correlation in assessing causes of creep than in measuring rates.

The peg is comparatively simple and inexpensive to replicate and only one level vial is required. Sensitive measurements can be obtained without disturbance and it is particularly suitable for short term results. On the other hand, the instrument is rather top heavy and unstable with a protruding part which makes it especially susceptible to damage. Therefore it is important to take regular short term readings which will reveal any interference. The design might further be criticized in that it is difficult to use the adjustable screw without moving the blade, and also that after a period of use the 'V' notches tend to lift owing to the tension in the cross piece. If the adjustable screw needs to be rotated to take a reading, there is no way of checking that particular measurement since the angle has been altered. It has also been suggested by Leopold (reported by Evans, 1974) that the width of the blade may not offer sufficient surface resistance to soil movement to measure it accurately. The other disadvantages are common to all the instruments in this category and will be discussed later.

2.4.3. Evans' 'T' Bar

Of the various modifications to the original design (Kirkby, 1963), that by Evans (1967) has been reported as particularly successful. His improvements included a redesigned lighter cross piece which was more stable and less liable to disturbance, and a broader blade. He also used an angular measuring device that was a completely separate unit.

The 'T' bar consists of a steel plate 5cm by 3.7cm by 1.2mm brazed to a steel blade 2.5cm by 6mm and 17.5cm long. The measuring instrument is a telescopic Abney level reading to 1 minute of arc, from which the heavy viewing column has been removed, mounted on a light alloy base plate of similar dimension to the 'T' bar top. With the aid of a plumb line, the 'T' bar is inserted, leaving 2.5cm protruding and the level is carefully placed on top. As a check, the level can be turned round and a second reading recorded.

The major advantages of this instrument over the Kirkby 'T' peg are that it is more stable and readings can be checked. It suffers from the problems typical of all the devices working on this particular principle.

Selby (1966) has also proposed a new model similar to the Evans 'T' bar in operation but different in design. The devices are to be of different lengths, 15cm, 30cm and 40cm, inserted along the contour between two fixed bench marks, thereby allowing the measurement of both tilt and bodily movement. The design is 'L' shaped, with both the blade and the plate being constructed of mild steel 2.5cm wide and 5mm thick. The measuring device will be similar to an Abney level, but from the size and shape of the 'T' bar it seems that there could be serious problems of stability.

2.4.4. Discussion

Angular measuring devices using the 'T' peg principle with a spirit level have many advantages in that they are sensitive, allowing short term readings, but inexpensive so that a research area can be fully instrumented. They can be easily installed with little soil disturbance and

can be read accurately and quickly. The Kirkby 'T' peg is the only one in which the complete measuring apparatus is not entirely separate. However there are certain limitations to the use of this technique, particularly the fact that soil shear is averaged along the length of the blade and neither the velocity profile nor bodily movement can be found. Also it must be assumed that the instrument pivots about its base point.

2.5. Conclusions

The basic idea of all the instruments discussed is that the mass movement of soil can be monitored when a soil column is replaced by some insert which can be measured. Clearly therefore, except in the case of the fine bore hole materials, any diffusion element cannot be investigated. It must be assumed that the device moves with the soil, for obviously if there is a tendency for flow to occur round it, the rate of shear will be underestimated. There is now a reasonable measure of agreement on the shape and size of insert required to indicate rates of movement but less is known about soil water and other effects at the soil/probe interface. Also while the gross soil disturbance caused by installation is clear, the effect locally on the soil system is unknown. A further discussion point is the angle of insertion, which can affect the results considerably. If the instrument is vertical, the influence of expansion and contraction must be considered, but the effect of gravity will be largely neutralised. To help counteract the rotation induced by expansion and contraction, a position normal to the surface could be used, but then it is likely that gravity will lead to an exaggerated measurement of the creep rate. However, perhaps most significant are the problems of the heterogeneity of the soil itself and the variations found in other hillslope variables (Carson, 1967). As a result, there may be markedly different rates of soil creep within a small area.

Therefore in selecting techniques for use in a drainage basin, these problems must be minimized as far

as possible and then, with a high degree of replication, the results should have maximum validity. No instrument which is expensive or causes great soil disturbance can be employed, although a sophisticated measuring device which can operate with simple inserts is clearly most suitable. However, the S.G.I. Inclinator, which could be classed within such a category, has the problem already discussed, of inaccuracy. The most sensitive within the other categories are the angular measuring instruments, although these exhibit obvious limitations. If it is accepted that the lower layers of the soil are static in terms of seasonal creep, 'T' pegs and the modified versions have much to recommend them in principle. They are inexpensive to replicate and can be read quickly and accurately, giving results in the short term. As they do not register bodily movement or indicate the velocity profile, they need to be combined with other techniques if a complete measurement of rates is to be obtained. If fixed positions are available, pillars are the simplest device for measuring bodily movement, while velocity profiles can be provided by bore hole inserts. Both categories are long term and lack sensitivity, but if they are being used to complement short term results this need not be a problem. It must be concluded that the apparatus employed imposes its own limitations on the interpretation of results, and for most research programmes, more than one instrument is likely to be required.

CHAPTER THREE

INSTRUMENT SELECTION

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3. INSTRUMENT SELECTION

3.1. Introductory

When considering instruments which might be used to measure rates of soil creep, the basic requirements for this part of the study were listed. Factors being assessed as possible controls can be broadly grouped under the headings of surface, internal and external, and measurements needed in each group do not necessarily coincide.

Surface variables such as aspect, slope, distance from base level and vegetation, remain comparatively stable for the period of the study and can therefore be evaluated by long term techniques. The heterogeneous nature of soil presents different problems with internal factors particularly in that there is a further dimension of depth. The main points of significance would therefore seem to be a facility for producing a velocity profile with depth and also a high degree of replication. However, soil moisture like the major external climatic variables investigated, can alter over a very short time period and for accurate assessment, demand regular short term readings. To complete the programme then, instruments are needed which can:

- (a) measure in both the long and the short term
- (b) give regular readings over a period
- (c) produce a velocity profile
- (d) measure both bodily and angular movement
- (e) be replicated cheaply and easily

It is clear that more than one device is required, and as will be described later, this fact played a prominent part in the experimental design. With detailed replication and a variety of instruments it is possible not only to compare results obtained on different sites, but also to check on the variability within each site. Since soil is the basic medium involved in the study and since its characteristics can change considerably over short distances, this approach

to the fieldwork is regarded as vital.

The advantages and limitations of all the main techniques for measuring soil creep have already been discussed and it can be seen that none of the extremely accurate instruments is really suitable in the context of this study. The linear motion transducer cannot be replicated on the scale required and its installation causes gross soil disturbance. A device embodying strain gauges could be installed in large numbers but the provision of an electricity supply and the insulation of the wires would cause great problems. The S.G.I. rod inclinometer, or some development of this, would appear to approach the ideal with accurate readings being obtained from simple inserts. However, the doubts as to its limit of accuracy in the short term together with the relatively high cost, tend to militate against it.

Within the category of long term devices, most of the techniques are simple and inexpensive to produce. Pillars have several disadvantages but one great advantage is that the number employed is only limited by the time available to read them. They also feature commonly in the literature on the subject and therefore comparisons can easily be made. Bore hole techniques and Young's Pits provide a velocity profile and have the added advantage of giving at least an indication of diffusive movements (Culling, 1963). Cassidy's Tubes also allow an estimate to be made of movement variation with depth. Selby's Cones are subject to a number of problems in the field, particularly the difficulties of installation and the likelihood of disturbance. The use of hydrofluoric acid cylinders, apart from the dangers involved, would place a severe limit on the number of readings which could be regularly obtained. Marked rocks and vegetation measures are considered to be too inaccurate especially within the time scale of this work.

The last group, the instruments which magnify and measure movement, presents many advantages, notably in that sensitive readings can be obtained regularly in the short term. Furthermore, as the actual measuring device can be separate, a large number of probes can be cheaply installed. The major limitations of this group can be

summarized:

- (a) The assumption must be made that the instruments average shear strength throughout their length and pivot about their base points.
- (b) The instruments provide a measure of the rate of movement at or near the soil surface and give no readings either for a velocity profile or absolute movement (unless fixed by survey).

It should be noted in this respect that Leopold (quoted in Evans 1974) felt that unless sufficiently large numbers of T pegs could be employed to allow the pivot point to be defined, the technique was of little use. In the Anderson Tube to be discussed later, this problem is overcome. All three types of T peg described suffer from being somewhat topheavy and unstable and therefore may easily be disturbed. On exposed sites, particularly those with a large population of grazing animals, these points are extremely important and only short term measurements, which would allow such disturbance to be recognised, are reliable. One other aspect which must be mentioned is the safety of animals as protruding metal probes with sharp edges can be dangerous and are certainly likely to bias farmers against instrumentation.

Kirkby T pegs have been used experimentally (Anderson, 1971) and design problems which became obvious have already been mentioned. However, the major weakness would appear to be one of technique rather than design in that once a reading has been obtained using the adjustable screw, the angle has been altered and no further check is possible. Many of the difficulties have been overcome with the Evans T bar although its shape renders it still liable to disturbance and rusting has proved a hazard (Evans, personal communication). The main criticism concerns the method of fitting the Abney level to take the measurements as there are no guides into which this fits, and although checks are possible, the whole procedure under field conditions is time consuming and liable to inaccuracy. A similar design has been used with horizontal pegs (Anderson, 1971) and, particularly in strong winds, the problems were clear.

Taking into account these considerations, it was decided that angular measuring devices offered the best possibilities for a high degree of replication combined with short term accuracy but that they would need to be supplemented by a number of other instruments if the basic requirements listed earlier were to be met. However, as none of the T pegs appeared entirely suitable, the specially designed Inclinator already tested with wooden pegs (Anderson, 1971) was used.

3.2. The Anderson Inclinator

The readings of creep are obtained from wooden pegs which have been carefully inserted into the soil as nearly vertically as possible. The Inclinator (Plate 3.1) is fitted gently over a peg and the inclination from the vertical in any direction is measured using a spirit level. The reading can then be converted to angular or linear movement as required.

3.2.1. The Instrument

The Inclinator is constructed essentially in two parts (Fig. 3.1):

- (a) the head comprising an upper limb (A), containing the spirit level which can be pivoted vertically by the screw about the mid point of the lower limb (B)
- (b) the base consisting of the base plate (C) with the direction card and rotating joint and the peg housing (D)

The basic structure is of angle aluminium alloy to keep the instrument light and therefore avoid any distortion of peg readings, but the moveable and threaded parts are of brass.

The vital measurements in the construction of the instrument are the pitch of the measuring thread (1mm) and the distance of the centre of the thread from the pivot point (10cm).

The peg housing needs to be made of 1.3cm angle aluminium alloy to fit tightly round the wooden pegs.

The detailed measurements in the construction of



Plate 3.1

The Anderson Inclinometer

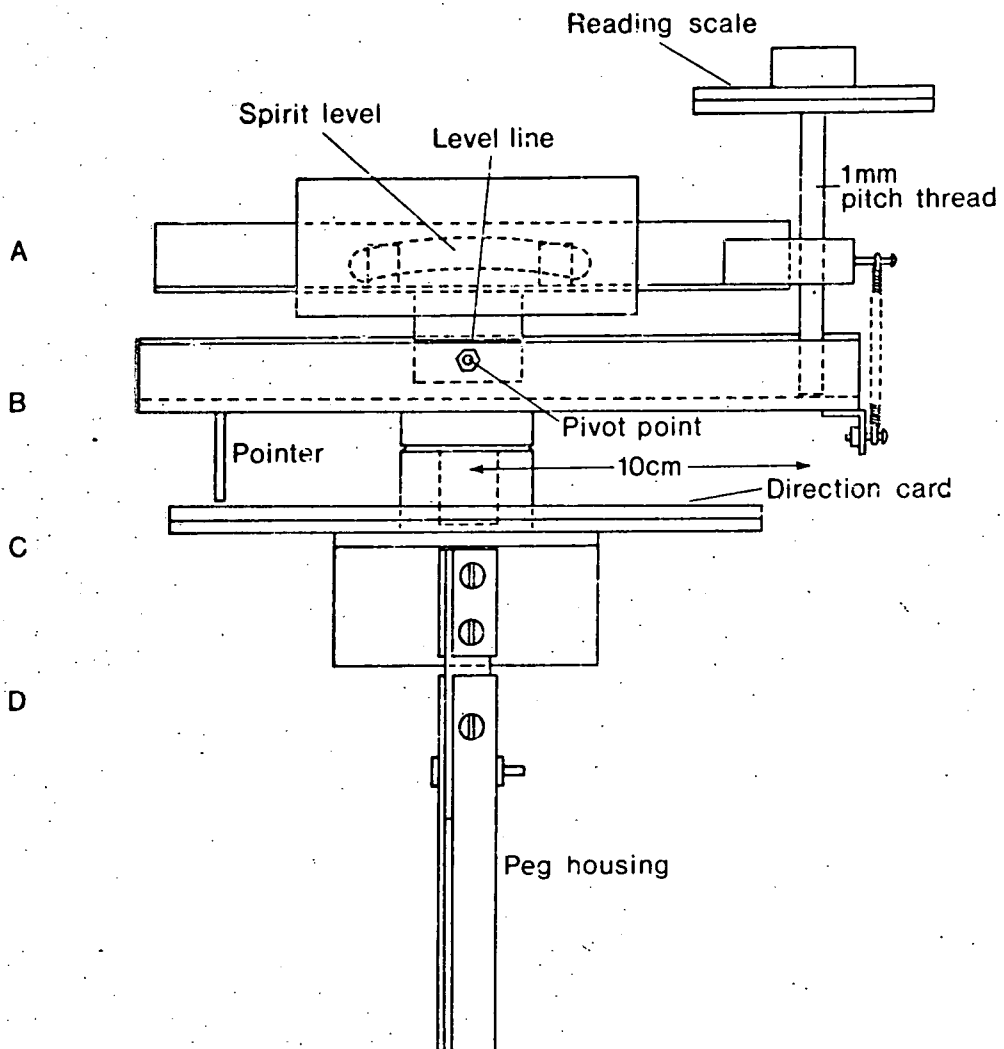


Fig. 3.1 Anderson's Inclinator

the instrument with the most important underlined, are given in Appendix 1.

Modifications

Since for the purposes of this study the Inclinator is only required to take readings in a downslope direction, it can be simplified and its weight reduced by fitting the peg housing directly under the centre of the lower limb (Fig. 3.2, Plates 3.2 and 3.3). Inter-cardinal measurements cannot then be made but check readings in an upslope or an across slope direction can still be obtained by resetting the peg housing. Later improvements in the design include the provision of a more easily read level position indicator and a better placed index marker. A further trial model incorporates a ball and socket joint (Plate 3.4) at the base of the measuring thread. However this modification has not been validated in the field and furthermore its importance is for use in the long term. Therefore readings for the present study were completed with the simplified model.

3.2.2. Procedure

- (a) Using the measuring thread the upper limb of the head is levelled. (The line on the pivot block should coincide with the upper edge of the lower limb and the measuring scale should read 0).
- (b) The housing bolts are slackened slightly and the Inclinator fitted over a peg.
- (c) If necessary, the housing bolts are gently tightened.
- (d) The measuring thread is turned until the bubble is central.
- (e) The reading on the scale and its direction (clockwise or anti-clockwise) is recorded. (In the original model the head can then be turned to another direction as required and a new reading obtained).
- (f) When the readings have been completed, the housing bolts are slackened and the Inclinator carefully lifted from the peg.
- (g) The upper limb of the head is then levelled before taking readings from another peg.

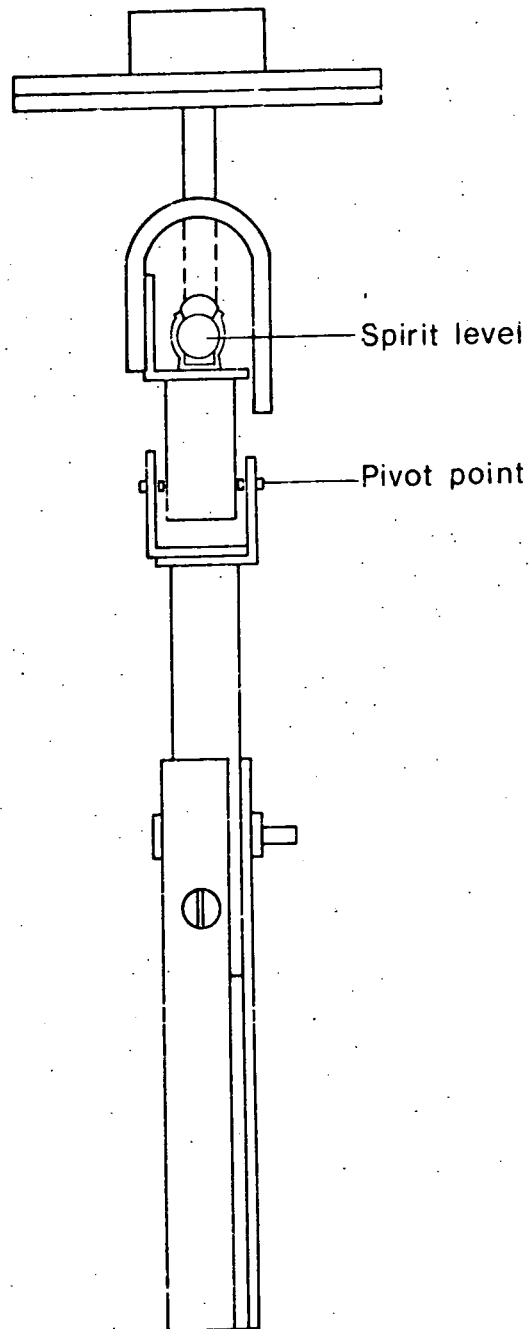


Fig. 3.2 Anderson's Inclinator: Simplified Model
(side view)

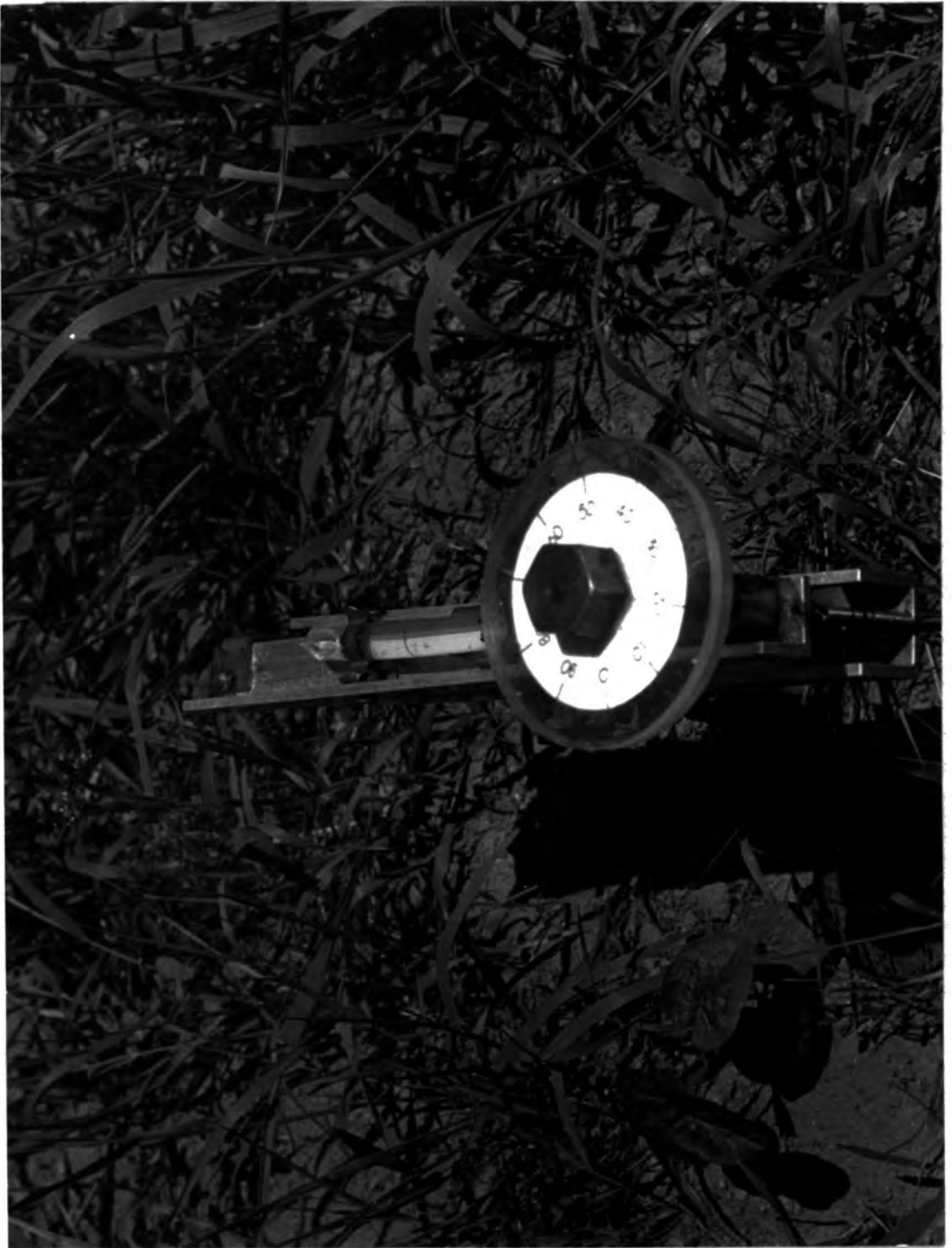


Plate 3.2 The Anderson Inclinator: Simplified Model
(top view)

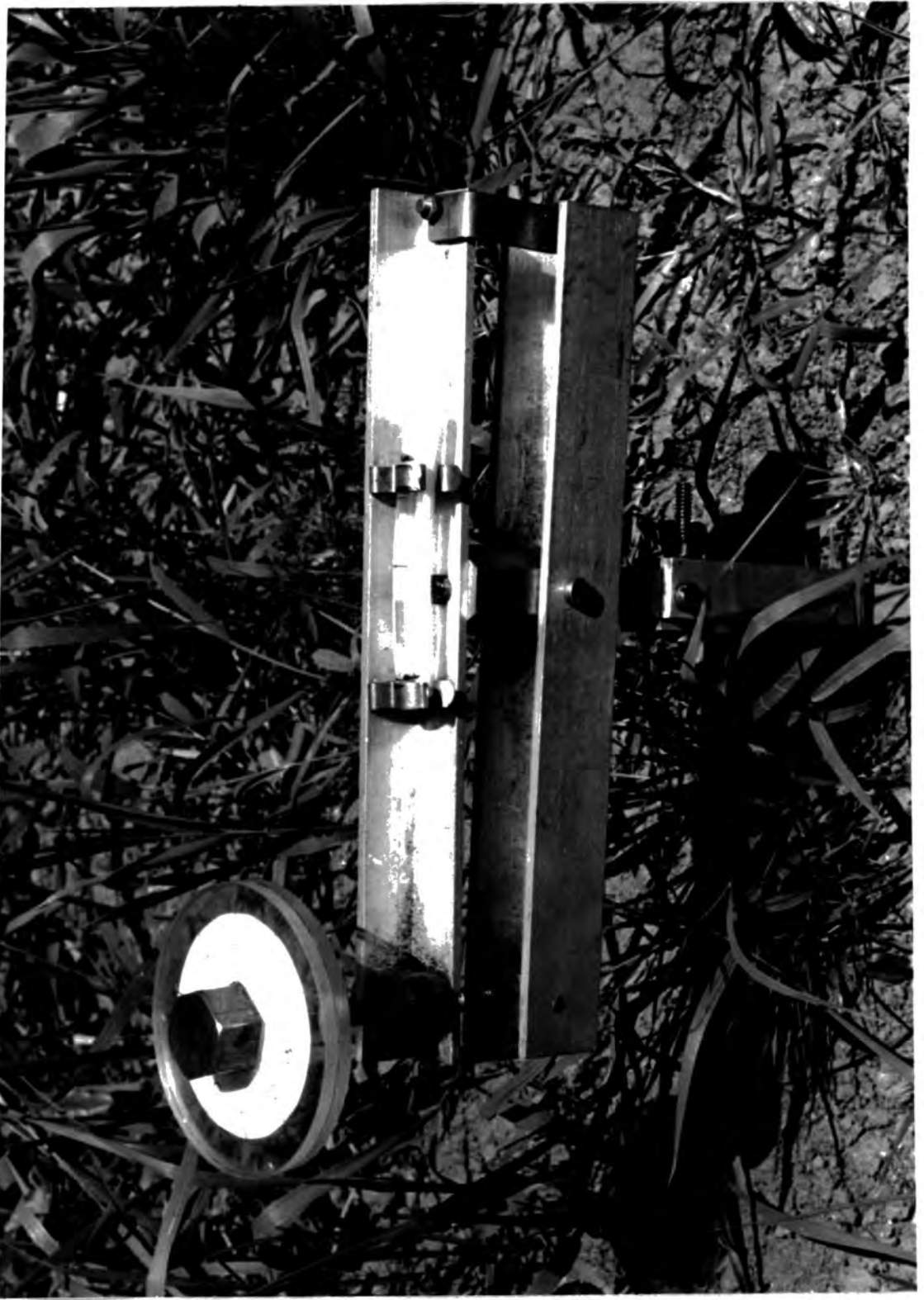


Plate 3.3 The Anderson Inclinator: Simplified Model
(side view)



Plate 3.4 The Anderson Inclinator: Modified Model
(with ball and socket joint)

3.2.3. Analysis

If readings are taken for different directions using the original model, they can be plotted on to a diagram (Fig. 3.3). This consists of direction lines drawn at the required interval (e.g. 30° steps) from the upslope direction. The circle joining the mid points of the lines is the level position, and the lines are calibrated inwards and outwards from this.

Plotting is as follows:

- (a) Select the direction line for the first reading taken.
- (b) Plot the reading from the level position, inwards for clockwise and outwards for anti-clockwise.
- (c) Select the direction line for the second reading taken.
- (d) Find the position of the previous reading on this line and plot the second reading from this position.
- (e) Having plotted all the readings join the points.

If the next set of readings is then plotted on the same diagram, a picture of peg movement is seen. Readings in a single direction can of course be isolated and plotted against time and perhaps some other factor such as rainfall.

The results from any of the models can be converted into angular movement very simply owing to the dimensions of the Inclinoimeters. (The pivot point being 10cm from the measuring thread and the thread pitch being 1mm). If the Inclinoimeter reading is presented in whole numbers for complete revolutions of the scale and decimals for parts of revolutions, division by 100 gives the tangent of the angle (e.g. reading 8.40: tangent 0.0840: angle $4^{\circ} 48'$).

If it is assumed that the peg pivots about its base, the angular measurement can be converted to movement at any depth down the peg by simple trigonometry.

3.2.4. Advantages

The advantages of the Inclinoimeter are:

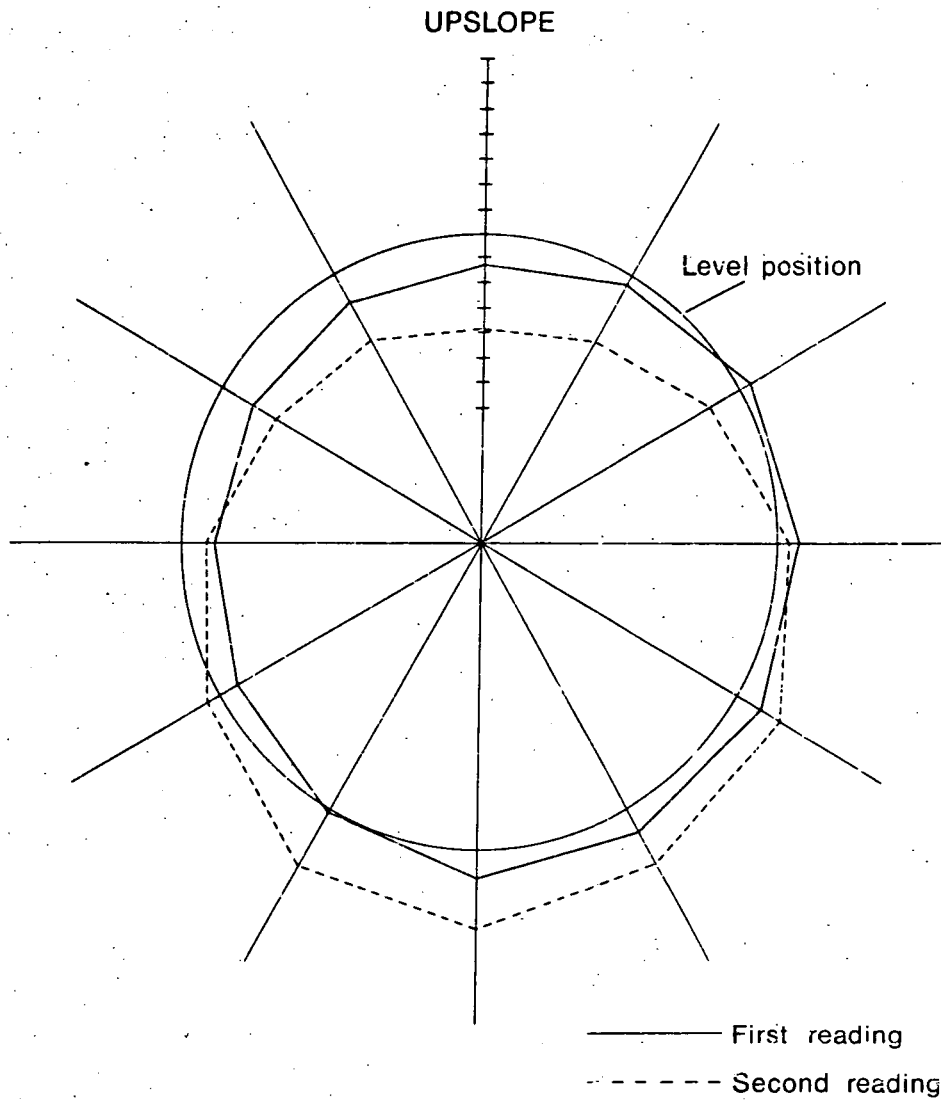


Fig. 3.3 Anderson's Inclinator: Plotting Diagram

- (a) It is simple to use and easy to read.
- (b) It is accurate to less than 1 minute of arc.
- (c) It can measure in any required direction.
- (d) Readings can be repeated if necessary as the peg position remains unaltered.
- (e) The Inclinator housing fits over the peg making tight contact on all four sides. This allows greater accuracy than a surface to surface contact only.
- (f) By taking readings with the Inclinator facing downslope, the upslope reading can be checked.

The advantages of the wooden pegs are:

- (a) They are cheap, convenient and replicable.
- (b) They can be safely left where animals graze.

The limitations are those encountered with any instrument attempting to measure soil creep by angular methods. The major difficulty arises in deciding where the pivot point of the peg occurs.

3.2.5. Pegs

The pegs are of a hard, durable knot-free wood such as Ramin and can be easily and cheaply constructed and also left safely where animals are grazing. Each peg has a flat top with an identification mark and a pointed end, and is painted with preservative. The most suitable type seems to be square in cross section with sides of 1.3cm. Square pegs have two advantages:

- (a) The Inclinator housing can be used to achieve a tight fit.
- (b) The peg can be inserted with a side pointing directly upslope. The Inclinator can then be fitted in the same position each time with the upslope direction for all readings exactly coinciding.

The Ramin wood is guaranteed against warping when in the soil and each peg was tested for initial straightness against a steel rule. On removal, after periods of up to three years, each peg has been tested and none has yet

been found to have warped. However, to help provide insurance against such an outcome, aluminium pegs of the same dimensions were also inserted during the instrumentation.

Opinions differ as to the most suitable shape and size of pegs but little empirical evidence can be cited in support. Generally pillars and similar inserts seem to be square or rectangular in cross section, whereas bore hole devices are mostly round. Experiments were conducted by fitting different housings to the prototype Inclinator (Anderson, 1971) so that a number of pegs could be measured. Three types were tested: round, 1.3cm square and 2.5cm square and no significant differences could be discerned.

The depth for peg insertion has not been standardised and would appear to depend greatly upon the location and characteristics of the site. According to Young (1958) there is definite evidence of soil movement only for the organic horizons and probably the upper 5cm of the soil, giving a total depth of approximately 10cm. Most workers seem to favour a peg length of between 15cm and 22.5cm.

<u>Authority</u>	<u>Length of peg (cm)</u>
Rapp 1960	15 to 20; 40 to 50
Miller and Leopold 1963	approximately 15
Kirkby 1963	theodolite pegs: 10;15;30;45 T pegs 15;30;45
Leopold, Wolman and Miller 1964	20
Emmett 1965	20
Leopold, Emmett and Myrick 1966	22.5

Kirkby (1963) found that the annual rate of tilt varied with the length of peg.

<u>Peg length (cm)</u>	<u>Annual tilt</u>
10	5° 05'
15	4° 50'
30	1° 12'
45	1° 32'

Washburn (1960) and Williams (1957A and 1962) report blades of far greater length than those quoted above, but both were concerned with areas of rapid solifluction. In temperate latitudes seasonal soil creep would seem to be limited to depth of 15cm to 20cm. If a peg is inserted below this level, the movement is likely to be inhibited by the compacted static soil, whereas if it is too short, bodily movement will result. These effects are likely of course only, if as is generally accepted, creep rates are at a maximum near the surface, declining with depth. If movement were greater with depth, the peg would be expected to tilt upslope about a pivot point near the surface. If the main shear plane should focus near the centre point of the peg, absolute or bodily movement would occur.

Bearing these arguments in mind, an initial plot was laid out with pegs inserted to a depth of 7.5cm, 15cm and 22.5cm respectively. It was hoped that as results became available, the length of peg would be standardised for the main part of the work. In fact it quickly emerged that the pegs inserted to 15cm responded more rapidly to soil moisture changes and this was the length selected for the major instrumentation. Since on average this allowed penetration of some 5cm to 7.5cm below the organic layer, it accorded well with the conclusions of Young (1958).

3.2.6. Peg Insertion

With all angular measuring devices, a basic necessity is to ensure that the peg or blade is inserted as nearly vertically as possible. If the peg should have an excess tilt in either direction, it is extremely difficult to assess, much less quantify, the effects. Clearly downslope tilt will tend to enhance gravitational forces while upslope will prove more resistant to movement. A further point is that in using the Inclinator, readings can be taken much more rapidly from nearly vertical pegs.

To facilitate such insertion, a plumb bob can be used but this appears to be a somewhat clumsy and inaccurate method, particularly in windy conditions. Therefore a

special piece of apparatus has been designed. The Peg Inserter (Fig. 3.4) consists of two parts:

- (a) The housing which is similar to the adjustable section of the housing on the Inclinator. The upper ends of two 11.7cm lengths of 1.3cm angle brass are fixed by the bolts round a 5.5cm length of 1.3cm square wood above the brass. 6.5cm of the housing protrudes below the wood to fit over the heads of the pegs.
- (b) The Tee Level is mounted on a small wooden block, 3.5cm square and 2cm thick fixed 1.5cm from the top of the inserter. The block is attached so that when the housing is vertical both bubbles in the level are central.

In use, the bolts are slackened and the housing placed over a peg. The bolts are then tightened and the peg pushed or tapped into the ground while the bubbles are kept central. If necessary, the vegetation mat is first cut to allow easy entry of the peg point. Using the inserter the peg can be installed to within 2° of the perpendicular.

3.2.7. Validation

Before any instrument can be employed in an experimental programme, the results obtained from it must be validated as to their accuracy and consistency. In the case of the Inclinator, validation naturally falls into two parts concerned respectively with the behaviour of the pegs and the behaviour of the measuring instrument.

The pegs are of course standard pillar devices and these have been used for measuring creep rates over the last fifteen years. Therefore it can be assumed that attempts at validation have been made although the actual resistance of the peg to soil movement is an unknown factor. Comparative tables showing rates and instruments have been produced by Young (1974A) and results from pillar devices accord well with those achieved by other methods. Furthermore, when more control is possible using soil tanks, the pegs behave in a predictable fashion and indicate at least the expected direction of movement. Although with such experiments, the conditions are too contrived to allow more than a general appraisal of rates, the actual results

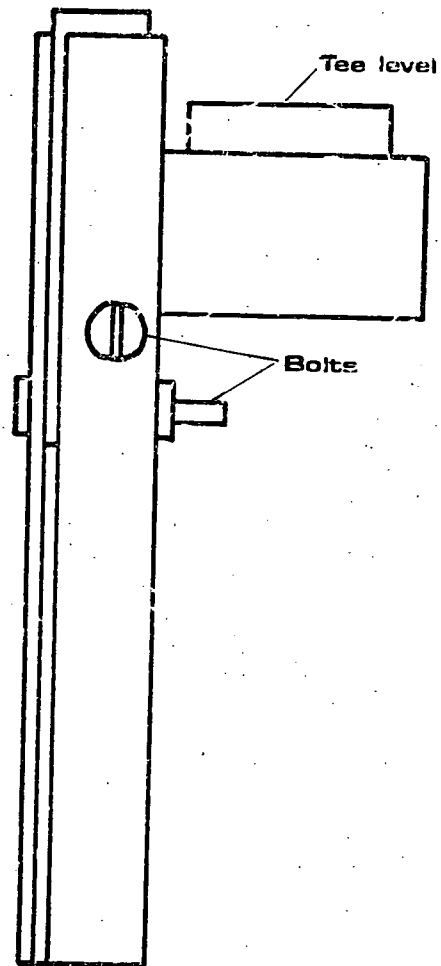


Fig. 3.4

Peg Inserter

obtained are discussed later. Other proof of movement was acquired when a peg was fitted with a stylus so that a continuous record could be kept. Therefore it seems highly probable that when a column of soil is replaced by an insert such as a peg, both the rate and direction of soil movement can be measured.

When the prototype Inclinator was constructed it was validated against two other instruments both of which had just completed a laboratory testing programme. Firstly, round peg housings were fitted to both the Inclinator and a machine-gun inclinometer and then each instrument was placed in turn over a series of variously tilted pegs. Secondly, the Inclinator was placed alongside a 'Stanley' telescopic Abney level on a plane surface which could be tilted. In each case it was found that with careful interpolation between the gradations, the Inclinator could be read accurately to 1 minute of arc. Further evidence is provided by the fact that if a peg is read conventionally with the operator facing upslope, and then the process is repeated facing downslope, the 'clockwise' and 'anti-clockwise' readings are equal. Also repeated measurements obtained from one peg over a short interval are highly consistent. Checks have been made in the field by comparing rates with those produced by other instruments (Anderson, 1971) and this procedure has been incorporated into the experimental design at Rookhope where five other instruments have been used. Finally, the sample rates of creep measured in the Etherow valley (Anderson, 1971) are very similar to those reported by Young (1958) and Evans (1974) both of whom worked on neighbouring sites.

3.2.8. Discussion

Since the Inclinator can provide accurate short term readings allowing possible correlation with short period effects such as wetting and drying and freeze-thaw, it was adopted as the main instrument for the study. However, owing to the nature of the drainage basin and the spread of plots within it, the provision of base points for theodolite surveying would have been extremely difficult

and time consuming. Therefore the measurement of bodily movement could not be attempted by this means and it was necessary to design a new device which would provide, in the short term a guide, and in the long term an accurate measurement against which the peg readings could be assessed. If bodily movement is disregarded, peg results can be treated as valid only for a limited period and in consequence it is important that instruments used for monitoring this aspect should be cheaply and easily replicated so that a good coverage is possible.

3.3. The Anderson Tube

Anderson's Tube was constructed to measure bodily as well as angular movement produced by soil creep and also to allow the pivot point to be located. When placed in a plot alongside pegs it can therefore be used to help clarify and interpret the readings obtained. Effectively the Tube gives a general guide to short term tilting while monitoring the longer term overall downslope creep. Other advantages inherent in the design are that a base point is provided from which other measurements can be made and the Tube itself acts like a river flood gauge, recording movements in the level of saturation. As the water level rises, particles of litter and a line of staining are recorded giving a direct reading of the maximum height achieved.

The principle of the Anderson Tube is that the position of a tube can be accurately measured with regard to that of a rod placed near its centre. The rod is inserted into rock and with very little soil pressure on it, acts as a fixed point about which the tube moves.

3.3.1. The Instrument

The device is constructed of the following two parts (Fig. 3.5):

(a) The Tube

A 22.5cm length of 7.5cm diameter aluminium downspout, bevelled on the bottom outside edge. Lines 7.5cm long are painted vertically down

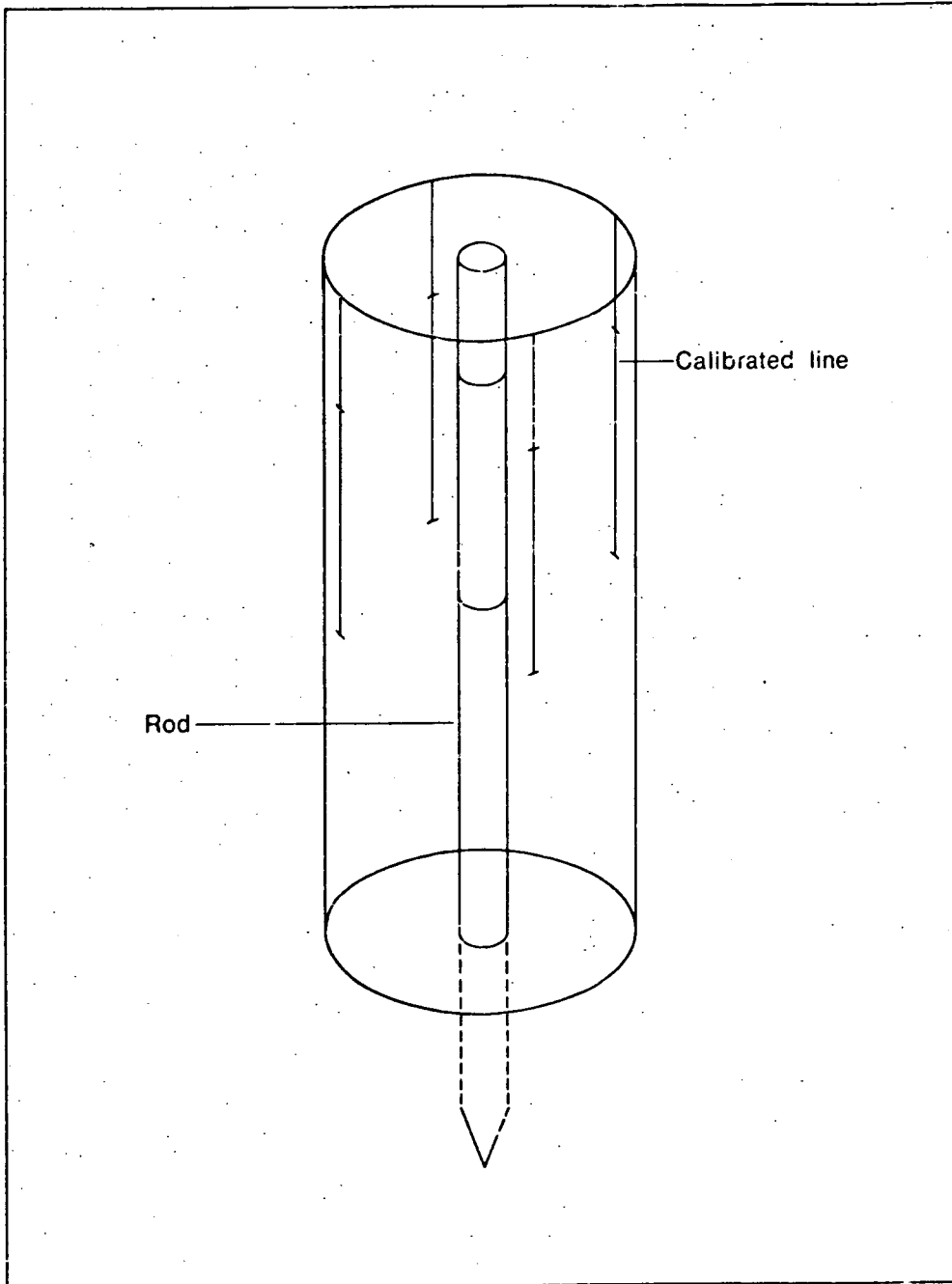


Fig. 3.5

Anderson's Tube

the inside from the cardinal points at the top of the tube. Each line is calibrated from the top in required intervals; for example, 1.3cm to the 7.5cm mark.

(b) The Rod

A 1.1cm diameter silver steel rod 45cm long is pointed at one end. Calibrations using the same intervals as on the tube are painted round the top 7.5cm of the rod.

The rod and the tube are best painted with polyurethane or some similar preservative. To prevent damage and protect grazing animals, a plastic cap can be loosely bolted over the top of the Tube (Plate 3.5).

3.3.2. Procedure

Field Assembly

- (a) A length of 7.5cm diameter aluminium downspout is pressed vertically into the soil to a depth of 15cm and then removed with the core of soil leaving a cylindrical hole.
- (b) The Tube is slid gently into the hole with one of the cardinal points on the upslope side.
- (c) The rod is placed in the centre of the Tube and driven into the rock below until its top is level with the upper edge of the Tube.

Measurements

In taking readings the cardinal points are identified appropriately with 'north' on the upslope side. One arm of the Inside callipers is held against the 1.3cm mark on the north line and the callipers extended until the other arm just touches the rod on its matching line. The width of the calliper arms is read to 0.01cm using Vernier callipers. This procedure is then repeated for the south, east and west lines at the 1.3cm level and for all four cardinal points at required lower levels.

3.3.3. Analysis

The readings for each level are plotted on to a separate circular diagram (Fig. 3.6A), a circle of 7.5cm



Plate 3.5

The Anderson Tube

(showing plastic cap and aluminium pillar)

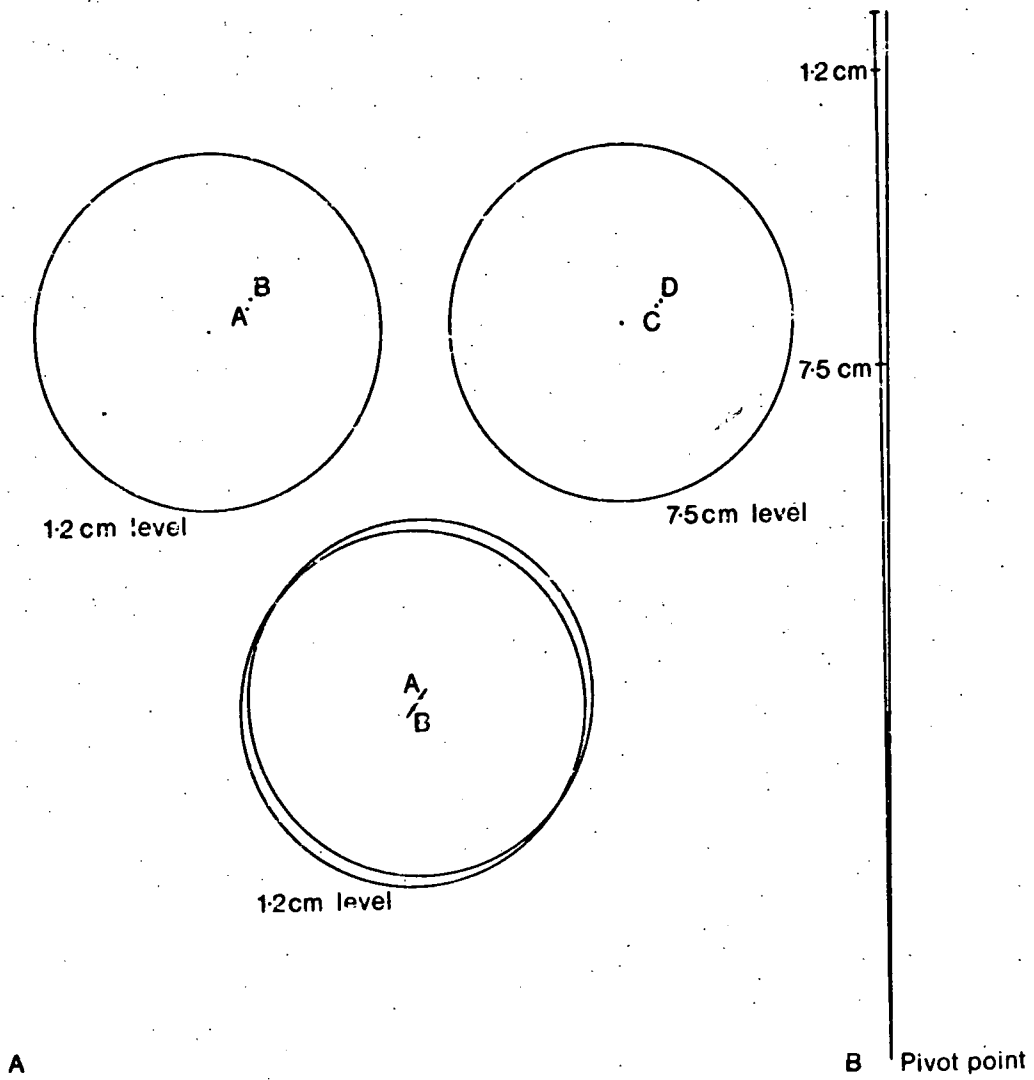


Fig. 3.6

Anderson's Tube

A Circular diagrams

B Movement diagram

diameter with the centre and the cardinal points marked. Also required are a pair of compasses and a transparent overlay on which is drawn a circle of radius 0.55cm with its centre marked.

- (a) From each cardinal point an arc is drawn inside the circle, the radius being equal to the measurement for that point.
- (b) The overlay is placed on the diagram so that its circle is tangent to all four arcs and its centre spot is marked on the diagram. This is the position of the centre of the rod. (A)
- (c) The procedure is repeated with the next set of readings for that level and the new position of the centre of the rod is found. (B) (It is of course the tube which has moved).
- (d) The readings for a lower level taken on the same dates as the above two sets are plotted on a second diagram and the positions of the centre of the rod found.
- (e) The apparent distance the rod centre has moved is measured for each level and the two readings are plotted at the appropriate level on the movement diagram (Fig. 3.6B). This consists of a vertical line 22.5cm long representing the original position of the tube and calibrated from the top in the same fashion as the rod and the tube.
- (f) The two plotted positions are joined and the line continued downwards. The position where it cuts the diagram-line is the pivot point and if this is more than 22.5cm from the tube top, bodily movement has occurred and can be measured at the 22.5cm level.

NOTE Subsequent readings can be plotted in the same way, the apparent movement being measured from any previous rod position. However they cannot be entered on the same movement diagram unless movement is in the same direction as the readings already plotted.

3.3.4. Advantages and Limitations

The advantages of the Tube are that:

- (a) It is cheap to make and simple to use
- (b) It is accurate to 0.1mm
- (c) The pivot point can be found

- (d) Both angular and bodily movement can be measured
- (e) An overall picture of movement can be obtained
- (f) Readings can be repeated if necessary

The main limitations are that the velocity profile cannot be measured and that there is some soil disturbance during insertion.

3.3.5. Modifications

Various modifications of the basic design have been attempted but the only one undergoing trials consists of a sectional tube allowing a velocity profile to be produced. This instrument differs from the normal Tube in that the aluminium tubing is divided into a series of rings each 2.5cm high. Three such tubes have been installed at Rookhope and the results are discussed later.

3.3.6. Validation

The short term readings obtained from the Tube were compared with those from the peg and from other instruments. It was found that the Tubes gave an accurate indication of the direction of tilt but the accuracy of the rates calculated depended of course upon the type of callipers used for measurement. The rates of bodily movement accorded well with those described by Young (1958) and Evans (1974). It seemed clear from these points and the visual evidence of the firmness of the instrument in the soil, that the results could be considered valid. However, this question will be illustrated later when the readings from the Etherow valley and Rookhope are discussed.

3.3.7. Discussion

The Inclinator and the Tube together provide a firm basis for measuring rates of soil creep and also for attempting to evaluate the influence of certain controlling factors. They allow extensive replication while readings can be obtained in the short term and the long term as desired. However, despite the fact that both instruments

were validated over a one year period, it was considered that continuous monitoring on the site using other techniques was desirable. Aluminium pillars have been employed to measure tilt and Young's Pits to provide an assessment of bodily movement.

3.4. Other Instruments

The only basic requirement not covered by these techniques is the production of a velocity profile, although the sectional Anderson Tube gives a coarse long term indication. Young's Pits provide readings of creep rate variations in depth and these have been supplemented by the use of Cassidy's Tubes and dowelling pillars. The dowelling pillars were validated over a two year period in the Etherow valley (Anderson, 1971) while the other instruments have been accepted within defined degrees of accuracy. Other devices sited at Rookhope are sand pillars, to check on possible diffusion and open tubes and rods to provide some link with the laboratory programme.

3.4.1. Young's Pits

The basic types of pit have been described and as it was considered vital to minimize soil disturbance the modified version was adopted. A narrow slit trench approximately 25cm long, 15cm wide and 25cm deep, was excavated and the six rods, 10cm in length and 3mm in diameter were inserted 2.5cm apart in a vertical column from the surface. This procedure was simplified by using a plastic template, in which the appropriately spaced holes had been drilled, with a short plumb bob attached below (Plate 3.6). Clearly more accurate final measurement is also facilitated since when the template has been fitted over the lowest rod, movement in any direction of the other rods can be marked on the plastic.

3.4.2. Aluminium Pillars

To overcome problems of locating fixed bases for a theodolite, the pillars were placed immediately upslope and downslope of each Tube so that any movement could be



Plate 3.6

Young's Pit
(showing plastic template in position)

measured from the central Tube rod. The pillars, 22.5cm lengths of 1.5cm wide and 3mm thick aluminium rod, were inserted to a depth of 15cm. The distance from the 1.2cm mark on the Tube rod to a nick cut in the head of the pillar was measured by Inside callipers.

3.4.3. Cassidy's Tubes

Thin walled P.V.C. tubing was cut into 22.5cm lengths and a bolt driven through the base of each to prevent soil entering during installation. The external diameter selected was 1.5cm so that the tubing could be pushed down a hole produced by a soil sampler of the same dimensions. The sampler was inserted vertically using a plumb bob and the tube eased into place with a steel rod so that while disturbance was minimal there were no gaps around the tube and extra packing was not necessary.

3.4.4. Dowelling Pillars

Dowelling of the same diameter as the tubing described above was cut into 22.5cm lengths and columns 22.5cm long were inserted. A vertical sampler hole was made and each piece of dowelling pressed into place. Four such columns were immediately excavated and found to be vertical and so tightly fitting in the borehole that no packing was required.

3.4.5. Sand Pillars

Sand grains of median diameter (0.35mm) appreciably finer than those commonly found on the site, were poured in vertical columns 15cm long using the soil sampler. It was hoped that the colour and textural contrast would allow any diffusion to be identified in the organic horizon.

3.4.6. Open Tubes

As laboratory experiments were in progress using unconfined soil blocks, it was considered necessary to attempt similar measurements in the field. Therefore the open tube was designed to use a cylindrical hole of the same dimensions as that into which the Anderson Tube

is fitted. The device consists of a central rod, driven into the bedrock, which supports smooth bolts pushed into the upslope wall of the hole. Each bolt is fitted through a hole drilled at the required level in the rod and fixed firmly with a nut. A washer is supported on each bolt and pushed against the soil face (Plate 3.7). The distance from the washer to the central rod is then measured by Inside callipers and changes produced by creep are easily detected.

A simplified version of the same technique was used to measure bulging at the foot of the drainage basin. 15cm nails were inserted into the soil wall at various levels and their distance from marks at the same level on a fixed steel rod, measured by Inside callipers (Plate 3.8).

Finally, as the soil blocks mentioned were unvegetated, pegs were inserted into certain plots from which all vegetation had been removed.

3.4.7. Discussion

Despite the heterogeneous nature of soil and the variations in the drainage basin at Rookhope, it is considered that by using the range of instruments described and a carefully constructed experimental design, accurate measurements of creep rate can be obtained. Furthermore, the different devices provide internal continuous evaluation allowing 'within-plot' values to be assessed before 'between-plot' variations are compared.



Plate 3.7

Open Tube

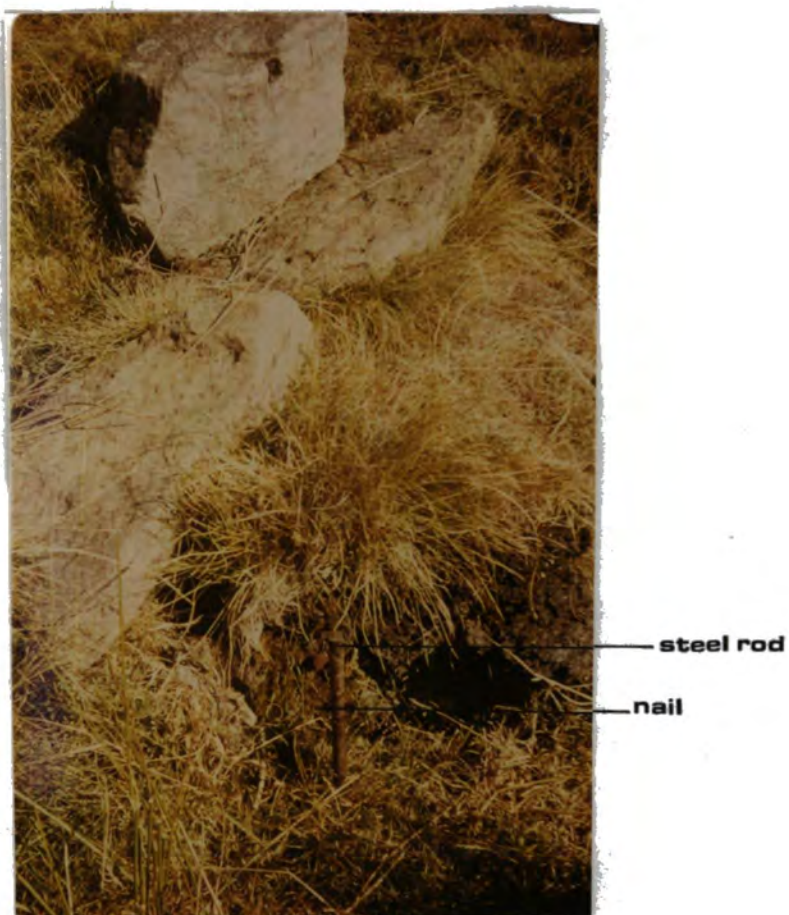


Plate 3.8

Steel Rod and Nails

CHAPTER FOUR

TECHNIQUES FOR MEASURING BASIN FACTORS AT ROOKHOPE

- 4.1. Introductory
- 4.2. External Factors
- 4.3. Surface Factors
 - 4.3.1. Location
 - 4.3.2. Slope
 - 4.3.3. Vegetation
- 4.4. Internal Factors
 - 4.4.1. Soil Moisture
 - 4.4.2. Field Capacity
 - 4.4.3. Linear Shrinkage
 - 4.4.4. Plastic Limit
 - 4.4.5. Liquid Limit
 - 4.4.6. Organic Matter
 - 4.4.7. Soil Depth
 - 4.4.8. Saturation Level
 - 4.4.9. Bulk Density
 - 4.4.10. Shear Strength
 - 4.4.11. Texture
 - 4.4.12. Root Factors

4. TECHNIQUES FOR MEASURING BASIN FACTORS AT ROOKHOPE

4.1. Introductory

While many of the variables which possibly control rates of soil creep are likely to be closely interrelated, particularly within a single small drainage basin, they can be grouped as discussed later (Chapter 12) into the broad categories of external, surface and internal factors. Since a large number of variables has been examined in the field, descriptions of instrument selection and measurement technique need to be restricted. It has been decided therefore that only when controversial points arise or in cases of particular interest, when for example devices have been specifically developed for this study, will detailed accounts be given. Standard instruments and techniques were not validated and are merely listed for completeness, while those which were employed in the laboratory programme will be included in that section.

4.2. External Factors

The major climatic elements considered were those which appear to exert a 'triggering' effect on soil creep (Young, 1972) through freeze-thaw or wetting and drying. Temperature was measured with standard instruments: a thermograph, soil thermometers at 2cm, 6cm and 9cm depths and a grass minimum thermometer. For rainfall a Meteorological Office stamped rain gauge was used.

4.3. Surface Factors

These surface or site factors include all those which cannot be considered directly climatic or pedological. Unlike the other two groups, they vary considerably in scale and form what, for the period of the study, are comparatively large scale fixed variables (Schumm and Lichty, 1965)

4.3.1. Location

The Rookhope watershed was surveyed by a standard plane table intersection survey using multiple base lines. Range rod positions denoting such factors as breaks of slope and vegetation changes, were marked permanently by small red pegs.

Distances, depending upon the accuracy required were measured directly from the completed survey, from aerial photographs, or from Ordnance Survey maps. For shorter distances on the scale of a single plot, a steel tape was used.

Aspect on a macroscale was inferred from Ordnance Survey maps while on the microscale it was read from a prismatic compass.

4.3.2. Slope

The problems of slope profile analysis have been examined in detail (e.g. Savigear, 1956, Young, 1972 and 1974B), but of more direct relevance to this section of the study has been the prolonged discussion on the subject of slope angle measurement (e.g. Pitty, 1969, Blong, 1972) especially concerning scale. Depending upon the particular type of investigation and the nature of the terrain, an overall gross reading with an Abney level might suffice, or for a detailed analysis, a surveyors level or pantometer might be needed. In the present study, microfacets are considered significant and it was decided that an instrument based on the Pitty pantometer design should be constructed. With a length factor of 1.52m the main changes and breaks could be identified while smaller variations would be eliminated.

The pantometer (Fig. 4.1) consists of two 1.2m vertical rods held 1.5m apart by two horizontal bars (Pitty, 1968). Wing nuts are fitted at the joints so that the device has a controlled mobility. On one upright is a Tee spirit level and a large protractor which can be read against a metal plate fitted into the underside of the upper horizontal rod. Validation took place in the workshop, using a surveyors level for comparison^{and} it was found that the pantometer could be read accurately to 30 minutes of arc. In use,

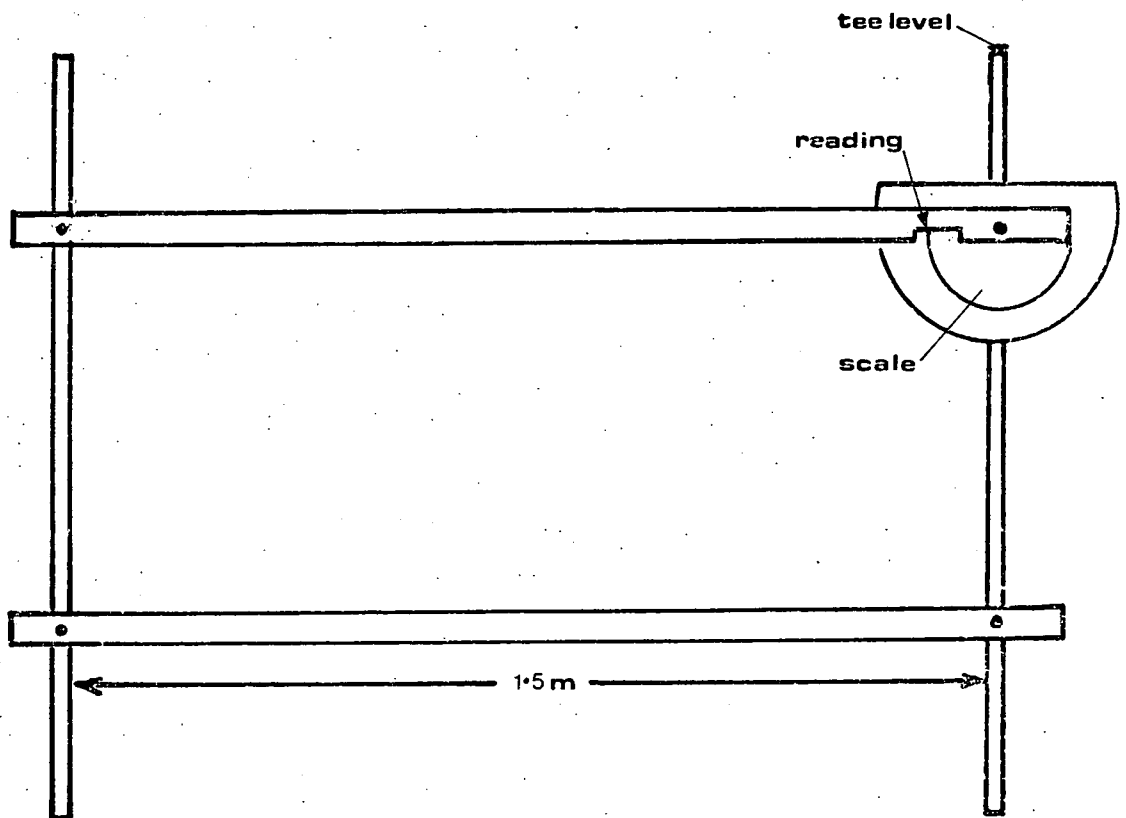


Fig. 4.1 Pitty Pantometer



the pantometer is placed in the required position, levelled, and the protractor can then be read. The advantages of the instrument are:

- (a) Measurements can be made quickly and sufficiently accurately, bearing in mind the irregularities characteristic of most slopes.
- (b) The fixed distance involved allows the results to be fitted easily into a computer program.
- (c) The use of 1.52m facets eliminates minor detail from slopes.

For the smaller scale measurement on actual plots where factors such as local variability become important, a flat steel blade 1m long, 2.5cm wide and 3mm thick was employed. This was laid on the surface and readings were obtained from an Abney level placed on it. This allowed an accuracy of 10 minutes of arc.

4.3.3. Vegetation

As with several of the factors already described, there are two distinct scales of measurement. The major groupings within the watershed were distinguished using the surveyed map and aerial photographs. On individual plots, vegetation coverage was estimated to 5% using a steel tape and a quadrat made to fit the grid (1.5sq.m.)

4.4. Internal Factors

Since creep is a phenomenon of the soil, a large number of factors was measured within this group. Certain soil variables share the characteristic of the climatic group in that they are capable of rapid change over short periods of time. Generally however, the distinguishing feature of this category is that variations can occur over short distances and therefore an index of variability is required before results can be assessed. For any one point in the watershed it has to be assumed that for the duration of the study, factors such as soil depth, bulk density and texture remain constant.

4.4.1. Soil Moisture

In any study of creep rates the moisture content of the soil would appear to be a vital factor and the selection of measurement methods is therefore important. Techniques have been reviewed (Marshall, 1959, Johnson, 1962, McKay, 1965, Curtis and Trudgill, 1975) but the majority are indirect measures, in many cases requiring elaborate and expensive equipment. For example, the use of nylon conductivity blocks (Postlethwaite and Trickett, 1956) and neutron probes (Douglass, 1962) have been discussed in detail and in both cases the possible error in assessing total soil moisture content is large. In fact Postlethwaite and Trickett conclude that the conductivity blocks can usefully provide only qualitative data.

In selecting a particular technique there are factors other than extreme accuracy to be considered, and as with the creep measuring devices, more than one instrument may be required for a particular piece of work. Selection criteria include:

- (a) accuracy within the context of the study environment
- (b) speed, especially when rapid changes are occurring
- (c) portability and the possibility of use in the field
- (d) the prevention of site damage by soil removal
- (e) logistics of transporting soil samples

For the present study each of these points assumed significance at some stage and four methods were therefore employed. For an approximate guide to moisture variations within the basin a meter (produced by J.M.A. Engineering) was useful although accurate readings cannot be obtained under anaerobic conditions. The meter gives a good measure of conductivity and was calibrated using the gravimetric method. The electrodes generate a steady 0.8 volts and their configuration ensures a fairly constant 'cell constant'. When tested in the laboratory against other similar devices such as the Riken Moisture Meter this instrument proved to

be the only reasonably reliable inexpensive model. With the standard meter, readings of moisture variations within the depth range normally associated with creep would not be obtained without excavating a pit and thus nullifying the major advantage of leaving the site intact. To overcome this, the manufacturers supplied a specially constructed model with a 30cm probe.

For laboratory calculations and for validation purposes the standard gravimetric method was used. The soil sample is weighed, oven dried at 105°C for 24 hours or to constant weight and reweighed. However, there are doubts as to the validity of this procedure for organic soils as at that temperature matter will undoubtedly be burned. Therefore samples from the organic horizons were dried at 60°C to constant weight. The results could then be calculated:

$$\begin{array}{ll}
 \text{wet soil} & W_{\text{grms}} \\
 \text{dry soil} & D_{\text{grms}} \\
 \text{water} & W - D_{\text{grms}} \\
 \text{water content} & \frac{W - D}{D} \times 100\%
 \end{array}$$

The major disadvantages of this technique are that the site is damaged and the results cannot be obtained rapidly. It cannot of course be used in the field and it may involve transport problems. However for one-time moisture content determination it is probably the most suitable method.

In the work on the experimental plots, it was not possible to remove more than a small sample and results were required quickly. Furthermore it was necessary to measure the soil moisture at the same depth each day. The most appropriate instrument was found to be the Infra-tester (Fig. 4.2) which requires a 5g sample. The precise procedure as given in the manufacturers' manual was followed throughout the series of water content determinations. Briefly, this involved placing ca. 5g of soil on the weighing pan, which had been allowed to cool to room temperature. The sample was dried under the infra-red lamp for 15 minutes and the percentage loss of weight of the sample was read by counter-

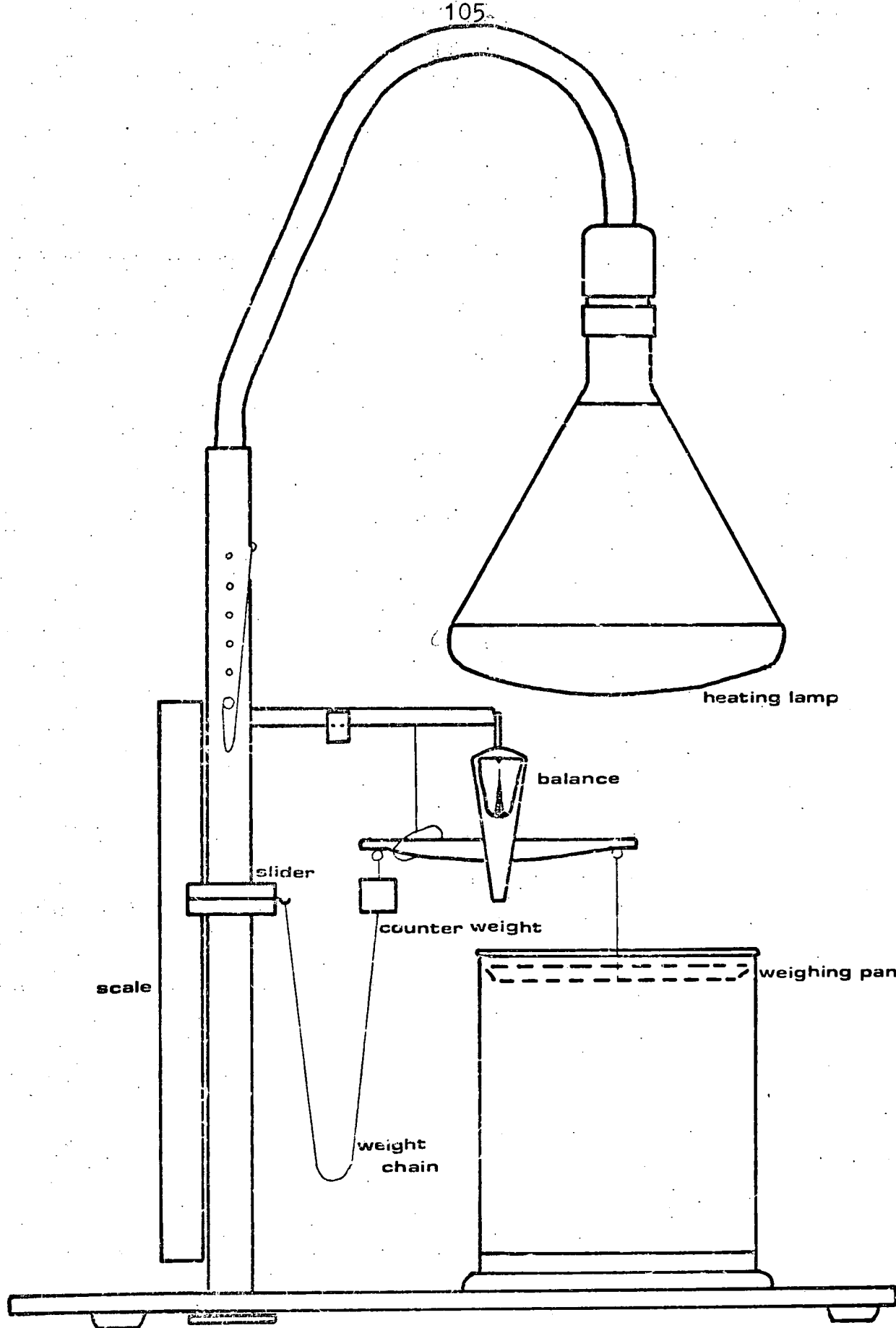


Fig. 4.2

Infra-tester

balancing the pan by moving the slider up the vertical scale. Special 'rider' weights were used if the moisture percentage was above 10%.

For validation, the Infra-tester results were compared with those found from standard oven drying at 105°C for 48 hours. The results demonstrated the accuracy of the Infra-tester.

Table 4.2. Infra-tester Validation Results

Method	Time	<u>% wet weight</u>				
		1	2	3	4	5
Infra-tester	5 min.	20.3	14.1	11.8	25.1	16.6
	10 min.	20.7	14.3	11.8	25.5	16.8
	15 min.	20.7	14.4	11.8	25.6	16.8
Oven	48 hr.	20.7	14.4	11.8	25.6	16.8

While giving extremely accurate results these last two methods both suffer from the severe handicap of being inapplicable in the field. For rapid on-site soil moisture determination allowing a large number of readings to be obtained at one time, the 'Speedy' (Akroyd, 1964, Smith, 1970) was used. This instrument is a steel flask with a gastight top and a pressure gauge in its base (Plate 4.1). A weighed amount of soil is placed in the body of the flask with two steel pulverising balls. The 'Speedy' absorbent is placed in the flask top which is then screwed tightly into place. The flask is rotated on a horizontal axis for up to 3 minutes until the pressure gauge reading is constant. This reading gives the water as a percentage of the wet soil weight. The absorbent, principally calcium carbide, reacts with the water to produce acetylene gas; clearly the volume of gas produced depends on the moisture content of the soil.

After consultation with the manufacturers, it was decided that the Large D12 model would be most suitable and two dials were supplied, one reading from 0 to 20% and the



Plate 4.1

'Speedy' Flask

other from 0 to 50%. With an additional weight the latter can be employed to measure from 0 to 100%. The actual instrument was then laboratory checked for accuracy by the manufacturers.

Validation tests were made by assessing 'Speedy' values against those obtained by the gravimetric method. The manufacturers claim that 'Speedy' readings are within 1% of the true moisture value.

Table 4.3. 'Speedy' Validation Results

<u>Soil</u>	<u>% wet weight of sample</u>	
	<u>'Speedy' (mean)</u>	<u>Gravimetric</u>
1	19.0	19.2
2	27.7	28.1
3	11.3	11.1
4	10.8	11.0
5	11.7	11.6

Bearing in mind the marked spatial variations of soil moisture even over very short distances, these results are highly satisfactory, particularly when it is remembered that the samples actually tested were of course only neighbouring. Therefore it can be accepted that the greatest loss of accuracy is likely to be of the order of 2% and this is not considered significant in the context of the differences within the basin and when weighed against the advantages of the instrument. It is thought that any apparent deficiency is amply compensated by the obvious benefits of testing in the field. It must be remembered that in transporting specimens, water movement within the sample and even losses resulting from condensation on the soil container are usually discounted.

4.4.2. Field Capacity

The concept of field capacity is to a degree controversial but is also of significance in the present study as it is the condition commonly occurring in the Rookhope watershed. The major problem in establishing the field capacity of any soil was to remove a sample without too much compression taking place. To obtain such samples, small tins similar to those used for baby food with a capacity of approximately 50ml were used. The lid was cut from the tin and the remaining edge smoothed and sharpened slightly so that it could cut without the exertion of undue pressure. Several 0.6cm diameter holes were bored in the base of the tin. The tin was then pressed into the ground until the soil level just reached the holes. The specimens were then sealed in plastic bags.

To achieve saturation, the tins were stood upright in a bowl of water, so that their tops were adequately covered, for two days. The tins were then removed from the bowl, stood for approximately 30 minutes to allow surplus water to drain away, weighed, and then placed in the oven. The samples were dried at 105°C for 24 hours and reweighed. The field capacity was then calculated.

Calculation

weight of saturated soil sample	S
weight of dried soil sample	D
weight of water	S - D

$$\text{field capacity} = \frac{S - D}{S} \times 100$$

4.4.3. Linear Shrinkage

Since creep results from expansion and contraction caused by meteorological cycles including wetting and drying, it was considered important to measure linear shrinkage. However the British Standard (B.S.1377) test 5 for the determination of linear shrinkage uses soil at approximately its liquid limit and can therefore be employed as an indication of the plasticity index (PI=2.3 LS). As the

plasticity index had already been calculated and as it was thought more relevant to the process under discussion to maintain, as nearly as possible field conditions, a modified test was adopted.

Soil cores 5cm long and 2.5cm in diameter were extracted when the basin was at its winter moisture content. The length and diameter of each was then checked with Vernier callipers before the cores were allowed to air dry for 48 hours. They were then placed in an oven and dried at 65°C for 24 hours and at 105°C for a further 24 hours. After this, the cores were cooled and their dimensions measured.

The percentage linear shrinkage was calculated.

$$\text{Linear shrinkage} = \left(1 - \frac{\text{length of oven dry core}}{\text{initial length of core}} \right) \times 100$$

4.4.4. Plastic Limit

The standard procedure (B.S.1377 test 3) was adopted for measuring the plastic limit of a 15g sample from each horizon. The soil was sieved through a No.36 British Standard sieve, placed on a glass plate and mixed with distilled water until it could be shaped into a ball. The ball was then rolled between the hand and the glass plate until it formed a thread of 1/8in (3mm) diameter. This rolling process was then repeated until the thread just crumbled at 1/8in diameter, when its moisture content was measured. The mean moisture content obtained from three such tests was calculated and expressed as a percentage of the dry weight to give the plastic limit.

4.4.5. Liquid Limit

The standard procedure (B.S.1377 test 2A) was also used to measure the liquid limit, and from this together with the plastic limit, the plasticity index was found. For this programme the liquid limit apparatus was serviced and tested by Engineering Laboratories Ltd. A sample of soil weighing approximately 120g was air dried, sieved through a No.36 British Standard sieve and placed on a

glass plate. The soil was then mixed with distilled water until it formed a thick paste and was left to stand for approximately two hours. The paste was then placed in the cup of the apparatus, levelled with a spatula to a maximum depth of 1cm and divided by an 'American Society for Testing Materials' type grooving tool which leaves a V-shaped gap 2mm wide at the bottom, 11mm wide at the top and 8mm deep (Akroyd, 1964). The handle was then turned at two rotations per second, causing the cup to fall a prechecked 1cm on to the rubber base of the instrument. This was continued until the bottom of the gap in the soil was closed for a distance of 1.3cm. The number of blows required was recorded and the process rapidly repeated twice more, soil from the sample being mixed with that already on the cup on each occasion. When the three similar values had been recorded the moisture content of the soil was tested using soil specimens from each of the three tests with the addition of two more, one from each side of the groove.

This whole procedure was then repeated four times with different increments of water producing a paste of lesser or greater moisture content. Throughout, the average number of blows must fall between 10 and 50 with at least one greater and one less than 25. To find the liquid limit, the 'average number of blows' was plotted against the moisture content shown as a percentage of the dry weight and the resulting curve produced. The liquid limit or moisture content corresponding to 25 blows, was then found.

As this is an extremely time consuming process a shortened method reported in Akroyd (1964) and designed by Olmstead and Johnstone was also employed. This procedure is also reported as B.S.1377 2B. A single measurement of moisture content is required but this must correspond to a number of blows between 17 and 36. A special chart has been constructed to facilitate the necessary calculations. Results for this method are reproducible within 2% rather than the 1% of the longer process, but it is considered that this loss of accuracy is justified when weighed against the advantage of the

accelerated method which makes it possible for all horizons to be tested.

It should also be stated that conditions outlined in the B.S.1377 notes on test 2A obtained and samples of natural soil were used.

4.4.6. Organic Matter

The gross distribution of organic matter was assessed from variations in the depth of the organic horizon measured with the sampler and in the soil pits.

More accurate values were obtained from weight loss on ignition calculated for every horizon at each plot. A weighed oven dried sample was heated in a crucible for 16 hours at 375°C. Although such a value also includes material other than the purely organic, affecting carbonates to some extent, it was considered sufficiently discriminating to be used to illustrate the variability of soil properties (Skempton and Petley, 1970, Ball and Williams, 1971).

4.4.7. Soil Depth

The overall pattern of depth variation was established using a Swedish sampler graduated from 0" to 30" (0cm to 75cm). The sampler provides a 1.25cm diameter core for inspection so that horizon changes can be readily ascertained. For larger cores a screw auger giving a sample of 3.75cm diameter was used. However, for assessing depth, particularly where drift occurs, an auger reading cannot be accepted with confidence as it may denote merely the existence of a large broken fragment below the surface. To overcome this problem and to locate the bedrock accurately, two procedures were employed. Firstly, five auger readings were taken in a set pattern, a central one and one at each of four cardinal points 1m from the centre. These results were obtained after the measurement period but care was taken to avoid disturbing instruments and by using a rod of the same diameter, to remove as little soil as possible. These results were then averaged, discarding any obviously anomalous reading. Since within the basin the diameter of rock fragments seldom exceeds 30cm, these distances would seem to give an acceptable

estimate. Secondly, a soil pit was dug downslope from each plot near enough to represent the plot but sufficiently removed to leave the local drainage undisturbed. The depth within each pit together with the horizons and root depth, was measured with a steel tape and the overall reading to the bedrock checked against auger readings averaged for the actual plot.

4.4.8. Saturation Level

In monitoring creep rates, the effects of fluctuating levels of saturation within the soil may be important. While measures of winter moisture and field capacity provide a guide to this factor, it was thought that a value should be obtained for the highest level on each plot. To measure this, Anderson's Tubes were employed as river flood gauges. The highest level to which water rose inside them was marked by a line of debris adhering to the Tube side and the height could be easily monitored.

4.4.9. Bulk Density

Since the specific gravity of soil is extremely difficult to measure accurately (Reid, 1973), and refers to particles rather than the total soil, bulk density is the most relevant variable which can be determined and is likely to influence soil stability. This factor is normally expressed in terms of dry weight and for this the method described by Chepil (1950) was used. A known weight of oven dried soil was ground using a pestle and mortar and then placed in a measuring cylinder. The cylinder was then tapped gently with the palm of the hand for 1 minute, when the volume was read. This allowed the apparent density to be calculated.

Calculation

$$\text{Bulk density} = \frac{\text{Apparent density} \times 1.53}{2.65}$$

1.53 is the bulk density of oven dried quartz grains of any sieve diameter

2.65 is the real and apparent density of quartz grains

However, the bulk density can also be calculated for soils at field capacity and as this is nearer the likely field condition, measurements were made. A soil core was immersed in water for 72 hours, and then a smaller core 2.5cm x 7.5cm was extracted from it and weighed. This procedure clearly gives a more direct reading than the dry method described, but inaccuracy can occur through compaction in extracting the core and also from undisplaced air in the sample. However, the original soil core measured 6.3cm in diameter and it was felt that, over the time period, this should allow sufficient water percolation for saturation to occur. The smaller core could also be removed with minimum disturbance.

4.4.10. Shear Strength

The measurement of shear strength illustrates many of the problems inherent in attempting to use apparatus designed for one discipline to produce meaningful results in another. The detailed and accurate techniques of soil mechanics are commonly used on very restricted sites and rarely on anything like the scale of even a small basin. In fact if the site is large, it is normal practice for a portable laboratory to be erected to facilitate rapid on-site investigation. Geomorphologists on the other hand are often attempting to use the same techniques to the same level of accuracy but on an entirely different size of area. With a substance so notoriously heterogeneous as soil, it seems unlikely that the application of such methods with their inbuilt constraints can be justified. When testing for foundations, it may be possible to obtain a very accurate picture of soil properties, but when the scale is extended, it is doubtful whether such accuracy is possible or even required. Furthermore, the recognition of safety factors is unlikely to be significant in all but applied geomorphology. Before examining the techniques available for measuring shear strength and their suitability for geomorphology, the basic requirements of the subject might be broadly distinguished:

- (a) geomorphology usually operates on a larger areal scale

- (b) geomorphology requires less extremes of accuracy
- (c) geomorphology normally deals with soils in situ

Therefore, if possible, instruments should be portable and flexible in their application, allowing work to be carried out in the field. For shear strength determination, most measuring devices require large samples, and specimens of the order of 30cm x 10cm must be obtained. Since most of the apparatus is restricted to laboratory use, this entails the packing and transport of the soil while maintaining its water content and minimizing disturbance. Furthermore, with the stony nature of many soils, it may be extremely difficult to even extract samples of such a size. The result is that a necessarily restricted number of possibly unrepresentative soil cores is meticulously tested.

The laboratory shear box needs a cubic sample and is consequently normally used on reconstituted specimens. As a result, this type of direct shear measurement is basically unrealistic for use in geomorphology. The standard Golder and Cooling unconfined compression tester is portable, but extremely cumbersome, requiring both a mechanical extruder and a sampler, since it uses cores of 3.8cm x 15cm. This size of sample may also entail a loss of precision if it is required for example, to locate minor shear planes. The triaxial compression tester is not portable but is of course the only machine which can measure very friable or soft soils. However with field problems such as slope erodibility determination, soils are generally sufficiently firm and cohesive for the unconfined compression test.

The inherent difficulties of using these types of machine have been recognised, but possibly more as a result of inconvenience than any criticism of the experimental design. Various methods of penetrating the soil surface have been employed, for example using an iron shot (Melton, 1957) or penetrometer (e.g. Chorley, 1964) but the interpretation of results has been somewhat controversial.

A more satisfactory solution has been the King and

Cresswell combined unconfined compression and shear test apparatus (King and Cresswell, 1954). This is a small piece of equipment, measuring 40cm x 14cm with which both tests can be completed in a matter of perhaps five minutes. It was designed for Middlesex County Council for the rapid determination of shear strength in the field and has since been modified by Slater and myself to further reduce friction. It has been extensively tested against the laboratory apparatus by all of us and found to give results consistently within $\pm 10\%$. In fact with one operator observing research care the correlation varies by no more than $\pm 5\%$. When it is considered that the coefficient of variation for shear strength is of the order of 18 or 19% (Carson, 1967), this is highly satisfactory. Also, as the sample is only 2.5cm in diameter and 5cm in length, it can be extracted and extruded by hand. Thus for a slight loss of accuracy it is possible to obtain a very large number of results and assess the shear strength variation within a drainage basin more realistically. Furthermore, it has been possible to adapt the apparatus to measure the stress at the onset of creep and also the strength of vegetation root mats. When arranged for shear testing (Plate 4.2) the lower block was placed against the stop and the upper block laid on top so that the holes in the blocks exactly coincided. The upper block was then connected to the 7-lb spring balance. The soil extractor is an 11cm long sharpened steel tube of 2.5cm diameter, its wooden handle being held in place by a steel pin. For extrusion, the pin was removed and the handle pushed down the tube. With a soil core of 2.5cm diameter, better extraction and extrusion can be easily accomplished by hand. For testing, the soil was extruded, placed in the hole through the blocks and trimmed with a sharp knife to the level of the upper block. The stress to sever the core was then applied evenly by the screw. For measuring the unconfined compression the fixed plate was slotted into position behind the stop and the cage was attached to the spring balance (Plate 4.3). The dial gauge, used for measuring the decrease in length of the core under test, was fixed with the dial at zero and the extension piece

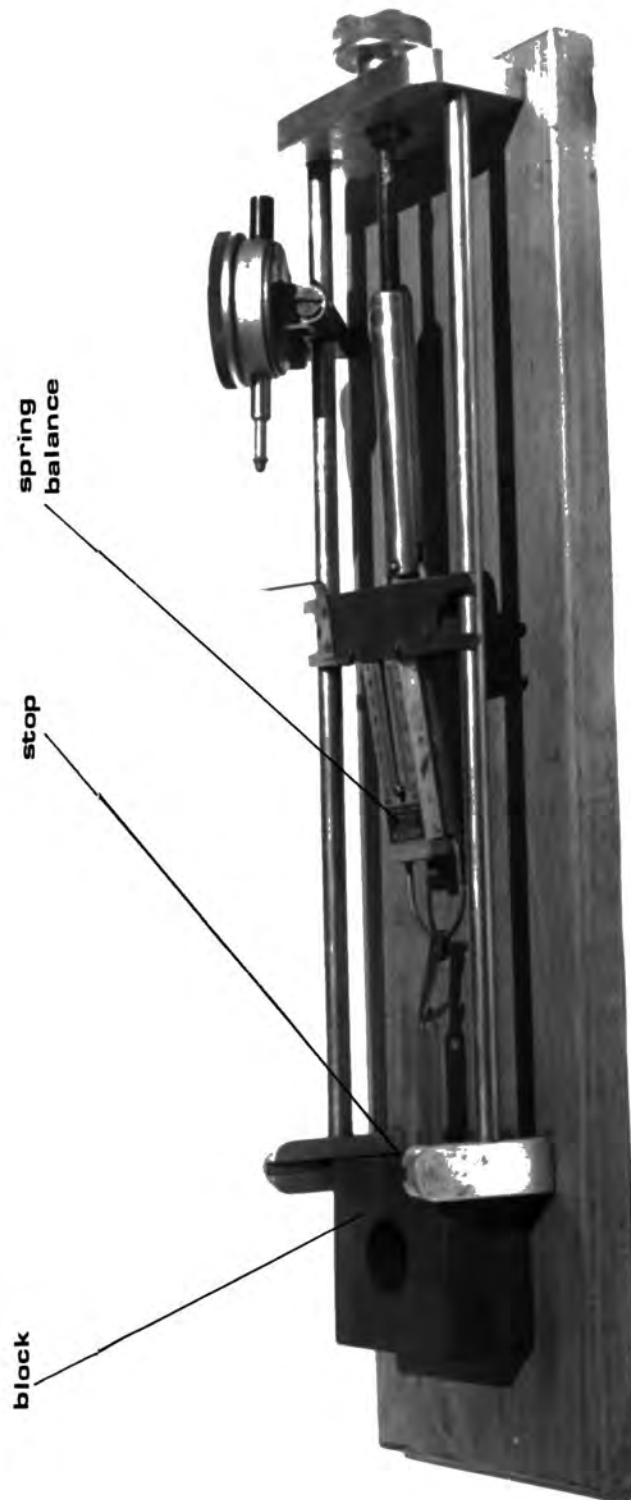


Plate 4.2 Combined Unconfined Compression and Shear Test Apparatus (arranged for shear test)



Plate 4.3 Combined Unconfined Compression and Shear Test Apparatus (arranged for unconfined compression test)

against the stop on the spring balance guide. For testing, the soil was extruded and the ends shaped to fit the cones on the two plates. With the soil in place, the stress was applied evenly by the screw, readings being obtained on failure from the dial gauge and the spring balance.

Various modifications to the procedure and the actual instrument have been introduced to improve accuracy and versatility. The major areas of friction occur between the spring balance guide and its rails and between the blocks. To reduce the former, the guide was cut to give a minimum area in contact with the rails. The blocks were impregnated with wax and before each reading, a layer of oil was placed on them so that, in shearing, the upper block floated on an oil film over the lower. To reduce friction further and to align the test more closely with that employed in the Golder and Cooling apparatus, the tester was placed in a vertical position to obtain unconfined compression readings.

For assessing the strength of the root mat, a core 2.5cm x 5cm was removed with a specially sharpened sampler. This was then fitted into two reception tubes of similar diameter, with half the sample in each tube (Plate 4.4). Three steel nails were then pushed through each half of the sample and stress evenly applied until the root core severed.

To measure stress at the onset of creep, the instrument was assembled as for the shear test but the dial gauge placed in position against its stop. Thus as movement began it was registered and the appropriate stress could be recorded.

Despite readings obtained at Surrey University and Ewell Technical College (Slater, personal and oral communication), it was considered necessary to validate the apparatus for work in geomorphology. This process was completed through comparative measurement and a field exercise.

Samples from the Etherow valley sites (Chapter 6) were tested in the field with both the King and Cresswell apparatus and also the Golder and Cooling machine. Later samples from Rookhope were checked against the laboratory equipment at Salford University (Clarke personal communication).



Plate 4.4 Combined Unconfined Compression and Shear Test Apparatus (arranged for root strength test)

In the first case the results accorded well being within $\pm 5\%$. In the second, variation was nearer to $\pm 10\%$, but it must be remembered that the two sets of instruments were used by different operators.

To test its suitability for detailed geomorphological study in the field, the King and Cresswell apparatus was employed in a study on terracette formation (Anderson, 1971) to locate any slip circles. Newly formed terracettes near the slope crest were selected and cores 5cm long extracted.

Table 4.1. Shear Strength and Slip Circle Identification

<u>Position</u>	<u>Number of readings</u>	<u>Percentages</u>	
		<u>over 454g</u>	<u>under 284g</u>
Through slip circle	54	22	28
Above slip circle	55	56.5	7.5

From these results it is seen that there is a line or probably zone, of weakness which can be located using the apparatus. The readings from samples extracted through the assumed slip circle position show a significantly higher proportion of low shear strengths and lower proportion of high shear strengths.

These procedures indicate the precision of the King and Cresswell apparatus and confirm earlier reported results already noted.

For a rapid determination of shear strength variation, a standard pocket penetrometer (Engineering Laboratories model) was used (Turan, Durgunoglu and Mitchell, 1972). The instrument is extremely simple to use and results were taken to indicate merely the order of magnitude and any changes.

4.4.11. Texture

As a general guide to variations in soil stratigraphy within the watershed, an initial distinction between sand and fines was made (Carson, 1967). A sample from every mineral horizon at each plot was oven dried, ground with

a pestle and mortar and sieved using British Standard sieves numbers 10 and 200. The sieves were shaken for three minutes on a mechanical shaker and the three samples retained were weighed.

Since the silt/clay fraction passes through sieve 200 and cannot be separated mechanically, an application of Stokes' Law was used. Initially a simplified version was used to give an indication of the average diameter of the soil grains. 5g of the silt/clay fraction obtained from sieving were added to 10cc of distilled water in a test tube which was shaken vigorously for 1 minute. The time for the water to clear to 1cm from the meniscus was then taken.

Calculation

C^{cm} /sec velocity of settling

p specific gravity of soil grains

p_w specific gravity of liquid

d cm diameter of soil grains

u poises coefficient of viscosity of the fluid

g /cm/sec/sec gravity acceleration

$$V = \frac{2(p-p_w)}{9u} (d/2)^2 g$$

taking the following average values

$$p = 2.65: p_w = 1.00: u = 0.01$$

for constant velocity

$$h = 8800 d$$

where h distance fallen through (King and Cresswell 1954)

A further division between clay and silt was also achieved by flotation. A weighed sample of fines was stirred vigorously in an evaporating dish full of distilled water. It was then allowed to settle for five hours (Bennett and Humphries, 1965) before the liquid was removed by pipette. This process was repeated six times after which the deposit remaining was dried and weighed, giving a guide as to the silt content.

Samples from the mineral horizons of each plot were

accurately analysed using the British Standard (B.S. 1377 test 7C): Standard Method of Fine Analysis (Pipette Method) and it is the results from this procedure which are recorded in the study.

As the soils contained few particles above the texture of coarse sand and as pH readings throughout the basin had produced a lowest reading of 4.4, certain stages in the standard procedure could be modified. The stages can be outlined:

- (a) The samples were dried, broken by pestle and mortar and sieved with numbers 25, 72 and 200 British Standard sieves using an automatic shaker.
- (b) The material retained on each sieve was weighed.
- (c) The material passing sieve number 200 was pre-treated with hydrogen peroxide to remove organic matter and dispersed after a sodium oxalate solution had been added to prevent flocculation. Dispersion was effected by the addition of 25ml of sodium hexametaphosphate solution.
- (d) The suspension was then transferred to a number 200 British Standard sieve and the fines washed with jets of distilled water into the receiver.
- (e) The material retained on the number 200 British Standard sieve was dried and re-sieved with numbers 25, 72 and 200 British Standard sieves. Soil retained on each sieve was then weighed.
- (f) The suspension passing the number 200 British Standard sieve was washed into a 500ml measuring cylinder and made up to the 500ml mark with distilled water. The cylinder was then shaken for 60 seconds and then placed on a water bath at 20°C.
- (g) Using the pipette, a 10ml sample was withdrawn 10cm below the water suspension surface from each measuring cylinder. These samples were taken after 4min 5s., 46min and 6h 54min. Each was then delivered into a weighing bottle together with any suspension remaining in the pipette.
- (h) The samples in the weighing bottles were dried and weighed to the nearest 0.001g. The weight of sands smaller than particle sized can be calculated from the weight of solids in the sample.

$$W_d = \text{weight of solids in sample} \times \frac{\text{total volume of suspension}}{\text{volume of pipette sample}}$$

4.4.12. Root Factors

Since plant roots are likely to exercise an influence upon creep rates, it was considered necessary to complete a range of methods of measurement. The depth of the root mat was measured directly in each soil pit using a steel tape, but this only gives a basic indication.

Dry root weight is an extremely difficult variable to assess, but readings were obtained during the textural analysis described above. Roots were separated by sieving and removed by tweezers to be weighed. The procedure proposed by Gerwitz^{and Page} (1973) allows far greater accuracy but for this study it was felt that the expense involved could not be justified.

Perhaps the most crucial factor however, is root mat strength, and to evaluate this, the unconfined compression and shear tester already described, was modified.

CHAPTER FIVE

LABORATORY PROGRAMME

5.1. Introductory

5.2. The Soil Troughs and Measuring Instruments

5.3. Programme

5.3.1. Experiment 1

5.3.2. Experiment 2

5.3.3. Experiment 3

5.3.4. Experiment 4

5.3.5. Experiment 5

5.4. Summary

5. LABORATORY PROGRAMME

5.1. Introductory

A fundamental problem in observational science is the inherent lack of control. While environmental factors can sometimes be altered marginally, major changes can only occur naturally, and forecasting them may therefore present difficulties. In the context of this study and particularly within its time scale, such natural changes are broadly meteorological. A good example is the freeze-thaw cycle, only ten of which were recorded at the Brandon site during the whole of the period from the beginning of November 1974 to the end of March 1975. To achieve a reasonable measure of control it is necessary to move into the field of experimental science, and therefore a laboratory programme must be planned. Despite the problems involved it has been stressed that in such multivariate situations much can still be learned from highly simplified controlled experiments (Skellam, 1972).

Laboratory simulation in geomorphology has developed considerably during the last forty years. Work has ranged from simple weathering experiments such as that of Griggs (1936) to the use of sophisticated river tanks and drainage basin analysis (Ward, 1971). However, laboratory models of slopes and mass movement have been somewhat less ambitious, largely because of the great problems of scale. They have been constructed therefore to give ideas and general guidelines rather than definitive solutions. The first use of soil troughs was reported by Davison (1889) and more recently Young (1958) and Kirkby (1963) have described similar work.

When using soil troughs, the problems of scale are apparent in a number of aspects. If water is to be added as simulated rainfall, the spray must be scaled. When examining soil in an isolated block, the slope angle and effects of gravity must be considered. In the context of such a small portion of slope, it is possible that the scale of the natural soil particles impedes realistic processes.

A different medium could be used and an analogue model produced, but this would lead to further complications in the interpretation of readings. Such difficulties resulting from the substitution of one chemical reaction for another in soils have been considered (Watson, 1972).

Other major difficulties include the method of loading. If the trough is completely filled, conditions are as in the field but the potential for movement is obviously limited. If on the other hand the trough is not loaded completely to its lower end, creep can occur more easily and therefore the processes can be studied, but it is not as realistic a simulation. Furthermore, if the basic conditions are unnatural, the use of soil blocks lifted from the site rather than reconstituted soil may be merely adding spurious precision. There is also the question of drainage, particularly the relative importance of evaporation and gravitation. In a trough, water is likely to drain more freely downwards out of the soil than is possible in the field, but conversely, particularly with the effect of wind and temperature, losses upwards are likely to be greater under natural conditions.

Despite these limitations and bearing them in mind, it was decided to include in the study a laboratory programme with certain definite aims:

- (a) To simulate the major meteorological 'triggering' mechanisms and examine their effect on creep rates.
- (b) To obtain continuous readings of creep under changing meteorological conditions.
- (c) To relate any results to the field situation.

It was therefore designed essentially to test ideas rather than instruments. The work of Kirkby (1963) and Evans (1974) has demonstrated clearly that creep occurs in soil troughs and that it is possible to measure the rate in the short term. Evans used what was effectively a Young's Pit consisting of short lengths of thin rod to provide a correlation with the Evans T bar. It was assumed that the rods would tend to move with the soil particles and therefore provide a velocity profile which could be compared with the T bar reading. Kirkby also buried horizontal rods in the

soil and plotted their movements on the glass side of the trough. Therefore since it was proposed to use T pegs, instruments similar to the Evans T bar, it was felt that work could be justifiably concentrated on the aims stated. In fact, since the major part of the programme was concerned with undisturbed soil blocks, the problems of locating miniature Young's Pits accurately would have made it difficult to retain the blocks intact. If dowels were buried rather than being inserted in the side of the profile, the disturbance would have been considerable.

5.2. The Soil Troughs and Measuring Instruments

Since it is clearly vital to be able to relate laboratory results to those obtained under field conditions, the programme had to be seen in the context of the total study. This fact was recognised by the provision of special instruments in the field. The Open Tubes and steel rods were designed to provide results as far as possible analogous to those obtained from partially loaded soil troughs. It has already been stated that if the soil does not fill a trough to its lower end, creep rates are likely to be exaggerated, and it was felt that with the similar conditions in an Open Tube, comparable results should obtain. The other major difference between field and laboratory measurements was that certain of the latter were continuous. The problems of setting up a peg fitted with a stylus and a thermograph in the field were formidable, particularly as a result of the actual rainfall and wind effects which influence soil moisture and creep rates. Therefore it only proved possible to maintain the apparatus during one week when rainfall was high enough to alter conditions sufficiently for changes in the trace to be discernible.

When designing soil troughs for creep measurement, clearly the larger the dimensions, the more accurate the simulation is likely to be. However, the conflicting aspect of portability must also be considered, particularly when soil blocks taken directly from the field, are used. For this programme, troughs 60cm long, 20cm wide and 20cm deep

were built (Fig. 5.1). This volume represents something of a compromise which accords well with measurements reported by the workers already quoted. The troughs were constructed of marine plywood, the sides and ends being of thickness 9mm and the base 12mm. To prevent the soil blocks slipping en masse, three square retaining rods, 2.5cm by 2.5cm in cross section, were fixed to the base of each trough. These were attached at equal intervals down the trough and across its entire width. Three 5mm holes were drilled at the lower end to allow soil drainage, and the inside of each trough was painted with polyurethane. For later aspects of the study these troughs proved to be too large, and aquaria measuring 32cm by 22cm and 21cm deep were used.

Apart from the Anderson Inclinator and pegs, other simple measuring devices were constructed. Initially T pegs made from square dowelling, 1.3cm by 1.3cm in cross section (Fig. 5.2A) were installed to a depth of 15cm. The stem of each peg measured 22.5cm and the cross piece 10cm. Later a 22.5cm length of aluminium rod, of the same dimensions as that used for the pillars, was substituted for the stem. It was considered that the design of these probes provided a direct link between the Evans T bar, already validated for soil troughs, and the Inclinator pegs. Furthermore, with a lighter although less accurate measuring instrument, they were very stable in loose reconstituted soil. The instruments used with the T pegs to measure creep were a large mounted engineer's level bubble and an Abney level. The former measured 8cm in length and it was sunk into a trough in the top of a wooden block, using plastic wood. The wooden block measured 10cm in length and a 10cm length of 1.3cm angle aluminium was bolted to it to provide a smooth lower surface for measurement (Fig. 5.2B). While the plastic wood was setting, the apparatus was placed on a horizontal surface and the level adjusted so that the bubble was exactly central. With its index point on 0^0 , the Abney was then placed on the same surface and the position of its bubble marked on its level tube. The two devices were therefore calibrated to give comparable readings. For continuous readings, a stylus arm and stylus were fitted to the end

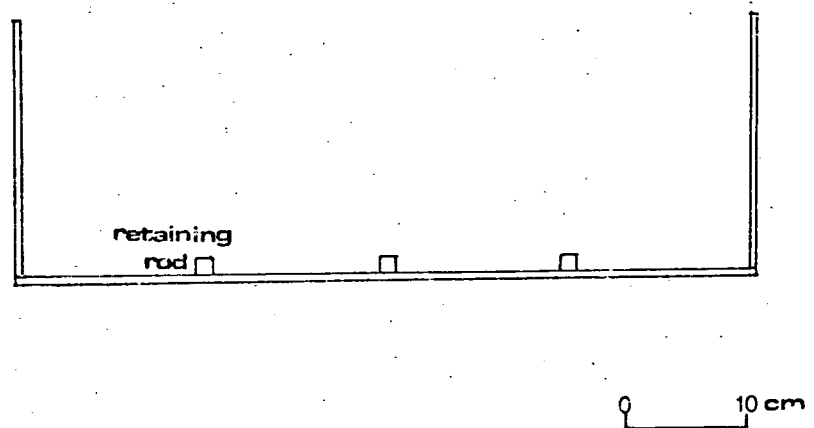


Fig. 5.1

Soil Trough

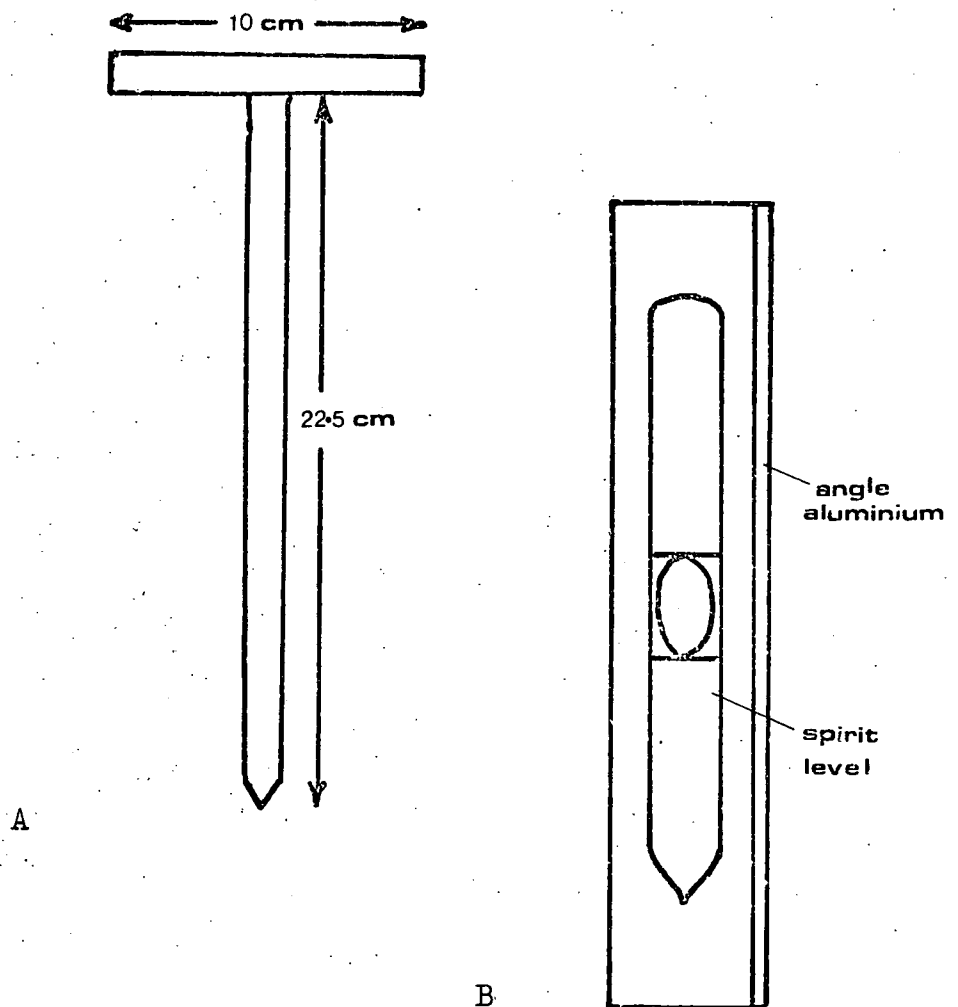


Fig. 5.2 Soil Movement Measuring Devices

A 'T' Peg

B Simple level

of the cross piece of an aluminium peg (Plate 5.1). To allow comparison throughout the study, all rates of linear creep, unless otherwise stated, were measured at a depth of 2.5cm. However the simple devices can provide merely an indication and valid comparison is only possible with the Inclinator results.

5.3. Programme

From the early field readings obtained, it was clear that the relevant meteorological conditions should be exaggerated to produce changes measurable in the short term. The major cycles are wetting-drying and freeze-thaw, and it is possible either to control or to allow any of the four to occur under natural conditions. During the study, various combinations of these approaches were applied.

5.3.1. Experiment 1

As an initial study to make a quantitative assessment of the reaction of soil blocks to wetting-drying cycles, reconstituted Wirral soils were used. However, each was loaded in the field and the profile was reproduced as faithfully as possible. The troughs were filled completely to a depth of 18cm and two Inclinator pegs were inserted to 15cm in each, one 6.5cm from the top and the other 6.5cm from the bottom. Three types of soil were used: one predominantly organic from the wooded area of Bidston Hill, one with a high sand content from open ground on Thurston Hill (Triassic sandstone) and the third based on till also from Thurston. As a control, a second trough was filled with Bidston Hill organic soil. This trough was instrumented with two pegs, but remained level throughout the experiment. All four troughs underwent three wetting-drying cycles, the water being applied slowly over a period of several hours until drainage from the base indicated that field capacity had been exceeded. To check any run-off or surface erosion, a fine spray was used and the soil surface was covered with fine absorbent tissues. The troughs were left as open as possible to the free flow of air and drying occurred



Plate 5.1

Soil Trough
(arranged for continuous recording)

naturally. For the first two cycles, troughs other than the control were tilted at 15° and for the third, their angle was increased to 25° . The position of cracks on the soil surface was recorded on specially prepared grid sheets (Fig. 5.3).

Results

The four cycles of experiment 1 were completed between mid-May and early July 1972. The soil troughs were open to the free flow of air and so drying rates were comparatively rapid and the resulting pattern of movement could be quickly recognised. The textures of soils B and C, the mineral soils, are given; soil A was organic.

Table 5.1. Experiment 1: Soils Texture

Soil	B	C
% sand	82.0	32.5
% silt	4.0	31.0
% clay	14.0	36.5

The first cycle, with the troughs at an angle of 15° , lasted 15 days and was intended to give a basic idea of the amount and direction of movement.

Table 5.2. Experiment 1: Soil Movement Cycle 1

Soil	A	B	C	Control
Movement (mm) upper peg	1.28	0.27	0.15	0.30
Movement (mm) central peg	0.94	0.38	0.19	0

As expected, all the pegs showed a downslope movement during the cycle. As the soil shrinks, it contracts inwards from the side of the trough and therefore the upper peg would

1 2 3 4 5 6 7							1 2 3 4 5 6 7						
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3							3						3
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23							23						23

BOX NUMBER

DATE

BOX NUMBER

DATE

Fig. 5.3 Grid Sheet for Recording Soil Cracks

be expected to tilt downslope, while any peg at the lower end should tilt upslope. Theoretically, a central peg should move little, but since the trough is tilted, the added effect of gravity is likely to displace the point of no movement further down the trough. The rates of movement were rapid and probably further exaggerated by the warm drying conditions. They are therefore considered to be to a degree analogous to rather than representative of the field condition. Movement was clearly the greatest in the organic soil, being some three or four times more rapid than that in the predominantly sandy soil. If the creep measurements for Rookhope are compared with these it will be seen that the purely organic (Juncus plots) exceed the sandier (Pteridium plots) by a similar proportion. Rates for soil C were surprisingly smaller, being far lower than that for one control peg and it seemed likely that the soil was not completely wetted.

To investigate this point and check the conclusions, the cycle was repeated over a period of 8 days, but with a rather longer period of wetting.

Table 5.3. Experiment 1: Soil Movement Cycle 2

Soil	A	B	C	Control
Movement (mm) upper peg	2.40	0.15	0.53	0.15
Movement (mm) central peg	0.83	0.19	0.98	0.15

Movement was again wholly downslope and the rates for the three soil types were related in predictable proportions. The upper peg in soil A became somewhat loose and the reading is exaggerated, while a crack developed near the central peg in soil C.

As the upper peg in soil A had become unstable, it was decided that for the remaining two cycles the central peg only would be used. Cycle 3, with the troughs at 25° lasted for 10 days.

Table 5.4. Experiment 1: Soil Movement Cycle 3

Soil	A	B	C	Control
Movement (mm)	1.56	0.11	0.38	0.11

All the pegs registered downslope movement. However, it would seem that creep is slower at the steeper angle, possibly because of the more rapid drainage. In fact from results in the field this explanation is advanced later in the study. Evans (personal communication) also considered this the most likely explanation,

The cycle was repeated for a further 12 days to attempt some confirmation of these conclusions.

Table 5.5. Experiment 1: Soil Movement Cycle 4

Soil	A	B	C	Control
Movement (mm)	1.28	0.45	0.38	0

Movement was broadly similar in direction and proportion to that recorded during the third cycle except that the highest rates for soil B during the complete experiment were measured.

It can be concluded that a pattern of movement is clearly discernible during the drying phase of each cycle. Furthermore if the soil properties are similar to those measured at Rookhope, the relative rates seem comparable. Ideas on the effect of slope angle must be more tentative but it would appear that other factors, such as possibly drainage rates, may be important.

5.3.2. Experiment 2

For this study, two reconstituted Rookhope soils were tested through two drying cycles at an angle of 20° . The soils were collected in the field as in the previous experiment, but the troughs were not loaded to their lower

ends. This made for a degree of instability, and measurement of movement was by T peg and the engineer's level. One peg was placed centrally in each trough. A sheet of thin plastic was fastened over the level and the position of both ends of the bubble marked on this, using a fine water-based pen. The two gradations inscribed on these levels were also marked on the plastic and these were used to transfer the positions to a record sheet.

Results

Experiment 2 was designed to examine the results from experiment 1 in the context of Rookhope soils and also to investigate the effects of trough loading. Four cycles were recorded between early February and early May 1973, with the result that conditions for air drying were less favourable. For each of the four cycles, wetting was completed with the troughs at the required 15° angle.

As explained earlier, the troughs were loaded to a position 10cm from their lower ends. As a result the soil was expected to be somewhat less stable and more easily disturbed, and therefore a different measuring instrument was used. The engineer's level device was calibrated against the Inclinator so that with a graph, readings could be converted to linear soil movement. There was however a loss of accuracy resulting from making measurements of the bubble edge.

The soils were selected to contrast the organic (A) and the mineral (B) horizons and were obtained from near plot 8. The texture of soil B was: sand 65%, silt 33%, clay 2%.

Since in each case the wetting procedure already described was conducted in a similar manner, the results need not be listed or discussed separately.

Table 5.6. Experiment 2: Soil Movement Cycles 1, 2, 3 and 4

Cycle 1	Soil	A	B
Duration 12 days			
Movement (mm)		0.70	0.32

Cycle 2	Soil	A	B
Duration 6 days			
Movement (mm)		0.70	0.30

Cycle 3	Soil	A	B
Duration 9 days			
Movement (mm)		1.35	0.75

Cycle 4	Soil	A	B
Duration 12 days			
Movement (mm)		1.70	0.75

All movements were downslope and it can be concluded that under the same conditions rates are distinctly greater in the organic than the mineral soil. In assessing the possible effect of the loading mode, the evidence is less obvious, although it must be remembered when comparing the results of this and the previous experiment, that only the B soils are strictly comparable. The organic soils were taken from entirely different environments but even so, the highest readings were obtained in experiment 2. If the rates recorded for the mineral soils are contrasted, the set taken during the present experiment are seen to be clearly higher with a Mann-Whitney 'U' test result of 0.026 significant at the 95% level.* However, any conclusions must be seen in the context of the duration of each cycle and the time of year that each experiment was conducted. While the durations were not identical, they were of much the same order, but on the other hand it must be expected that the seasonal differences would have exercised an influence. Certainly with so much less impedance at the lower end of the box it would be expected that gravitational and shrinkage effects would produce enhanced creep rates. In fact there is further evidence to support this contention since if these results are compared with those obtained from the steel rods at the lower edge of the basin and the Open Tubes it will be seen

*the use of significance levels is discussed later in the study (e.g. Chapter 13)

that they accord well (Chapter 10).

5.3.3. Experiment 3

To provide a comparison with the results from experiment 2, three soil blocks, one from under each main vegetation type (Nardus, Juncus and Pteridium associations) were removed from the Rookhope site for this experiment. Each block was carefully measured and then extracted from the 20° slope which occurs between plots 8 and 9. The vegetation was removed and each block placed in a soil trough filling it completely to a depth of approximately 18cm. The troughs were placed at an angle of 20° and the soils which were already virtually at field capacity, were allowed to dry naturally through one long drying cycle. For comparative purposes, three measuring instruments were used: Inclinator pegs and the two types of T peg (Plate 5.2). Each trough was instrumented with a wooden stemmed peg 10cm from the top, an aluminium stemmed peg 15cm from the bottom and an Inclinator peg centrally. The position of the lower compared with the upper T peg was dictated by the impedance to creep lower down the trough which was discerned in previous experiments.

Results

From a theoretical consideration it would be expected that pegs placed at the upper and lower ends of soil troughs would register movement in opposite directions. A main aim of experiment 3 was therefore to examine the direction and rate of movement of pegs placed centrally and at either end. Conditions were related as closely as possible to those in the basin by using soil blocks from each of the main plot groups with the soil at approximately field capacity. It was also considered important to record daily movements over an extended period and so the experiment was maintained for six months from 1st January until 30th June 1975. Since drying took place in an unheated building, rates were slow in the initial stages as they depended solely upon changing meteorological conditions.

With the convention of downslope movement being positive and upslope negative, the results for the six months can be



Plate 5.2

Soil Trough
(showing measuring instruments)

tabulated.

Table 5.7. Experiment 3: Soil Movement

<u>Soil block</u>		<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Movement (mm)	Upper peg	+3.58	+6.53	0
	Central peg	-0.03	+6.18	-0.25
	Lower peg	-0.20	-6.55	-1.80

These readings fit well into the expected pattern of movement with the upper pegs tilting downslope and the lower pegs upslope. According to soil conditions and probably the exact location of the central peg, so theoretically it could tilt in either direction. In fact the central pegs in two blocks are comparatively static, and considering its high moisture content, it is hardly surprising that the Juncus plot soil shows downslope movement. Its high wet bulk density together with the extra lubrication available would be expected to add to the effect of gravity and displace the point of no movement down the trough.

Furthermore it can be seen that rates of movement are far greater in the Juncus block and this can clearly be related to shrinkage. Mean linear shrinkage was measured at the top, bottom and sides of each trough but the surface was too irregular for a realistic value to be obtained there.

Table 5.8 Experiment 3: Mean Linear Shrinkage of the Soils

<u>Soil plot</u>		<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean linear shrinkage	Top	10	23	5
(mm)	Bottom	8	19	3
	Sides	7	13	25

The daily readings for each peg were plotted with the same convention of downslope movement being shown in a positive

direction. Results for the first three months are given as these indicate the local variability illustrated by Kirkby (1963) and reported by Evans (1974). With the upper pegs (Fig. 5.4) the overall downslope trend is discernible in the Nardus block and more obviously in the Juncus. The Pteridium soil shows a slight upslope movement over this period but is comparatively stable. If the major sudden changes can be interpreted as cracks within the soil mass, then three occur in the Juncus soil and one in the Nardus and none in the Pteridium. From the evidence of surface cracks recorded it would appear that the soils might be placed in this order of susceptibility to cracking.

The lower pegs (Fig. 5.5) show a similar pattern with two soil blocks prone to sudden changes and the Pteridium soil more stable. In this case however it is the Nardus plot soil which shows a slight trend in the opposite direction to the other two and also to the final movement.

The Inclinator peg (Fig. 5.6) plots each reveal the start of what amounts to a general movement, the Nardus and Pteridium soils upslope and the Juncus downslope. Measurements with the more precise instrument also show the erratic nature of the process resulting from the heterogeneity of soil and the very local changes which occur during drying. However there is a discernible overall pattern which can be attributed partly to meteorological influences (ie wetting and drying)

Experiment 3 thus confirms the mobility of the predominantly organic soil and illustrates the relationship between soil movement and shrinkage. However the drying cycle extended over a comparatively long term and it was thought that the effects could be better examined if conditions were exaggerated, so that they could be viewed in the short term. Furthermore a series of readings, each taken at one point in time tends to mask any smooth changes which may occur. It was therefore decided that continuous recording should be employed and compared with point readings during the remaining experiments.

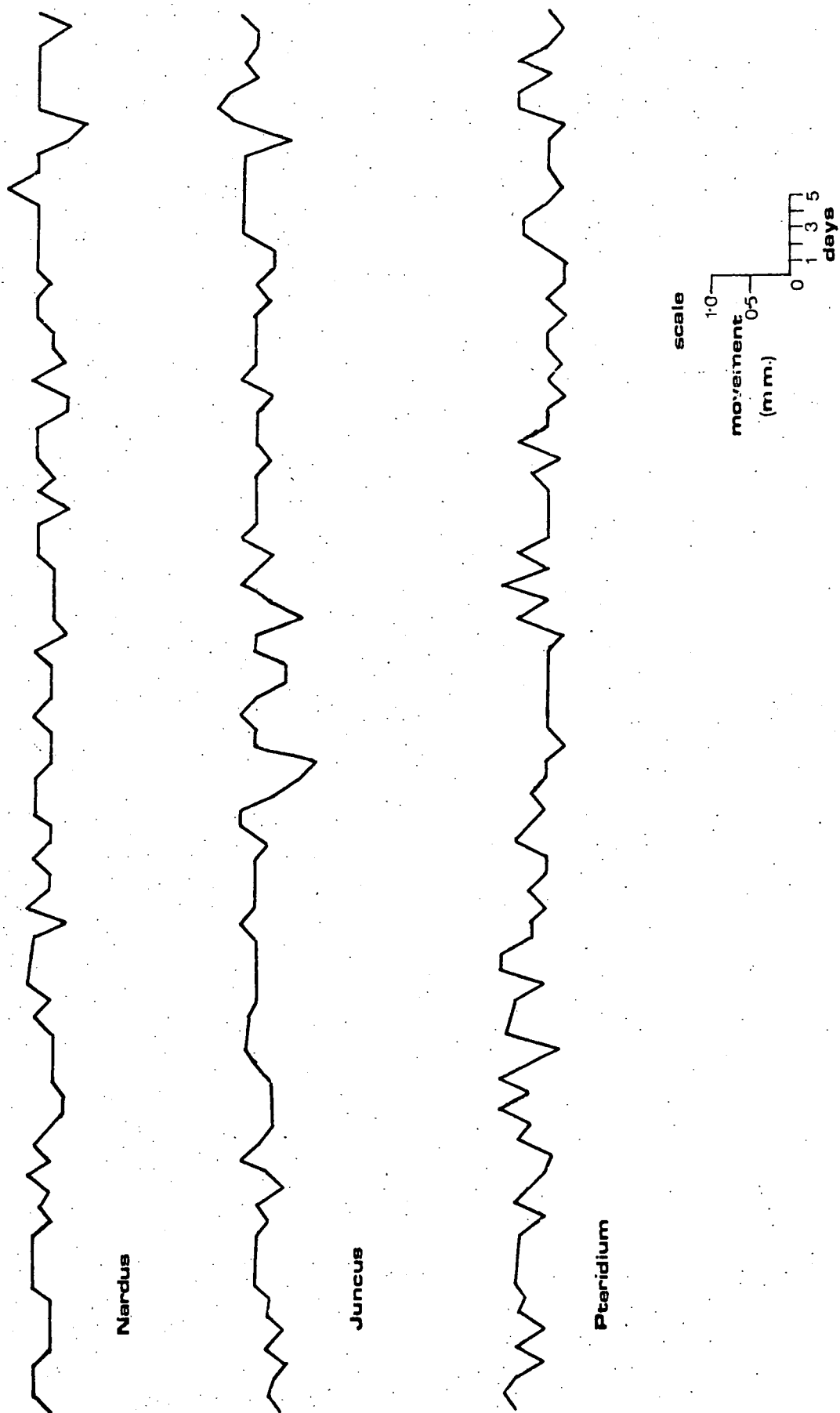


Fig. 5.4 Upper Peg Movement (Experiment 3)

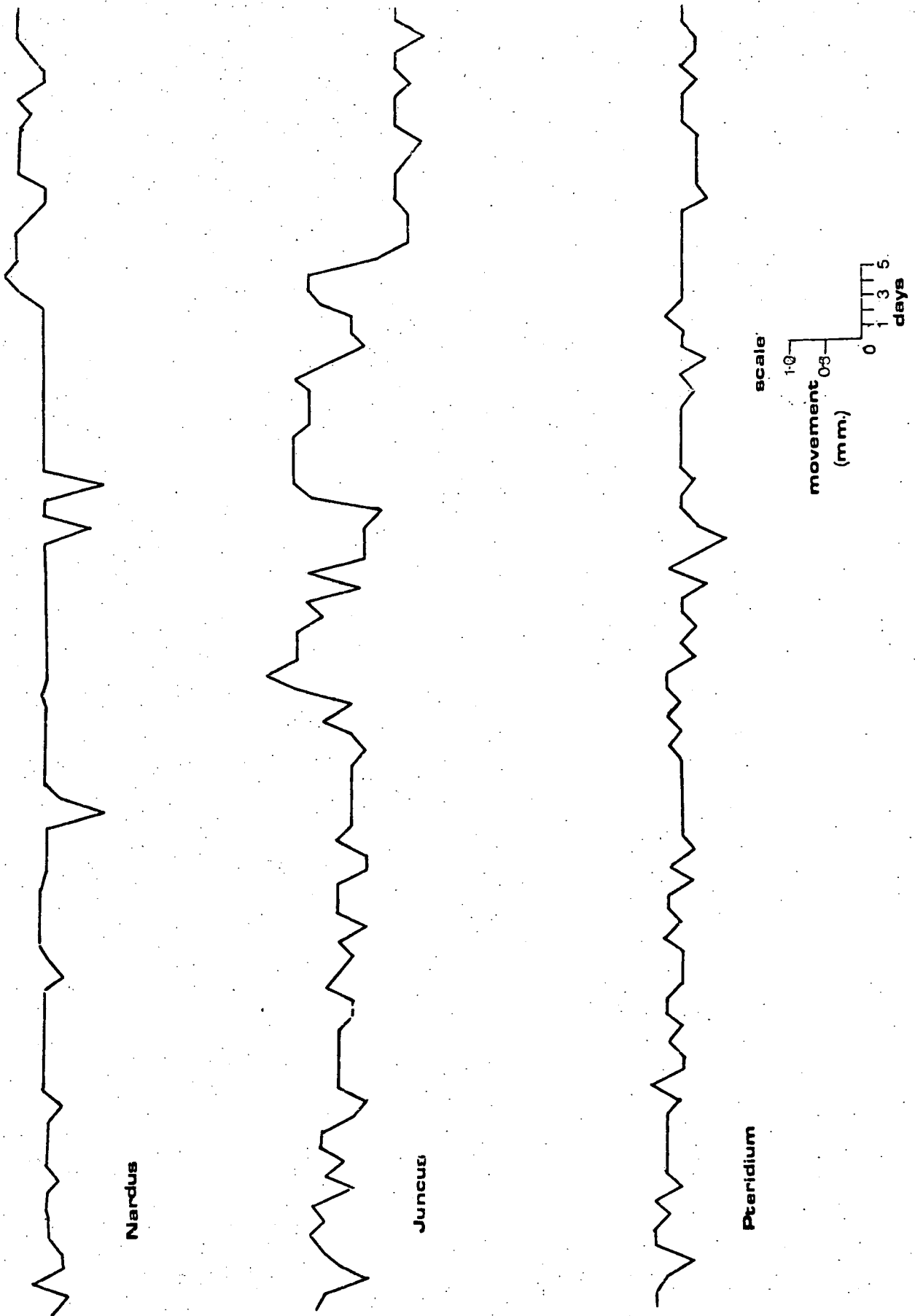


Fig. 5.5 Lower Peg Movement (Experiment 3)

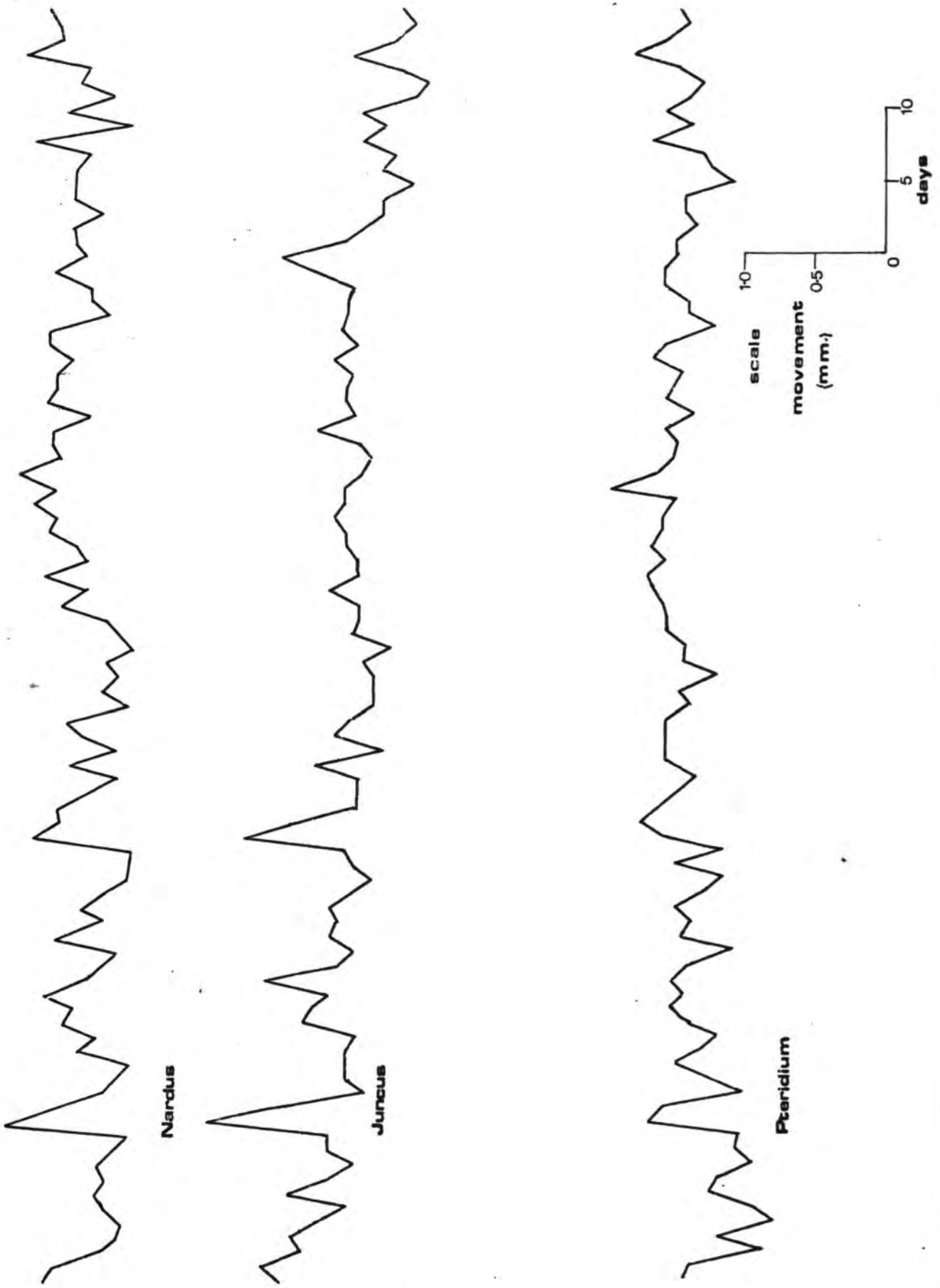


Fig. 5.6 Inclinometer Peg Movement (Experiment 3)

5.3.4. Experiment 4

As the soil blocks were removed for experiment 3, similar but smaller blocks were extracted to fit the aquaria for experiments 4 and 5. The limited space in the refrigeration room dictated that the larger soil boxes could not be used for the freeze-thaw study. It has been shown that vertical heaving can be produced by the freezing of soil water (Taber, 1930, Penner, 1960). Therefore, as the moisture content of the soil from the Pteridium plot (40%) and that from the Nardus plot (37%) are similar, the main comparison was thought to be between these and the soil from the Juncus plot with a moisture content of 73.5%. Therefore the experiment was conducted with paired blocks angled at 20°. A special cradle was built so that the aquaria could be fixed at a required angle but could remain portable. (Plate 5.1).

Freeze-thaw cycles were effected by programming the refrigerator to a temperature of -15°C and leaving it for a required period. It was then switched off to allow thawing to a steady reading of +15°C within 30 minutes. A range of 30°C clearly exaggerated the action of a cycle occurring generally in Upper Weardale, but it did allow short term readings to be taken. For the first eight cycles movement in the Nardus block was compared with that in the Juncus block, using measurements taken by Abney level from one aluminium stemmed peg placed centrally in each aquarium. For the remaining six cycles these readings continued with the same blocks but an Inclinator peg was added to each. Also a continuous reading peg was inserted into the soil from the Juncus plot to be compared with a similar peg installed in the block from the Pteridium plot. Movement was recorded on a thermograph trace. Soil heave has been plotted in detail by other workers (e.g. Outcalt, 1970) and its effects have been included in the traces obtained in the continuous measurement of soil movement (e.g. Everett, 1963).

Results

Experiment 4 was designed to test the effects of frost cycles with the temperature range increased as explained, and the time factor shortened. The Juncus and Nardus blocks were

instrumented to provide the contrast between predominantly organic and mineral soils already discussed in connection with experiment 2. The four resulting peg plots are shown with movement against individual cycles. The readings from the aluminium stemmed pegs (Fig. 5.7) illustrate very clearly the two phases of each cycle, particularly in the earlier part of the experiment. Later, probably owing to soil disruption and cracking, the pattern degenerates and is less recognisable. The overall similarity of the plots is evident, but they can best be contrasted if examined in stages. The first lasted from 16th until 20th December and comprised five cycles.

Table 5.9. Experiment 4: Soil Movement Stage 1
(Aluminium Pegs)

<u>Soil block</u>	<u>Nardus</u>	<u>Juncus</u>
Movement (mm)	-1.5	-1.4

This period of almost identical rapid rates was followed by four cycles (20th until 24th December) which produced a contrast. Both blocks recorded greatly diminished rates, the Juncus block indicating a slight reversal. From 24th until 28th December the two completed cycles showed virtually no net creep.

Table 5.10. Experiment 4: Soil Movement Stage 3
(Aluminium Pegs)

<u>Soil block</u>	<u>Nardus</u>	<u>Juncus</u>
Movement (mm)	-0.03	+0.06

However during this same period the Inclinator pegs were established at a slightly lower position in the troughs and they both indicated an upslope movement of similar proportions (Fig. 5.8).

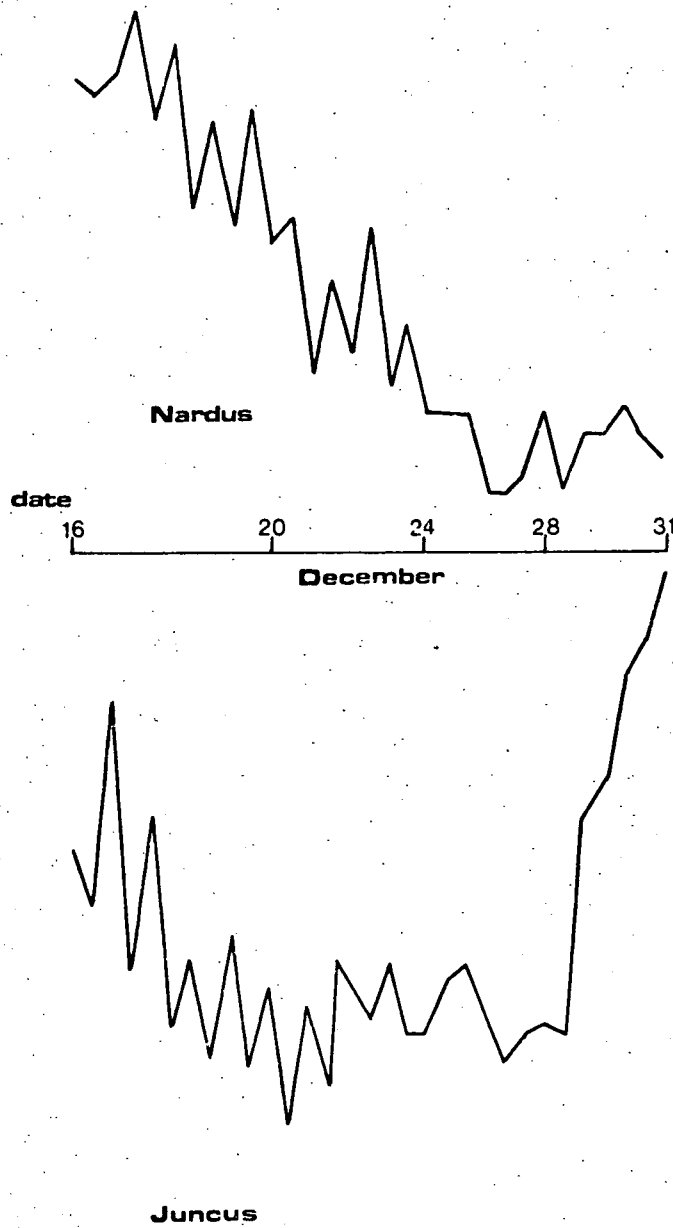
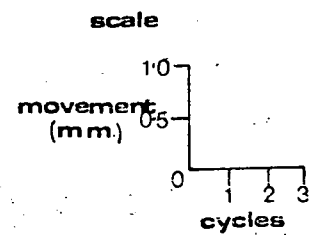


Fig. 5.7 Aluminium Stemmed Peg Movement (Experiment 4)



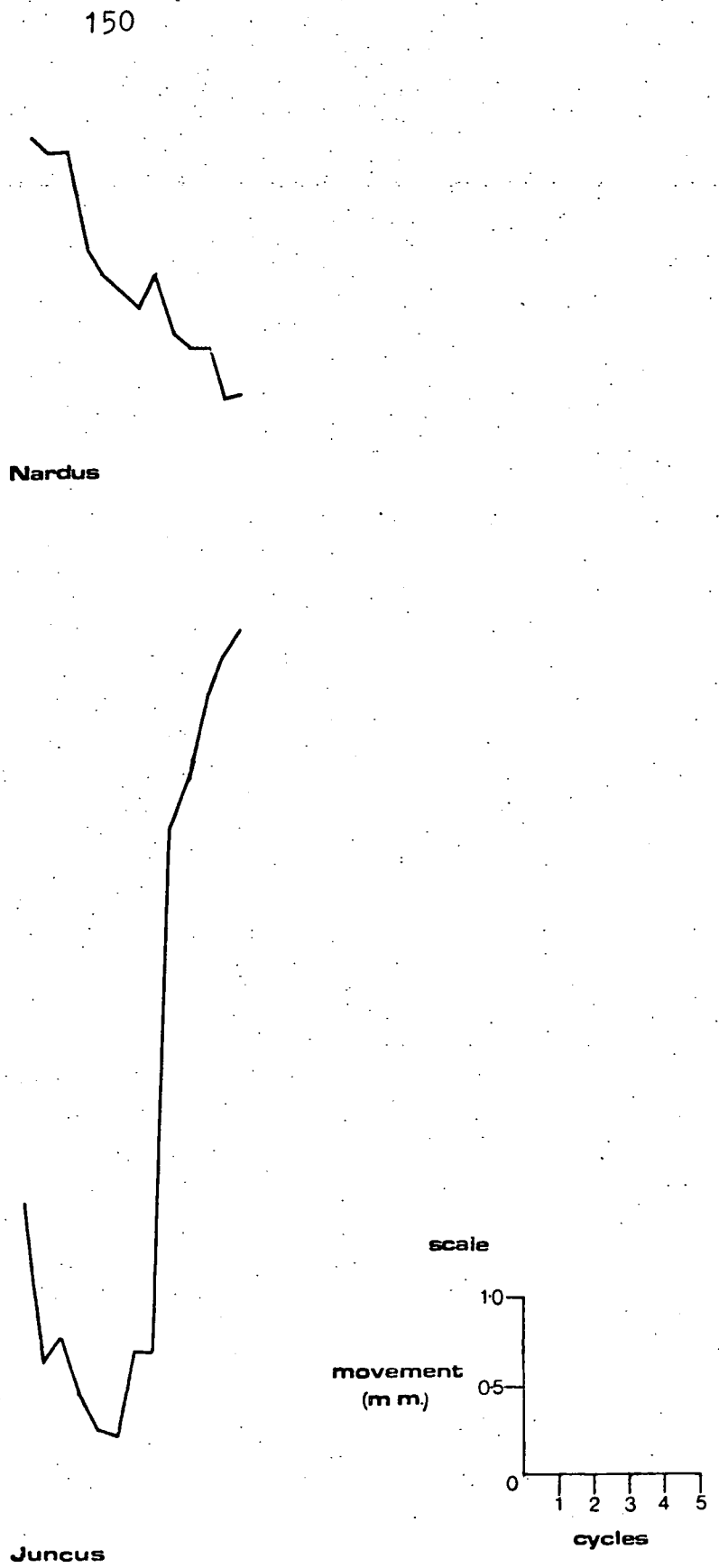


Fig. 5.8 Inclinometer Peg Movement (Experiment 4)

Table 5.11. Experiment 4: Soil Movement Stage 3
(Inclinometer Pegs)

Soil block	<u>Nardus</u>	<u>Juncus</u>
Movement (mm)	-0.92	-0.82

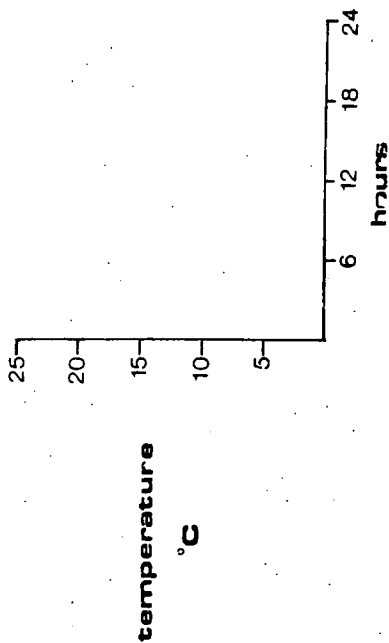
From 28th December onwards the dominant feature of the plots is the complete reversal of direction shown in the Juncus block. This indicates a major change such as a master crack, since it was recorded by both pegs. In fact if the whole recording period of the Inclinometer peg is compared with readings over a similar time obtained from the aluminium stemmed peg, movement is similar.

Table 5.12. Experiment 4: Soil Movement (Total Measurement Period) (Inclinometer Pegs)

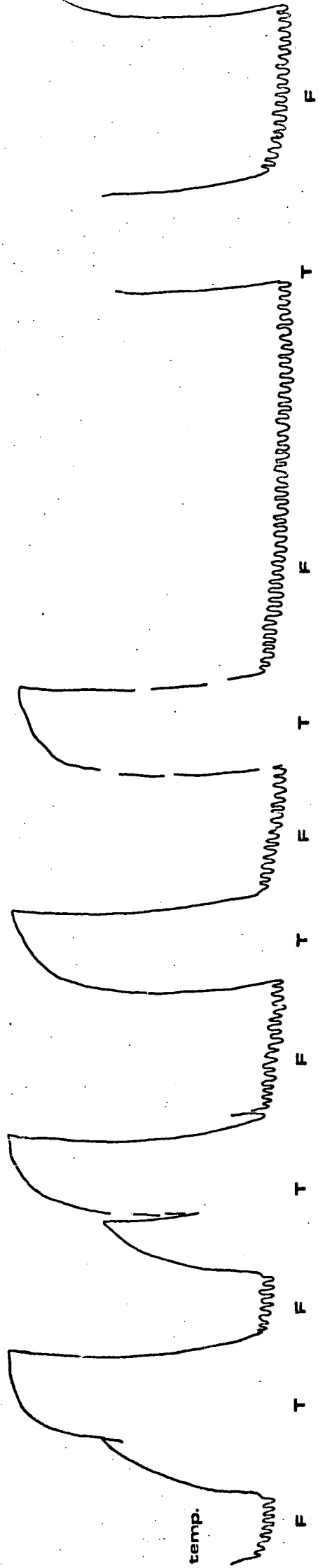
	<u>Inclinometer peg</u>	<u>Aluminium stemmed peg</u>
Movement (<u>Juncus</u> block) 24th-31st December (mm)	+3.1	+3.9

This result does indicate strongly that under the same conditions, the two pegs would give very similar readings for movement. Clearly, even on the scale of these soil blocks, there is differential creep and obviously two pegs cannot measure exactly the same soil column, but these two have recorded the same unusual trend. In contrast, the pegs in the Nardus block were farther apart and their plots are somewhat different.

For a three week period continuous movement was monitored in the Juncus and Pteridium blocks and a record produced on the thermograph trace (Fig. 5.9 A,B,C). While movements are too small to be measured accurately from the trace, directions are very clearly shown, and thus the direct effect of the freeze-thaw cycles can be discerned. During the period, twenty-two cycles of varying duration



stylus did
not record



Pteridium

Juncus

CYCLES
F freeze
T thaw

Fig. 5.9A Freeze-thaw Cycles
(Experiment 4)

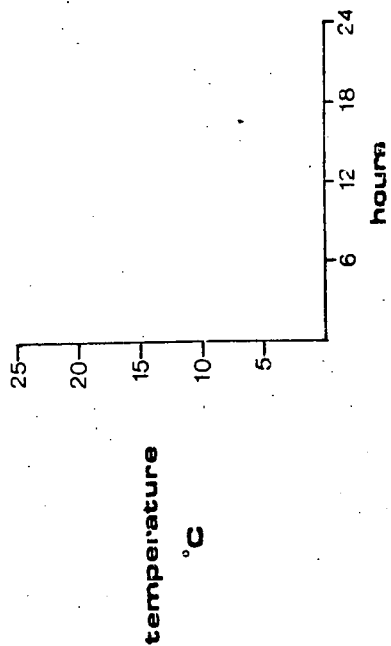
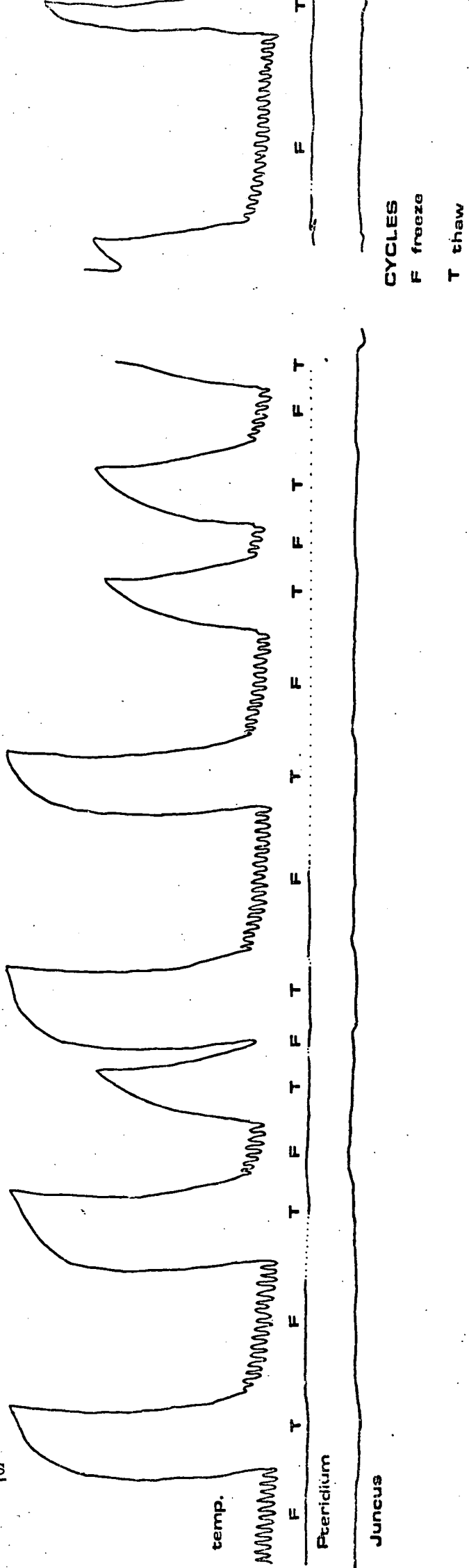


Fig. 5.9B Freeze-thaw Cycles
(Experiment 4)



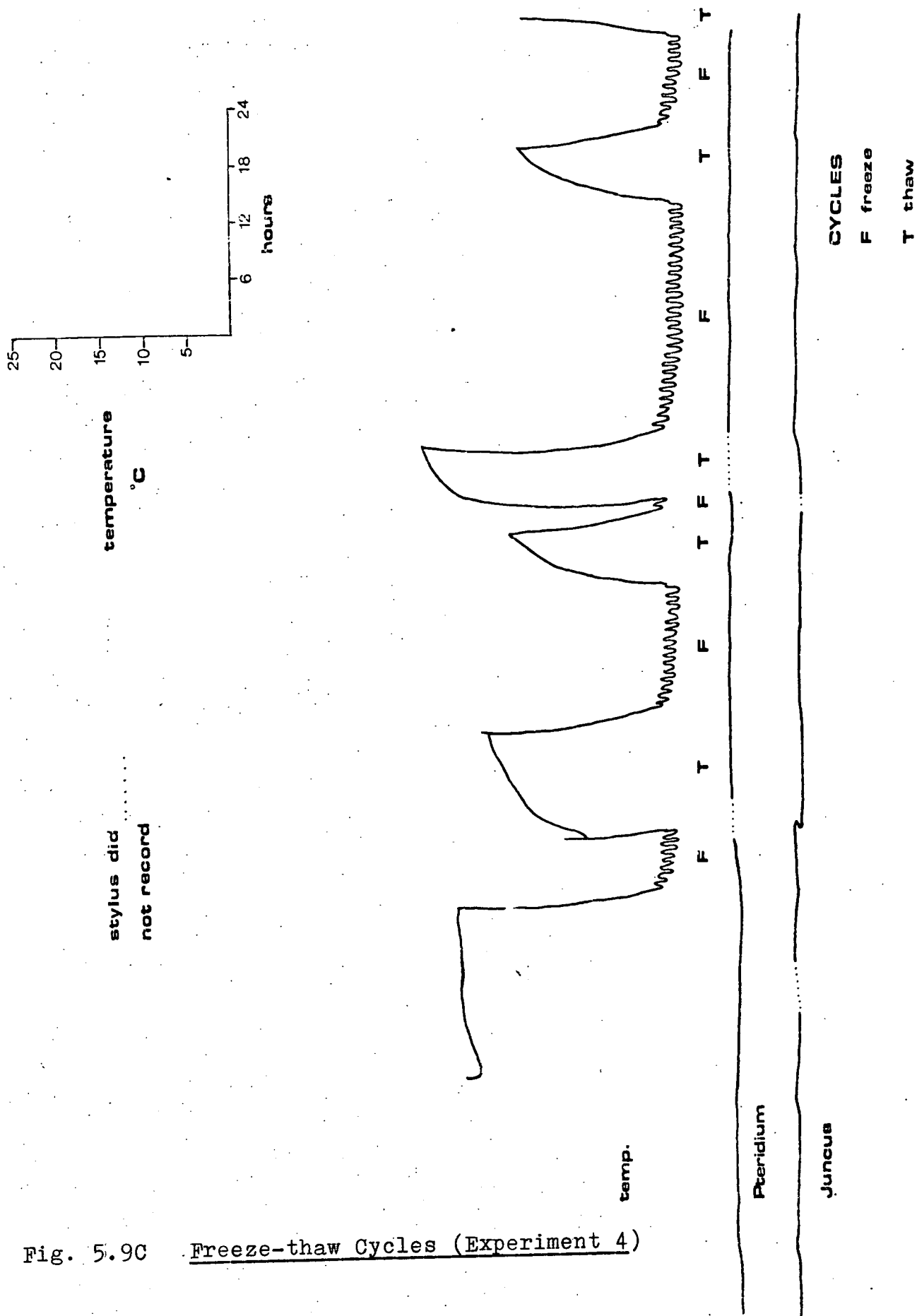


Fig. 5.9C Freeze-thaw Cycles (Experiment 4)

were recorded. Unfortunately, within the cramped conditions of the refrigerator, aligning the three styluses without disturbing the blocks, resulted in ink spillage on the traces, but the records can still be clearly seen. Since each stylus started measuring at a different position, the records needed to be carefully matched for time. This has been facilitated in the copies by realigning the plots so that coincident changes appear in a vertical line and then a definite sequence emerges. As the temperature drops and freezing occurs, the soil block styluses record a sharp upward movement. As the soil thaws, the records indicate a gradual downward trend, although the overall net movement is upwards. These changes are more easily seen in the lower record produced by the Juncus soil block as the Pteridium block had a superficial litter covering which tended to dampen the cyclical effects. In each case a dotted line indicates where the stylus did not record.

These traces demonstrate qualitatively that measurable soil movement, at least within soil blocks, occurs directly as a result of freeze-thaw cycles.

5.3.5. Experiment 5

As the natural drying rates had proved extremely slow, it was decided that exaggerated conditions should be introduced in much the same way as those simulated by Rose (1962) and Bryan (1968). Again the capacity of the drying room precluded the use of the large soil boxes and the experiment was conducted with soil blocks used in the previous experiment. To produce rapid drying rates a silvered 500-watt bulb was suspended centrally over the aquaria. Each aquarium was drilled with drainage holes at its lower end so that the soil could be brought to field capacity. The total cycle therefore consisted of the soil being brought to field capacity in approximately one hour and then being dried for several days. The blocks used were the same as those employed in experiment 4 but movement was recorded on a thermo-hygrograph trace.

Results

Experiment 5 was designed to parallel experiment 4, but with wetting-drying cycles and also to compare records obtained with the one produced in the field, thereby linking laboratory and plot evidence. The same two small blocks used in the previous experiment were transferred to the drying room and the first trace shows the large movement recorded during thawing and drying (Fig. 5.10). There were then four periods with wetting-drying cycles, each lasting one week. The relevant parts of the plot have been extracted from the thermo-hygrograph traces and realigned to show the evidence of changes (Fig. 5.11 A,B,C,D). When the soil block record is examined, it can be seen that there is a gradual downward movement following saturation, but as drying commences, the trend becomes upward. This accords well with field results which show clearly the opposing movement of wetting and drying. The one continuous record from the field illustrates the same downward movement following rainfall, although since the moisture change involved was far less, the amount is smaller (Fig. 6.8).

5.4. Summary

The results of the soil trough experiment show, qualitatively, that a definite relationship exists between soil movement and the two cycles: wetting and drying and freeze-thaw. The direction of this movement is almost uniform depending upon the peg position in the trough. With drying, the upper pegs tilt downslope and the lower pegs upslope. The pegs arranged for continuous monitoring were approximately central and display a very regular pattern. Freezing and drying produce an upward trend in the trace while with thawing and wetting there is a downward movement. Furthermore these results were monitored by the type of instruments used in the main study at Rookhope.

A further important point is that daily movement, frequently as high as 0.5mm is large compared with the rate of mean annual creep. For the Juncus block over a six month period, movement measured was approximately 6.5mm.

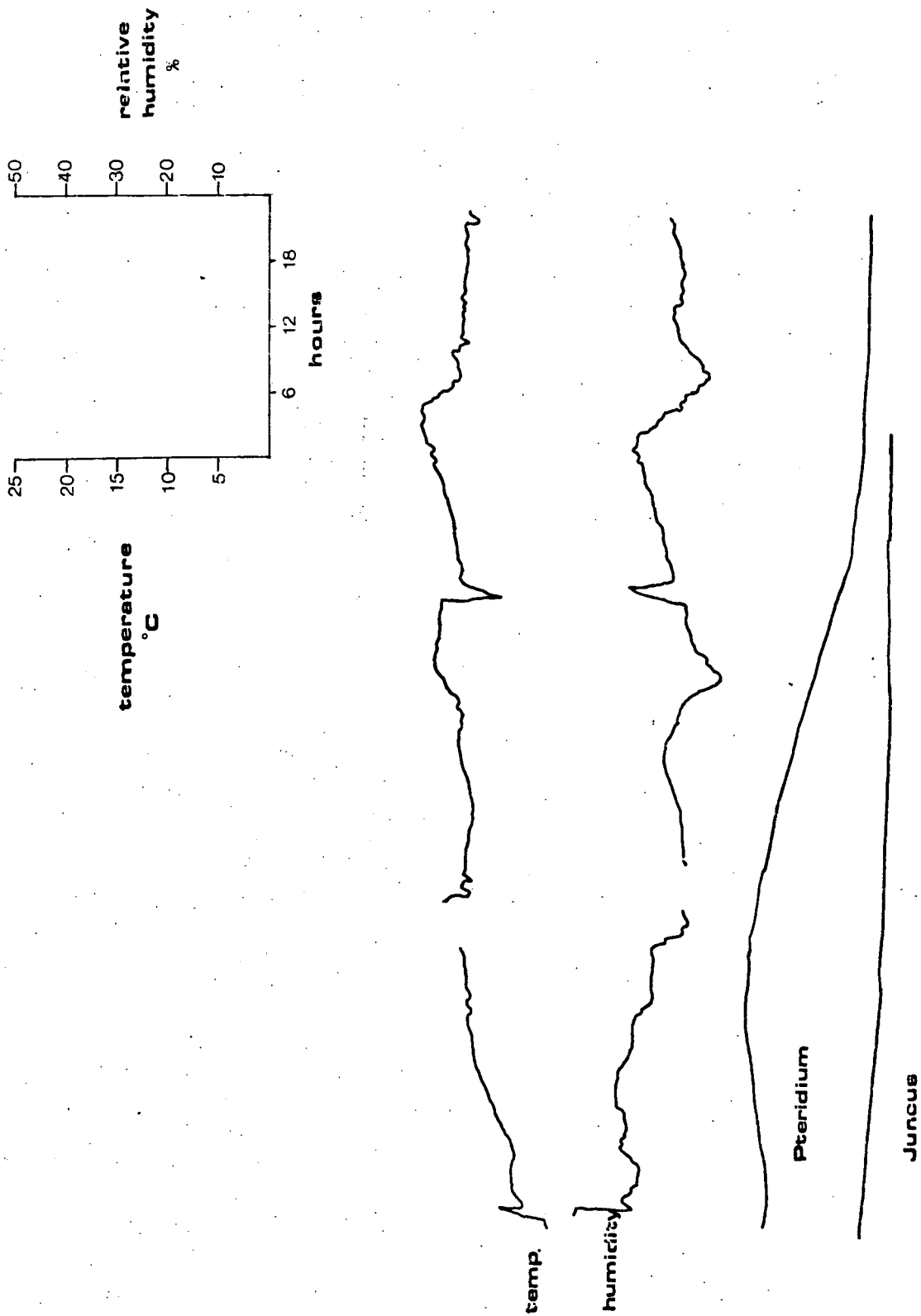
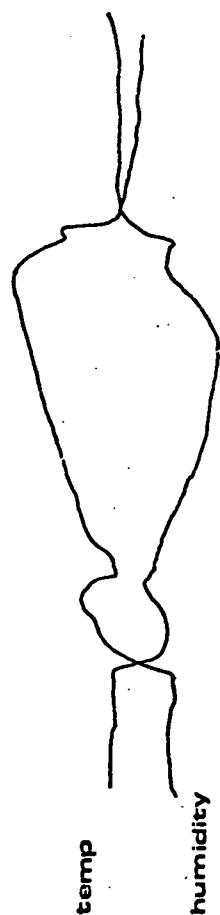
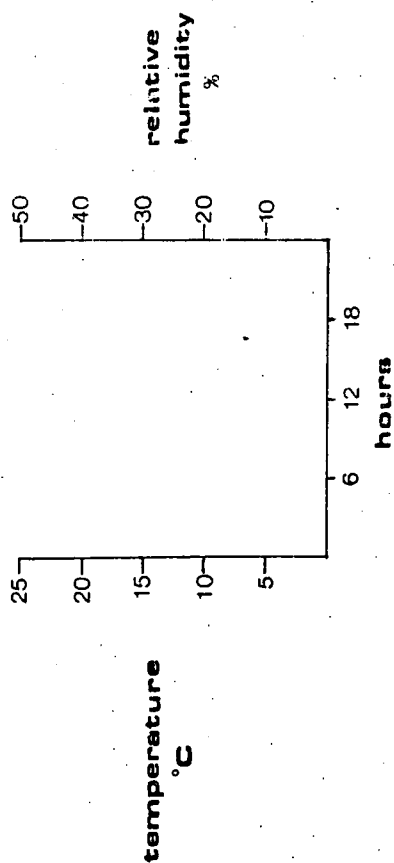


Fig. 5.10 Thawing and Drying Cycle (Experiment 5)



Juncus

Fig. 5.11A Wetting and Drying Cycles
(Experiment 5)

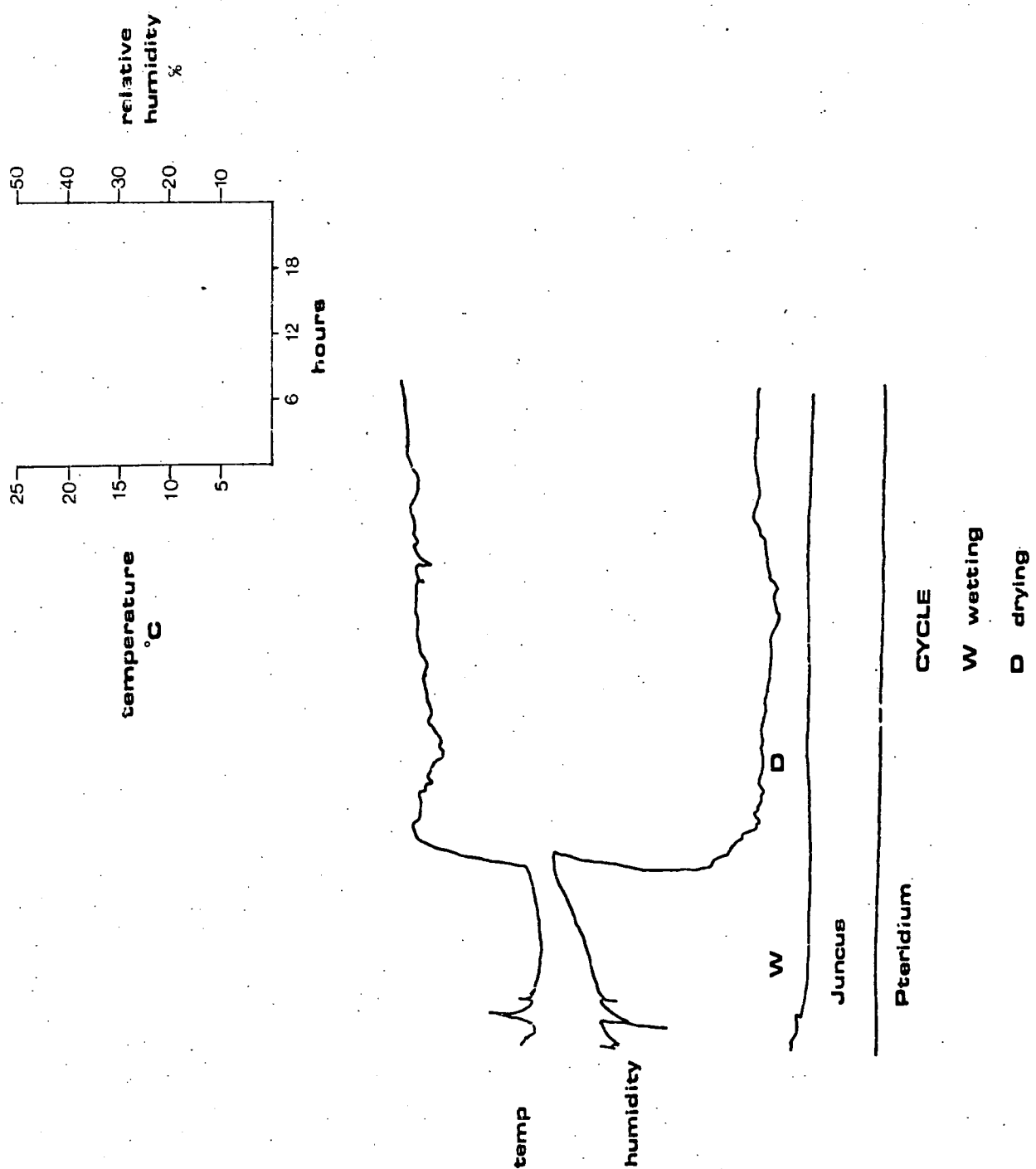


Fig. 5.11B

Wetting and Drying Cycles (Experiment 5)

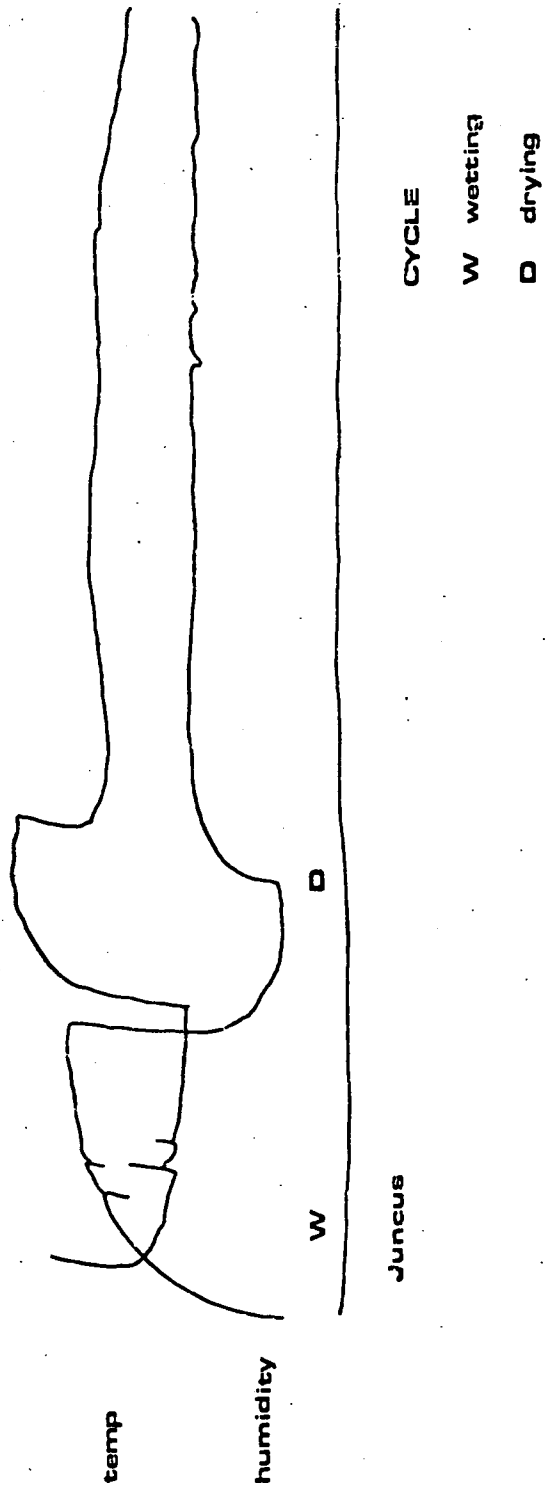
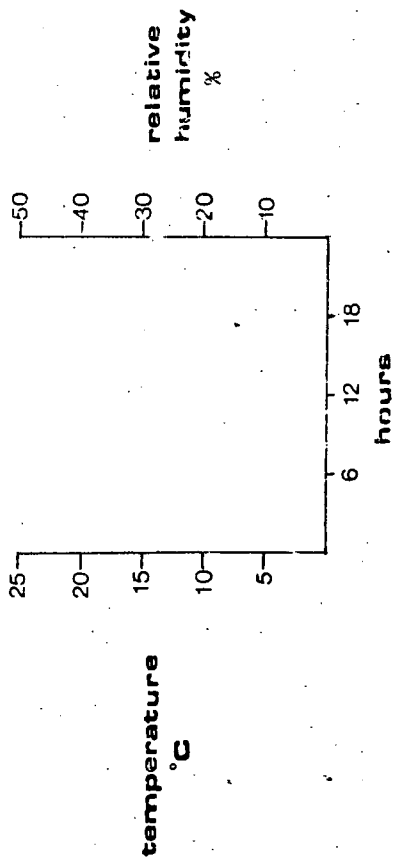


Fig. 5.11C Wetting and Drying Cycle (Experiment 5)

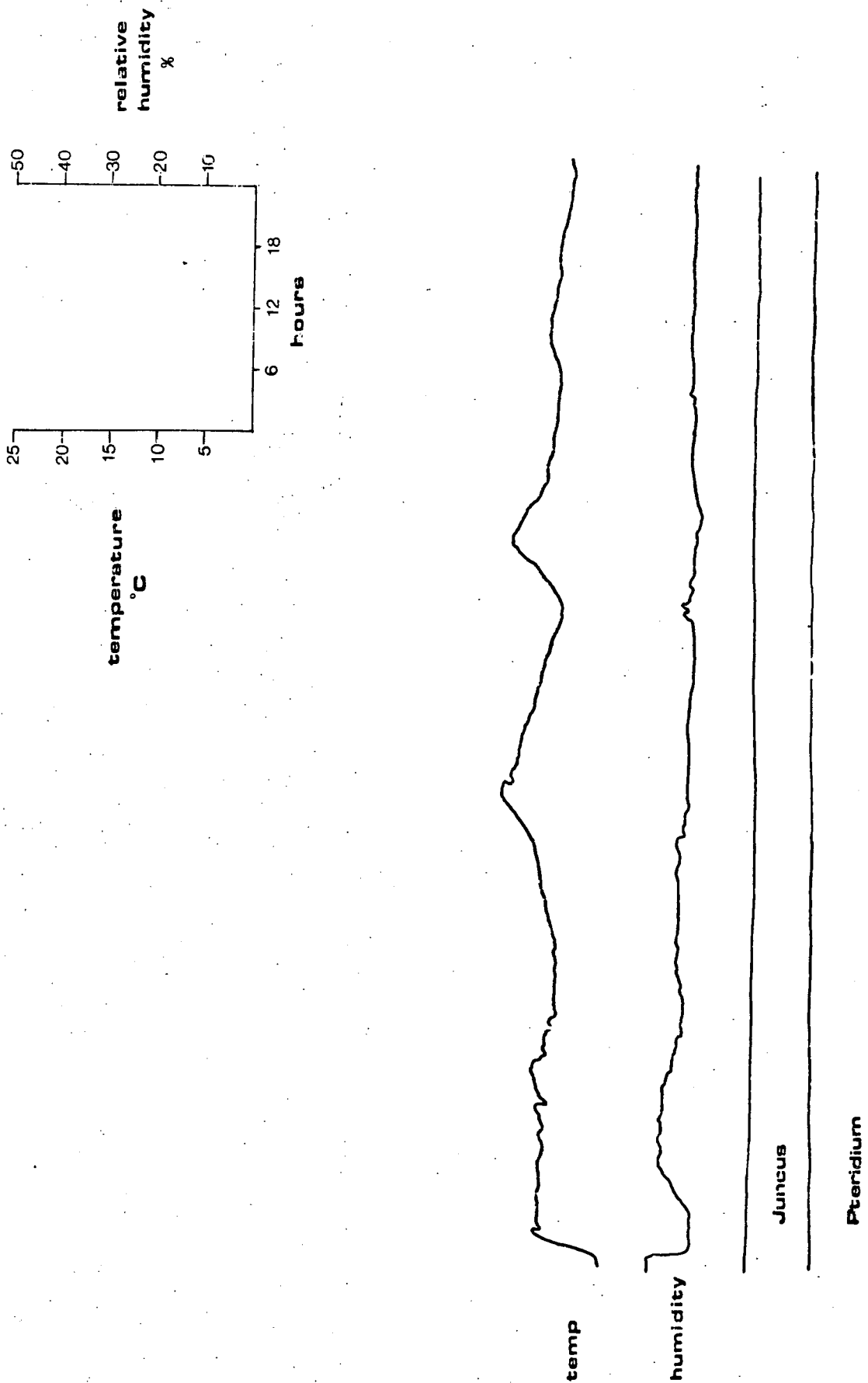


Fig. 5.11D Wetting and Drying Cycle (Experiment 5)

Daily movement is also somewhat irregular, indicating the possibility of a process of micro-shearing (Kojan, 1967).

The rate of movement is greater in organic soils than in mineral soils. Throughout the experiments the movement recorded over the particular time period, was at least twice as much in the organic soils. The effect of not packing troughs to the lower ends is more difficult to assess, but rates are again approximately twice those in fully loaded troughs. The relationship between movement and slope angle is not clear and needs further investigation.

Finally, links have been established between laboratory, plot and basin, so that results produced in one location can be considered at least analogous to those produced in another.

CHAPTER SIX

SUPPORTING RESEARCH SITES

- 6.1. Introductory
- 6.2. Etherow Valley
 - 6.2.1. Background
 - 6.2.2. Programme
 - 6.2.3. Results
- 6.3. Bidston Hill
 - 6.3.1. Background
 - 6.3.2. Programme
 - 6.3.3. Results
- 6.4. M53 Motorway
 - 6.4.1. Background
 - 6.4.2. Programme
 - 6.4.3. Results
- 6.5. North Wales
 - 6.5.1. Background
 - 6.5.2. Programme
 - 6.5.3. Results
- 6.6. Discussion
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6. SUPPORTING RESEARCH SITES

6.1. Introductory

While the major part of the research for this study has been undertaken at Rookhope, a number of other areas were also used at various stages. In each of these areas, plots or transects were established in the manner similar to that described in detail for Rookhope (Chapter 10). The advantages of plot work are discussed later, but they were seen in the present context as a vital link between the laboratory and the main fieldwork programme. Plots act in a measure as an analogue of the watershed since they exist in the natural environment, but it is such factors as accessibility and perhaps an element of control which make them valuable as a guide to expected or possible research results. The obvious limitations are that they cannot reproduce the actual conditions of the Rookhope basin since they are likely to vary to a greater or lesser degree in, for example, climate, geology, soil and vegetation. Also the particular aspects being studied tend to appear isolated from the actual system in which they occur. However, plots possess an inherent importance in that they allow the study in detail of particular selected systems. They are specially suitable when the system is comparatively simple with a small number of variables.

In the present study, plots were established initially to examine such facets of the problem as instrumentation and experimental design. Subsequently they have been used to monitor results in more detail and to overcome deficiencies in the Rookhope basin. The aims of the plotwork programme can therefore be summarized:

- (a) To validate certain of the measuring devices.
- (b) To provide background data for the design of the main programme.
- (c) To obtain more frequent and regular readings than is possible at Rookhope owing to the distance involved.

(d) To examine certain special situations which do not occur at Rookhope.

(e) To measure individual variables in isolation.

Before the pilot and main programmes could be designed, plots were established to investigate a number of basic factors related to creep and particularly its measurement. As the research was originally based at Manchester University and it was essential to have reasonable access to the facilities there, sites within a moderate distance offering a suitable range of slopes were examined. The areas considered were in the Central Pennines and North Wales, while a convenient local site was also found near Birkenhead (Fig. 6.1).

Plots had already been established for previous work (Anderson, 1971) in the Etherow valley (G.R. SK 115997) the nearest suitable area to Manchester itself. Since it was necessary to make comparisons with the results of this work, new experimental areas were located adjacent to these to validate the measurement techniques and give a general guide to the annual rate of soil creep.

Bidston Hill on the Wirral Peninsula (G.R. SJ 285896) offered a number of facilities and also a range of slopes varying in angle, vegetation and soil depth. Also it was possible to obtain daily readings, at least for limited periods, and thus there was the great advantage of detailed monitoring. This allowed the two main instruments to be checked, modifications to be tested, and the relationship between creep and moisture to be initially examined.

To obtain an impression of changing creep rates through time, two assemblages of slopes with immature soils were selected. Since the M53 (Mid-Wirral) motorway was in the process of construction and the slopes in the cuttings had only just been covered with fill, this provided an ideal situation for measuring creep at a very early stage of soil settlement. The results could be contrasted with those from more mature slopes in a quarry near Mold, Clwyd (G.R. SJ 276 664). The quarry had been abandoned twenty years previously (1952) but several of the steeper slopes remained unvegetated with a regolith of weathered marl. Therefore while the slopes

themselves were rather more mature than those on the motorway, the soils were skeletal.

After the initial basis for the work had been established using readings from these plots, the major part of the programme was designed. The research for this was supervised from Durham University with a drainage basin at Rookhope in Upper Weardale (G.R. NY 945437) as the main experimental area. To allow monitoring in great detail and to examine creep rates at lower altitudes, plots were selected near and within Durham City. The most accessible piece of open land is at Brandon (G.R. NZ 238402) and a plot for taking daily readings was sited there. To investigate rates of creep in lowlands, two plots were set up near Sherburn Hill (G.R. NZ 334418) and one at Leaze's House (G.R. NZ 276426) in Durham City itself (Fig. 6.2). Readings from all these plots were obtained during the measurement period of the main programme at Rookhope.

Each area will be briefly described and then the programme and results will be discussed.

6.2. Etherow Valley

6.2.1. Background

This small, incised valley on the western slopes of the Central Pennines was the research area for a previous study (Anderson, 1971). It was selected because the slopes appeared active with a river at their base. There was a range of vegetation associations and it offered easy access within a reasonable distance of the laboratory facilities at Manchester University (Plate 6.1 A,B).

The length of the valley used measured approximately 400m and was based on interbedded gritstones and shales of the Kinderscout Grit. The lower vegetated slopes on which the plots were established were comparatively steep, averaging 40° and carried a soil cover 25cm deep. The soils were classified as basically Brown Ranker and on them was established distinctive and separate associations each dominated by Nardus stricta, Vaccinium myrtillus, Pteridium aquilinum, Molinia caerulea or Calluna vulgaris.

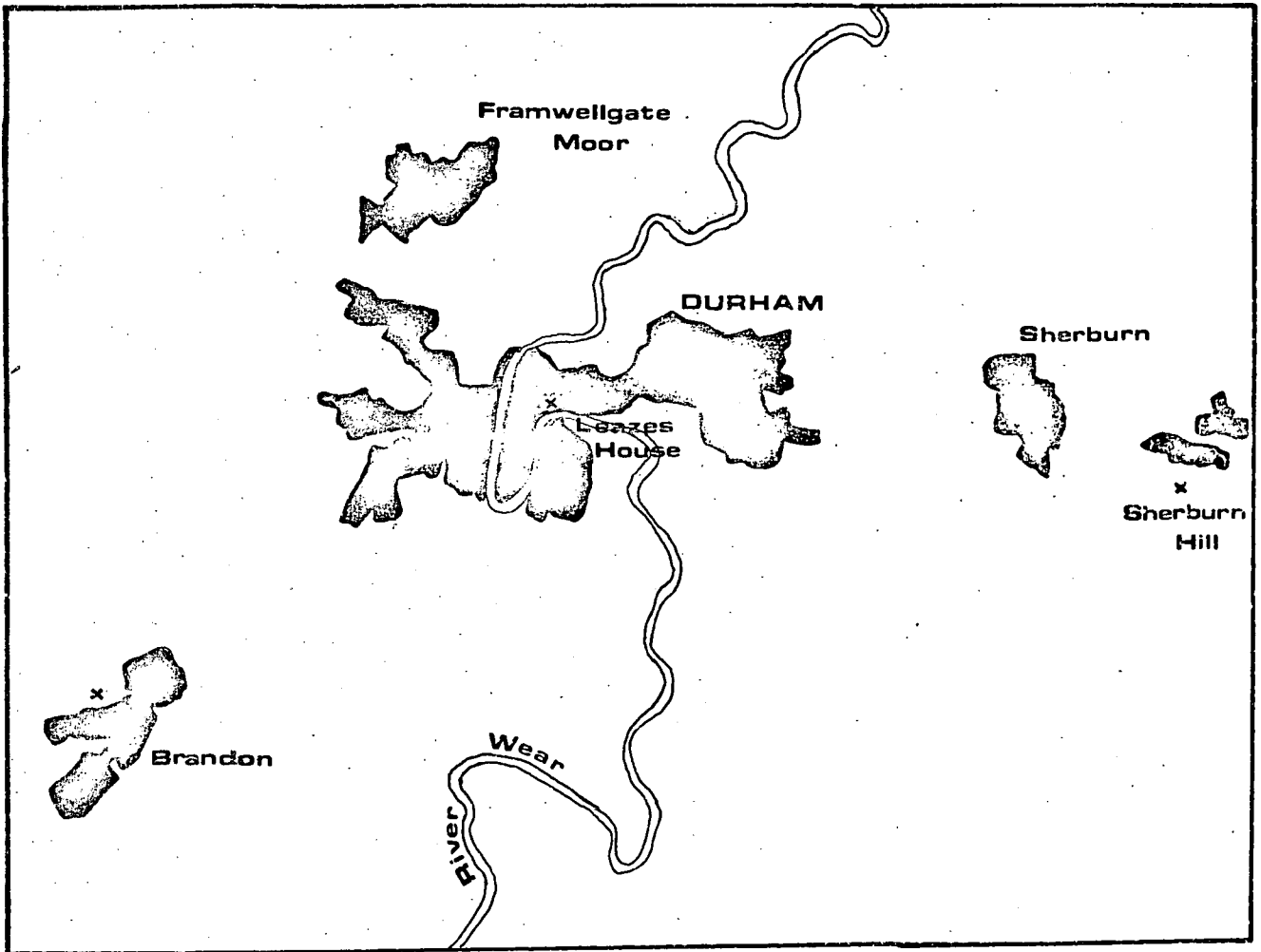


Fig. 6.2

Durham Area Sites

0 ————— 5
km

A



B



Plate 6.1

Etherow Valley

A north-east facing slopes

B south-west facing slopes

6.2.2. Programme

As the main study of terracette morphology and occurrence developed and deficiencies in techniques emerged, a series of parallel experiments was completed with a view to their use in the present programme. It was also realised that certain of the basic results, particularly those concerning the effects of vegetation type and slope angle, would form a useful starting point for later work.

The original Anderson Inclinator, designed specifically for this previous work (Anderson, 1971), proved to have two field deficiencies; it was rather heavy and it was time consuming in its use. The weight problem only affected the potential employment of pegs in loose skeletal soils such as those on fine shale, and it was shown from the readings to have no influence on pegs sited in mature soils. The time taken to obtain the eleven measurements required to plot the circular graph for each peg averaged twenty-five minutes, thereby greatly restricting the degree of replication possible. Furthermore, from the final graphs, it emerged that, as might be expected, the major component of movement was directly downslope; other components were of little significance. It was felt therefore that the instrument could be simplified and lightened by removing the direction card and its brass mounting. The modified version was tested alongside the original and found to give exactly the same readings. If other components of movement were required, the lighter Inclinator could be fitted to a peg in a cross slope direction.

However, it was considered that another instrument should be developed which would provide a check on the peg readings and would also overcome the major disadvantages of any angular measuring device, locating the pivot point and recording bodily movement. As a result, the Anderson Tube described earlier was designed and tested in the Etherow valley for a period of one year. Five Tubes were installed to a depth of 15cm as near as possible to peg plots so that measurements could be compared without disturbing the study then in operation.

Apart from this, the other constraints on Tube siting

were access from the main footpath with the attendant potential for vandalism, and locally, depth. Bearing these in mind, the Tubes were located under conditions such as slope and vegetation cover, which approximated as closely as possible to those of the relevant plot (Fig. 6.3).

Tube A was placed higher up the slope which in its lower section formed plots 1, 2 and 3. It was hoped that with its inconspicuous position, this Tube would not be disturbed, but for purposes of validation it was considered necessary to have other Tubes nearer these plots and risk damage to them. Tube C was installed centrally above plot 1, a horizontal transect of four pegs, Tube B was inserted immediately above plot 2 and Tube D beside peg 3 of plot 3. Tube E was set in an exposed position by peg 2 in plot 7.

6.2.3. Results

After one year only Tube B had been disturbed but six months later Tube E alone survived. Therefore the annual rates of surface creep from April 1970 until April 1971 are tabulated and compared with the results obtained from neighbouring pegs over the same period. Tube A, of course, was too far from the pegs to be realistically compared.

Table 6.1. Annual Creep Rates: Anderson's Tubes and Neighbouring Pegs

	Tube	A	B	C	D	E
<u>Movement (mm)</u>						
Tube		0.70	-	1.70	4.30	2.10
Peg		-	-	1.80	4.00	2.00

It can be seen that each Tube records a similar annual rate of creep to its neighbouring peg. This would certainly seem reasonable since both techniques are based on the same principle and differ primarily only in scale.

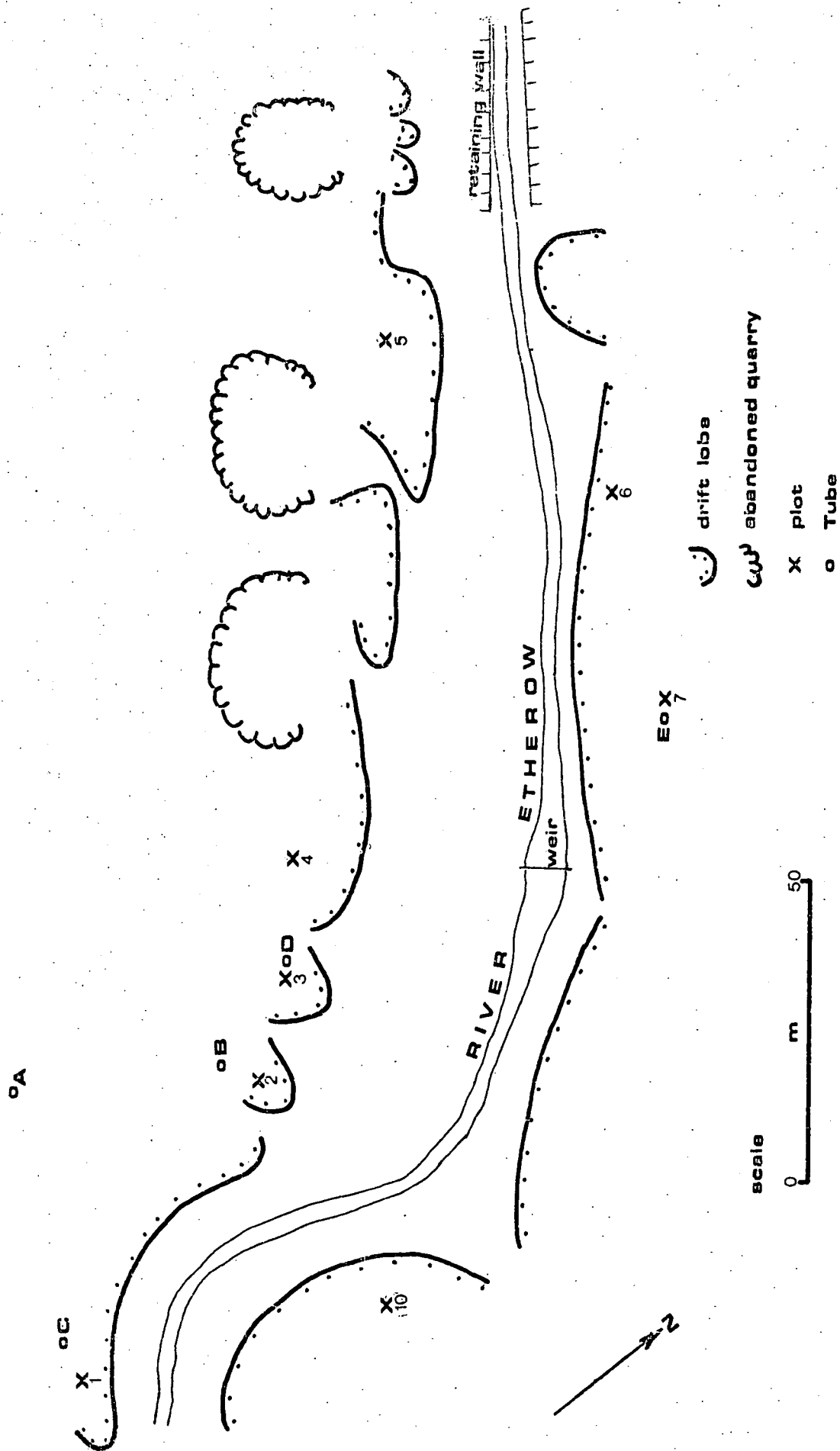


Fig. 6.3 Plan of Etherow Valley Instrumentation

Of more general importance at this stage of development was the fact that the Tubes were obviously responsive to soil movement and monitored rates of an order which accorded with those reported by other workers (Chapter 11). However, short term measurements are more easily made using pegs and therefore Tubes are seen as longer term instruments. As they allow an assessment to be made of bodily movement and also the position of the pivot point, they overcome the major limitations of pegs. The two devices are therefore envisaged as complementary for studies of soil creep.

6.3. Bidston Hill

6.3.1. Background

Bidston Hill is an outcrop of Triassic sandstone measuring some 5km by 1.5km on the Wirral Peninsula. It was selected because of its proximity to the Meteorological Station situated at Bidston Observatory and to the laboratory facilities available at Birkenhead School. There is also a variation of slope angle and vegetation cover which allows comparisons to be made.

The lower slopes of the hill are largely occupied by part of the town of Birkenhead on the north and its suburb, Upton, on the south. However most of the summit remains as mixed woodland and waste ground suitable for experimental purposes. Slopes average approximately 10° but facets at up to 40° occur, while soil depth varies from 0cm to 30cm.

6.3.2. Programme

The major advantage of this area was that measurements could be made at frequent intervals, daily if required. Two plots were selected to test instruments and to monitor certain individual variables.

Plot 1, measuring 5.4m by 1.8m, was laid out on waste land sloping at 20° with a sparse vegetation cover of grass. (Festuca spp, Poa spp), groundsel (Senecio vulgaris), dandelions (Taraxacum officinale) and Hieracium spp, and a soil depth of 30cm. The main aim was to investigate over a six month period, the effect of Tube length on recording rates of creep.

Three Tubes were installed, one to depth 22.5cm, one to 15cm and one to 7.5cm. Three pegs were inserted at the same time to act as a type of control. This plot was also used to examine the possibility of using plastic tubes, and two were installed, one with a central rod and one with the steel rod bolted to its downslope side (Plate 6.2).

Plot 2, measuring 1.8m by 1.8m was established on a grass covered slope (Agropyron repens, Festuca spp and Poa spp) of 24° with a soil depth of 25cm (Plate 6.3). The programme, which lasted twenty nine days (24th January to 21st February 1972) was to record and compare daily changes in rainfall, soil moisture at a depth of 2.5cm and soil creep rates as measured by pegs. A Meteorological Office stamped rain gauge was installed alongside the plot to measure rainfall. Soil samples were extracted by sampler, and approximately 5g removed for the moisture content to be determined by the Infra-tester. It was felt that the removal of so small a sample from the plot edge would cause little disturbance to the instruments or the soil drainage conditions. Although as a result of experimental evidence and a study of the relevant literature, the appropriate peg length had already been tentatively decided, this particular study offered an opportunity to confirm the decision. Accordingly three pegs were inserted, peg 1 to a depth of 7.5cm, peg 2 to 15cm and peg 3 to 22.5cm. To provide a comparison with plot 1 a Tube was also installed to a depth of 15cm.

6.3.3. Results

Readings were taken from plot 1 over a period of three months, from 30th January to 30th April 1972. Apart from the accuracy of the different Tubes, it was also considered important that they should provide a complement to peg measurements by giving an indication of the pivot point together with any bodily movement. Changes recorded at the 1.3cm and 6.3cm measuring levels within the Tubes are listed in mm with, conventionally, downslope being shown as positive.



Plate 6.2

Bidston Hill: plot 1

Plate 6.3

Bidston Hill: plot 2

Table 6.2. Soil Movement for Different Depths of Tube Installation

<u>Tube depth (cm)</u>	<u>Movement (mm)</u>	
	<u>1.3cm level in Tube</u>	<u>6.3cm level in Tube</u>
22.5	+0.1	0.0
15.0	+0.3	+0.2
7.5	-0.2	+0.3

In interpreting these results it must be remembered that each Tube is installed leaving 7.5cm protruding, and therefore it is the reading at the 6.3cm level which approximates to the surface creep rate. Results obtained from the three pegs, each inserted to a depth of 15cm, were averaged for the same period and gave a mean rate of 0.35mm with a standard deviation of 0.06.

While it is realised that only tentative conclusions can be drawn from so small a sample, certain clear indications can be discerned from the table. The 30cm Tube records little movement and it is reasonable to assume that the lower static soil layers have inhibited it. For the conditions of this particular plot, it would seem therefore to have been installed to too great a depth, at least for measuring shorter term movement.

The 22.5cm Tube slightly underestimates the creep rate if the peg readings are to be taken as accurate. However, if movement at the two levels is plotted on a movement diagram it can be seen that the device pivots near its base point. This is important for interpreting peg results and also seems realistic since bodily movement would hardly be expected under these conditions over such a short period.

The 15cm Tube gives a more accurate reading of creep rates but has pivoted at a point near its centre. This can be judged from the fact that readings at the two levels are in opposing directions. Initially downslope bodily movement could have occurred, accounting for the +0.3mm at

the 6.3cm level. Later pivoting about a point near the soil surface resulted in the -0.2mm reading at the 1.3cm level. With such a shallow depth of installation, approximately half the depth at which creep can occur, it would be expected that the Tube would show bodily movement. It appears more sensitive than the other Tubes but also unstable and more complementary to instruments like dowelling pillars rather than pegs. Therefore, despite the limited scale of the experiment, it can be seen that the 22.5cm Tube is satisfactory in helping to counteract the limitations of peg measurements by indicating such factors as the bodily movement and the position of the pivot point. It behaves in a similar fashion to pegs but allows the pivot point to be located while also recording the longer term creep rates.

The plastic tube results for the same three months are more difficult to interpret. As it was hoped that these tubes might provide a velocity profile, they were inserted level with the soil surface.

Table 6.3. Soil Movement: Experimental Plastic Tubes

<u>Plastic Tube (downslope rod)</u>		<u>Plastic Tube (central rod)</u>	
<u>Level in Tube</u> (cm)	<u>Movement</u> (mm)	<u>Level in Tube</u> (cm)	<u>Movement</u> (mm)
1.3	0.5	1.3	0.5
5.0	0.1	6.3	0.7
7.5	0.3		

Both tubes record similar rates at the 1.3cm level although these are well in excess of those measured by the other devices. However, the thinness of the plastic renders them liable to easy deformation and therefore these instruments are not unlike Open Tubes which also recorded enhanced rates.

With regard to velocity profiles, the tube with a rod on its downslope side indicates an erratic decline with depth, while the tube with a central rod shows an increase.

From other evidence, including that confirmed later at Rookhope, it is known that the creep rate decreases with depth below approximately 2.5cm. Therefore although theoretically they should combine the advantages of the Anderson Tubes with a facility for indicating the actual velocity profile, the plastic tubes are clearly unsatisfactory. They produce results inconsistent with known facts and there may be various explanations for this. For example, if the plastic is compressed in one area of the tube, it tends to expand in another. While in the present case it is most likely that a downslope constriction caused by creep will result in cross-slope expansion, changes will also be transmitted down the tube. This may account at least in part, for the reading at the 5cm level in the tube with a downslope rod. This limitation also precluded the use of these devices for long term measurement, as once they have contracted a certain amount, further creep will be increasingly inhibited by the limited possibilities for expansion elsewhere. Therefore it can be said that while plastic tubes offer possibilities, they need further development and cannot be used in the main part of the present programme. However a similar idea is being developed with Finlayson's Helix Tube described earlier.

For comparative purposes, the readings for the three pegs in plot 2 are best plotted so that changes can be seen in the context of rainfall and soil moisture variations (Fig. 6.4). When the plots for the pegs and the soil moisture are examined in detail, it can be seen that there is a marked similarity with a general coincidence of peaks and troughs. This could be reasonably expected as no time lag would appear to be involved. If this coincidence is analysed for each peg, it also gives an indication of the accuracy of that peg, always bearing in mind the micro-scale variations in local conditions. The peaks and troughs as the most obvious and accessible indicators of the peg plots are therefore compared with those for the soil moisture plot.

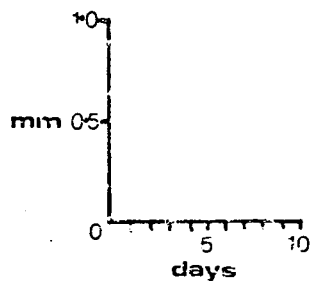
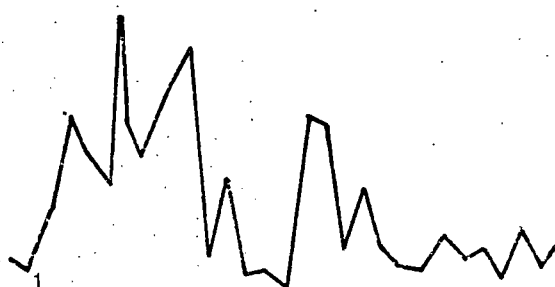
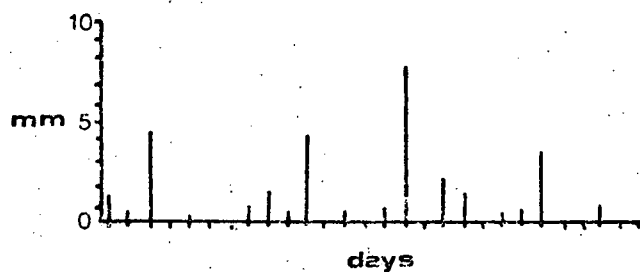
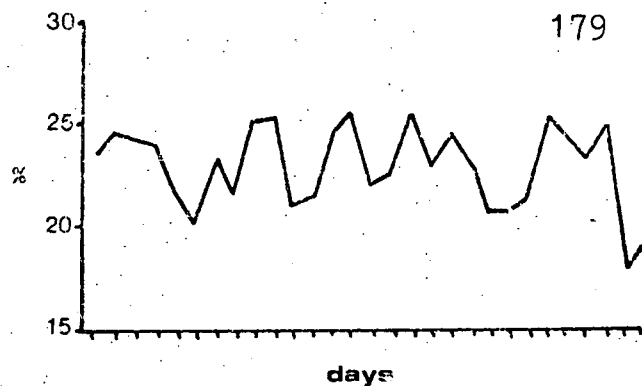


Fig. 6.4 Bidston Hill: Peg Movement, Soil Moisture and Rainfall

Table 6.4. Comparison: Peg Plots and Soil Moisture Plot

		<u>Accord</u>	<u>Non-accord</u>
Peg 1	Peaks	4	5
	Troughs	7	3
Peg 2	Peaks	6	2
	Troughs	7	2
Peg 3	Peaks	4	3
	Troughs	6	1

It should be noted that these counts did not include peaks and troughs during the two days when freeze-thaw occurred. Thus if it is assumed that soil moisture changes and creep rates are related, peg 2 clearly produces the most accurate record with fewer points not in accord. Peg 3 exhibits similar non-accord but also only ten points which do accord. Peg 1 shows a more equal balance between the two categories.

Rainfall is a more difficult factor to compare since during dry periods soil moisture may be depleted, affecting creep readings, but the rainfall totals remain constant at zero. Furthermore, infiltration is a factor, and a time lag between the rainfall and any resulting movement must be expected. It appears from the plots that a lag of a day or rather more, in fact occurs. This is seen obviously when rainfall and soil moisture are compared, although it also emerges clearly from the peg plots.

The peg plots themselves also show variations with the amplitude of movement, the detail decreasing from peg 1 to peg 3. The change in detail can be illustrated by a count of peaks and troughs.

Table 6.5. Comparison of Peg Plots

	<u>Peaks</u>	<u>Troughs</u>
Peg 1	9	10
Peg 2	8	9
Peg 3	7	7

Again frost movements are neglected in this table, but it will be noted that they also decline in the same direction. However, only peg 2 records movement consistently for each part of the cycle; downslope with freezing and upslope with thawing. The actual creep rates recorded also varied, although over such a short term, with comparatively large daily variations, definitive results would not be expected.

Table 6.6. Soil Movement: Pegs

	<u>Peg 1</u>	<u>Peg 2</u>	<u>Peg 3</u>
Movement (mm)	+0.05	+0.30	0

While the period of measurement was short, it did include a number of freeze-thaw and wetting and drying cycles and therefore significant movement would be expected. The Tube recorded surface creep of 0.2mm, a result of the same order as that measured by peg 2. If the Tubes of similar lengths on plot 1 are used to interpret these peg readings it is likely that peg 1 may have pivoted about a central point thereby reducing the surface creep measured, while peg 3 may have been inhibited by the static lower soil layers.

In conclusion, it can be seen that the plot patterns for all the pegs are similar and accord well with those for soil moisture and rainfall. However, that for peg 2, inserted to 15cm, is clearly the most accurate and in general this seems a suitable length for installation. Furthermore, as discussed earlier, this is the length adopted by many

other workers.

6.4. M53 Motorway

6.4.1. Background

When examining the concept of time with regard to soil creep rates, the subject can be approached in many ways. The most obvious aspect occurs in the relationship between meteorological factors and creep, but laboratory simulations can also be significant. These are discussed in detail elsewhere (Chapter 5), but it was felt that a third idea, considering creep from time zero, might produce interesting results which could affect the later development of the work.

While it is possible to find a naturally occurring 'altered' slope where, for example, erosional processes are active, to find a 'new' slope is extremely difficult. It was therefore decided that this study should take place on a man-made slope, and a particularly suitable environment existed on the Wirral Peninsula. The civil engineering company, Sir Alfred McAlpine and Son Ltd., was interested in testing the stability of the fill used in various sections of the M53 Mid-Wirral Motorway, which was to be opened within six months. It was therefore possible to combine a survey for the company with preliminary work for the present study.

The motorway cuts through Triassic marls and sandstones in a north-westerly direction, producing north-east facing and south-west facing slopes. The fill employed to form the motorway side slopes can be divided into three categories according to the proportion of sand present. Dry sieving indicated some variation within each category but the sand percentages listed by the contractors proved basically accurate.

Table 6.7. Sand Percentages in Categories of Motorway 'Fill'

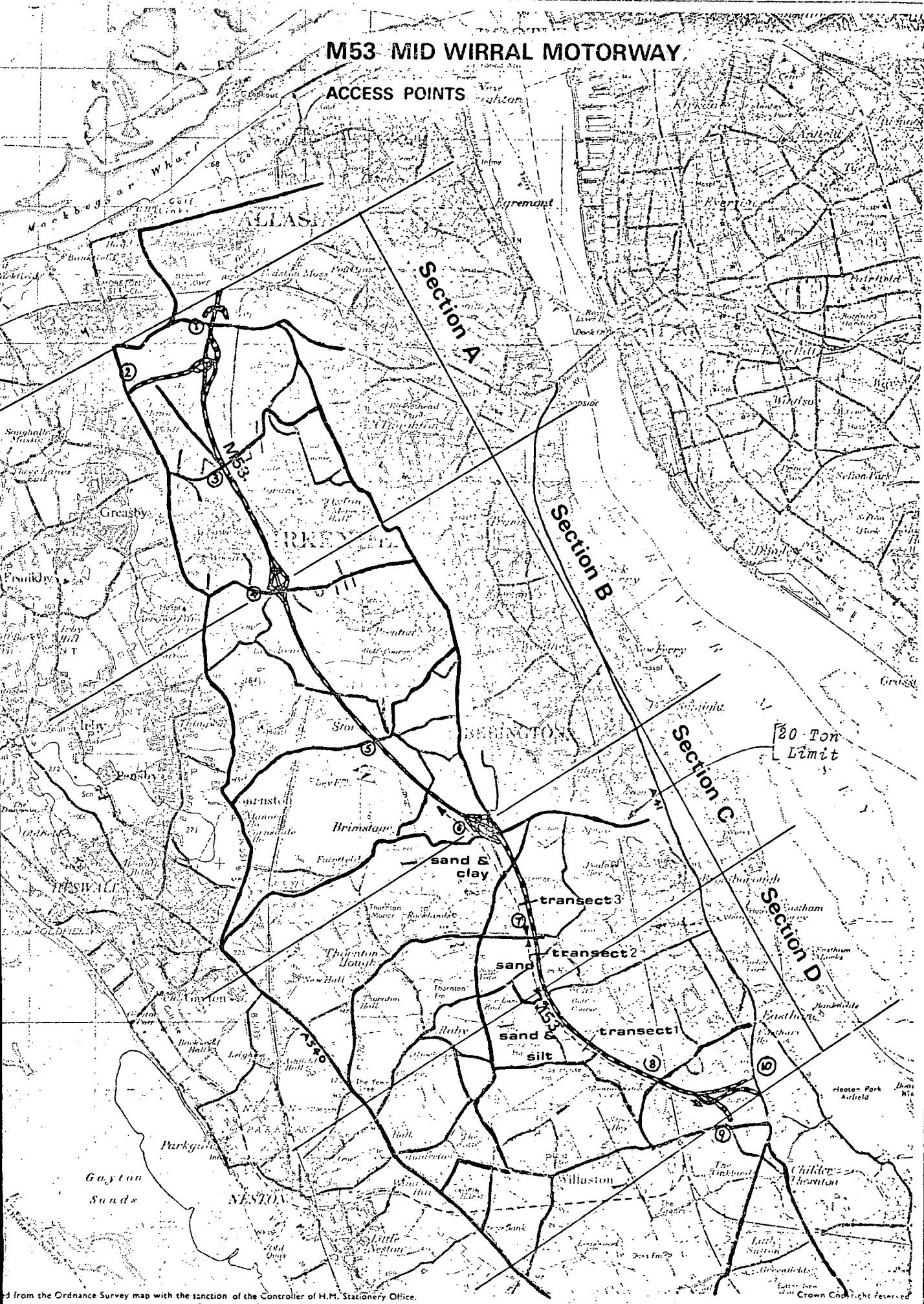
<u>texture category</u>	<u>sand %</u>
'sand'	45
'sand and silt'	30
'sand and clay'	20

This was the one percentage used for discriminating the fills and some variations in the other constituents was admitted. Since, for this preliminary stage of the study, only a general guide was required, no attempt was made at a detailed textural analysis. In preparation for opening, the banks had just been seeded with a mixture of grasses and clover. Therefore the factors of fill settlement and vegetation growth were operating together.

Thus a number of variables was present, certain of which were closely interrelated and could not be separated within the constraints imposed on the experimental design. As a result it was decided to concentrate on the measurement of two factors: variations in creep with aspect and creep rates on immature slopes. It was felt that an overall assessment of both these could be made despite the range of variables. In fact the motorway presented a rare opportunity of evaluating the effects of aspect on what were virtually matched slopes. As the fill was effectively a soil, placed to a depth of approximately 30cm on a prepared slope, it was considered that readings of creep would provide an interesting contrast with those obtained on mature slopes with settled soils and also those monitored on skeletal soils.

6.4.2. Programme

A length of motorway in which the three types of fill occurred closely together, was chosen and a transect line was sited on each type (Fig. 6.5). To locate a line exactly, measurements were made of slope length. The greatest length of motorway with a particular type of fill and the same length of slope on either side was then



M53 MID WIRRAL MOTORWAY

ACCESS POINTS

Section A

Section B

Section C

Section D

20 Ton Limit

transect 3

transect 2

transect 1

sand & clay

sand

sand & silt

Fig. 6.5

access point
M53 Motorway Transect

identified and the transect placed centrally on it. Each transect was continued across the motorway giving two sites, one north-east facing and the other south-west facing. At each site three pegs were inserted to a depth of 15cm, the first within 1m of the slope crest, the second in the middle of the facet and the third, to avoid any possible disturbance, 3m from the slope base. As a check, a Tube was also installed to the same depth, centrally in one site on each transect. The particular site was selected by die, and those chosen were 1SW, 2NE and 3NE. The site details can be summarized.

Table 6.8. Measurement Site Details

<u>Site</u>	<u>Texture</u>	<u>Facet angle</u> (°)
1NE	sand and silt	28
1SW	sand and silt	25
2NE	sand	30
2SW	sand	25
3NE	sand and clay	27
3SW	sand and clay	30
(NE - North-east facing; SW - South-west facing)		

6.4.3. Results

Six sets of readings were taken in the period between the end of March and the beginning of October 1971. From the pegs the following results were obtained.

Table 6.9. Estimated Annual Soil Movement: Inclinometer Pegs

<u>Site</u>	<u>Estimated mean annual surface movement (mm)</u>
1N	2.86
1S	1.46
2N	2.60
2S	2.46
3N	2.50
3S	0.62

The directions of movement of the pegs were aggregated to show the degree of variability.

Table 6.10. Directions of Peg Movement: Aggregates

<u>Direction</u>	<u>Upslope</u>	<u>Zero</u>	<u>Downslope</u>
number of pegs	4	2	12

With a study period necessarily limited to six months and those occurring in spring and summer, the calculation of annual rates must be somewhat conjectural. Therefore in the absence of other information, it was decided to double the results measured over six months, although it is realised that the estimate is likely to be conservative. Clearly this process does not allow a reasonable assessment of standard deviation to be made and variability is indicated by aggregates of the direction of movement.

Certain points can be made with regard to settlement. The rates of creep measured are at least twice those obtained from sites with similar moisture and vegetation conditions on Bidston Hill near by. Had measurements been possible during the winter with freeze-thaw cycles and more rainfall, the discrepancy might well have been larger. This would appear to indicate as expected, that the M53 slopes were

unstable and undergoing a period of settlement. The direction of peg movement helps confirm this since at Rookhope during the dry part of the year, it is likely that under normal conditions the proportion moving upslope would have been far higher. This is shown later when the Rookhope results are discussed in detail.

Perhaps the most striking result is the clear influence of aspect, which with winter freeze-thaw, might well be more obvious were a year's measurements available. On each transect, creep rates were greater on the more sheltered and moister north-east facing slopes.

With only three transects, it is not possible to make definitive statements about the relationship between creep rates and sand percentage. However the sandier soils seem to be the least stable.

Vegetation is also influenced by aspect, being more luxuriant on the moister north-east facing slopes. Therefore it is difficult to assess in isolation the effect of plant growth on creep rates. During the period of measurement, movement declined, but while this might be partly attributable to vegetation effects, it can also be related to the summer decrease in soil moisture.

Of the various indications which emerge from a study of the peg results, the most important concerns the significance of aspect. The measurement of creep rates from 'time zero' confirms initial ideas on the settlement of immature slopes. With regard to texture and vegetation, the evidence is less compelling, but it did show that a consideration of these factors could well be fundamental in producing experimental design for Rookhope.

The Tube results were also obtained.

Table 6.11. Estimated Annual Soil Movement: Anderson's Tubes

<u>Site</u>	<u>Estimated mean annual surface movement (mm)</u>
1S	1.8
2N	4.8
3N	3.5

Although they show the same trend, these rates are for each site larger than those measured by the pegs. This reflects the loose nature of the fill, which did not allow the tight installation of the Tubes which is possible in mature soils. Thus the Tubes themselves also settled during the measurement period.

6.5. North Wales

6.5.1. Background

Besides the work on Bidston Hill and the motorway, a more limited programme was completed over a period of three months on the series of quarry slopes near Mold. The geology was similar, being Triassic sandstones and marls, but there was a greater variation in possible sites and, as explained earlier, the soils were immature. The plot measurements in this area were made during a three month period from early May 1972. It was hoped that conditions would be generally dry so that soil contraction would lead to the recording of upslope movement, providing a basis against which the effects of extreme factors could be judged.

6.5.2. Programme

A control transect of six pegs was set up on an 8° grass covered (Festuca spp) slope with a soil depth of 16cm. Four pegs were installed on a slope base constantly wet through seepage, which was sparsely vegetated with Poa spp and sloped at 15°. The remaining pegs were placed in two transects on marl based slopes averaging 21°, in different states of plant colonisation. Two were installed in the bare marl and three on a partially grassed slope (Poa spp). All the pegs were inserted to a depth of 15cm. The pegs were sited to take account of local variations so that in considering the results, the rate recorded by each peg rather than a mean for the plot is given. Rates refer to a depth of 2.5cm.

6.5.3. Results

The control pegs, on a south facing dry slope, registered comparatively high rates of upslope (negative)

movement. This may have resulted from the fact that the soil had developed on quarry spoil and was particularly responsive.

Table 6.12. Soil Movement: Control Pegs

Peg	1	2	3	4	6
Movement (mm)	-0.81	-0.44	-0.69	-0.63	-0.37

Peg 5 was broken during the measurement period.

In marked contrast, the four pegs installed on the wet slope base all showed downslope movement, particularly excessive in the case of peg 1 which was sited in the middle of a seepage. In fact throughout the three months, some surface flow was always discernible across this slope element.

Table 6.13. Soil Movement: Slope Base

Peg	1	2	3	4
Movement (mm)	+2.62	+1.38	+1.06	+1.25

These results taken in conjunction with those for the control pegs, indicate strongly that drying is related to upslope movement while wet soil moves downslope. Conditions on the wet slope were extreme, particularly for peg 1 which was probably also affected by surface wash, but the difference in trend is very clear.

A similarly exaggerated situation occurred with the bare marl slope, which was subject to recurrent falls of debris. This was envisaged as an extreme case resulting from the effects of loose unvegetated surface material and the obvious influence of gravity.

Table 6.14.

Soil Movement : Marl Slope

Peg	1	2
Movement (mm)	+1.94	+8.30

In fact, there was a build-up of material behind peg 2 and this clearly subjected it to pressure. However, it does illustrate that under these conditions extremely high rates of movement may occur. Again, as with peg 1 in the wet slope base, there are probably processes other than creep affecting the rate.

The three pegs on the partially grassed slope were installed in a transect: peg 1 in a bare patch, peg 3 in the most densely grassed area and peg 2 between them.

Table 6.15.

Soil Movement: Partially Grassed Slope

Peg	1	2	3
Movement (mm)	-1.12	-0.69	-0.06

These rates illustrate the trend which would be predicted bearing in mind the previous results. A reduction in soil drying coincides with a decline in upslope movement.

As with the motorway transects, while no far-reaching conclusions should be drawn from these results, they do represent something of an experimental controlled situation and can therefore be taken as at least useful indicators. Certainly the effects of soil moisture and vegetation cover as illustrated, accord with those observed elsewhere.

6.6. Discussion

The results from these various plots, established to provide broad guidelines for the experimental design of the main study, allow a number of conclusions to be drawn. There is definite evidence that the Tube readings accord

with those obtained from the Inclinator pegs . Since results from both are very similar in order to those found in comparable environments by other workers, it can be reasonably assumed that the techniques are valid.

The depth of insertion has already been discussed and measurements made by pegs and Tubes indicate strongly that 15cm is appropriate. This allows the full velocity profile to be monitored without the impedance of static soil layers.

The relationship between soil moisture and creep rates has been examined and there is evidence that a link between them exists. They certainly appear to vary together but a more detailed investigation forms a major element of this study.

As might be expected, aspect seems to exercise a definite influence, with higher creep rates on north facing slopes. However, this may well be appreciated better when the effects of weather cycles are considered later.

Finally, the responsive nature and erratic movement of immature soils have been demonstrated. On a new surface there is accelerated creep downslope, while skeletal soils tend to show exaggerated movement upslope with drying and downslope with wetting.

The conclusions about the measuring instruments can be incorporated directly into the experimental design for Rookhope. The effects of aspect and immature soils are clear but need further confirmation during the main study. The relationship between creep rates and soil moisture is obviously crucial to the entire programme and requires detailed examination.

6.7. Durham City Area

6.7.1. Background

Since it was considered important to obtain daily readings over certain periods and this would only be possible using local experimental areas, plots were established in the Durham City area.

The plots were related in height and exposure to the Durham University Observatory (102m), since although

meteorological instruments were set up near the pegs in each case, there was an ever-present danger of vandalism and it was necessary to ensure the provision of continuous meteorological data.

6.7.2. Programme

Plot 1 was set up with easy access from Durham City, on the lower slopes of Brandon Hill. This hill, comprising Coal Measure shales and sandstones, is largely built over, but certain open spaces remain.

The actual plot, measuring 1.8m by 1.8m, was selected to coincide with a sharp vegetational boundary so that readings could be taken from pegs on both vegetated and bare areas. With an angle of 12° and a soil depth of 30cm, the plot provided a suitable comparison with several of those in the Rookhope basin, although the vegetation consisting predominantly of Lolium spp and Poa spp was different. As the slope base, just below the plot, was bounded by a retaining wall, there were also similarities with the laboratory programme, particularly the possible restriction of movement in the soil troughs.

Using a grid and random number tables, two pegs were installed on the upper grass covered half of the plot and two on the bare earth lower section (Plate 6.4). A fifth peg was placed nearly centrally in a flat facet to act as a control. All the pegs were inserted to a depth of 15cm. The programme was to take daily readings of peg movements for a lengthy period so that meteorological effects could be more accurately assessed. During the measuring period, the following were also set up: a thermograph, a Meteorological Office stamped rain gauge, soil thermometers at depths of 5cm, 10cm and 27.5cm, and a grass minimum thermometer.

Plot 2 was sited within the City itself in the grounds of Leaze's House, the Bede College School of Science. A small meteorological station was established using the same instruments as those at Brandon but with the addition of a soil thermometer at a depth of 1m and a Stevenson's Screen containing a maximum and a minimum thermometer together with



Plate 6.4

Brandon Plot

wet and dry bulb thermometers. The plot itself measured 1.8m by 3.6m and comprised an upper 2° grass covered slope (Poa spp) and a lower 20° slope with a sparse cover consisting predominantly of Poa spp and Hedera helix. The soil, based on Coal Measures sandstone, varied in depth from 20cm to 35cm. A transect consisting of four pegs was inserted down the slope and for a short period, one further peg, which was fitted with a stylus and a revolving drum so that a continuous reading could be obtained. The objectives for this plot were to obtain daily readings of creep together with a further range of meteorological data, but of necessity, for a more limited time period than was expected at Brandon.

As there are few estimates of soil creep published for lowland sites (Chandler and Pook, 1971), it was decided to supplement readings from these two plots by installing two further sets of pegs from which longer term results could be obtained. At Sherburn Hill, a Magnesian limestone promontory some three miles to the east of Durham City, two grids were laid out, one on an 8° slope and the other on a 25° slope. Using random number tables, four pegs were inserted to a depth of 15cm in each grid. The vegetation on both sides was similar, comprising a dense mat of coarse grass predominantly Agrostis spp, Bromus spp and Dactylis glomerata. The soil depth varied from 25cm on the gentler slope to 18cm on the steeper.

6.7.3. Results

Daily readings were taken on plot 1 from 20th January 1974 until 5th April 1975 with only two short breaks. Measurements could not be taken from 5th to 21st May 1974 or from 10th to 24th August 1974. However, apart from these periods and two further days, 10th and 17th March 1975, the series is complete. It is therefore possible to examine long sequences of results in detail. Before analysing these readings it should be noted that they refer to the linear movement of soil at a depth of 2.5cm.

The peg plots made from the readings taken on Brandon Hill illustrate a number of very important factors. For examples, five plots are included here (Fig. 6.6. A,B,C,D,E)

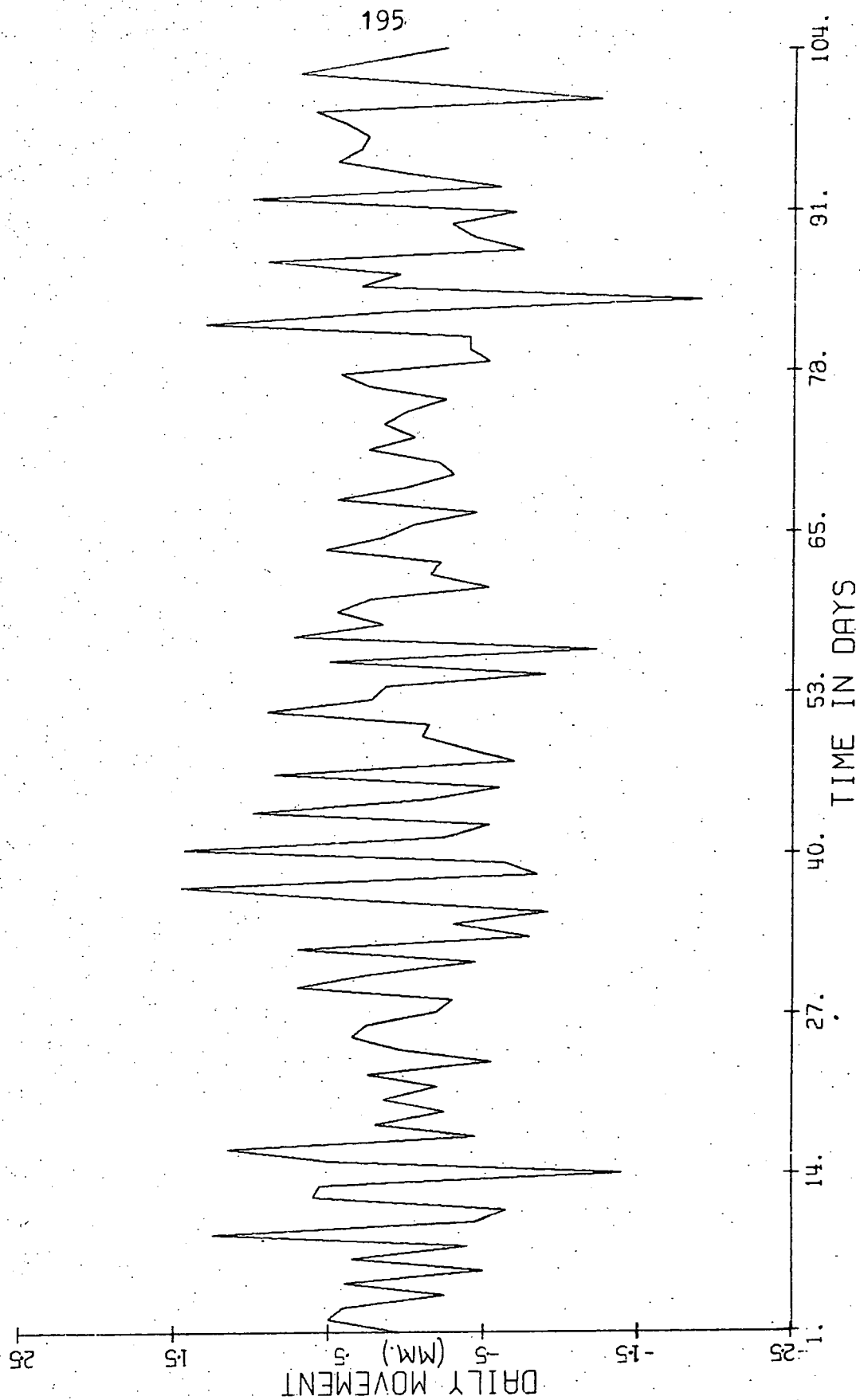


Fig. 6.6A

Brandon Plot: Earth Peg 1 Series 1

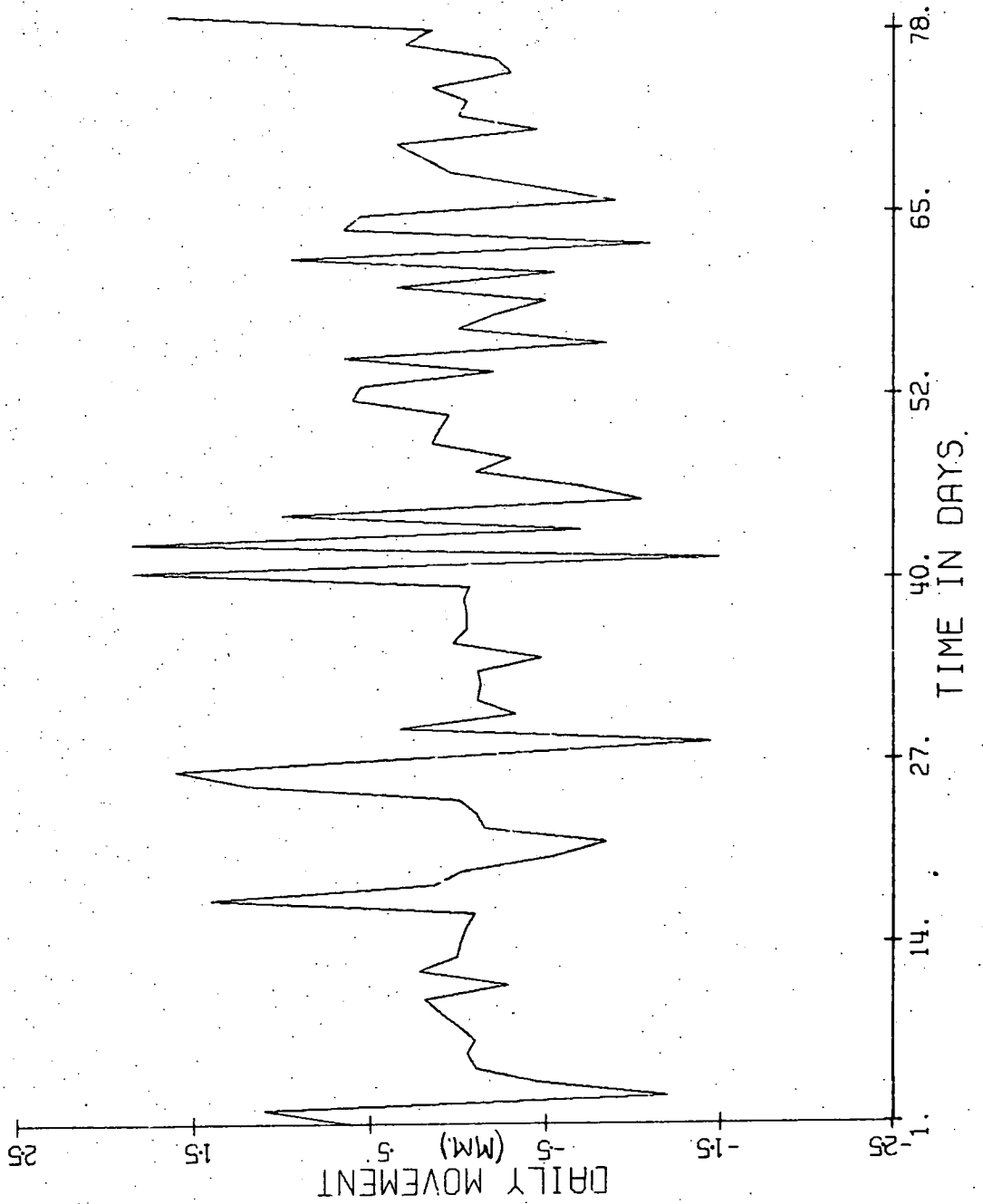


Fig. 6.6B

Brandon Plot: Earth Peg 2 Series 2

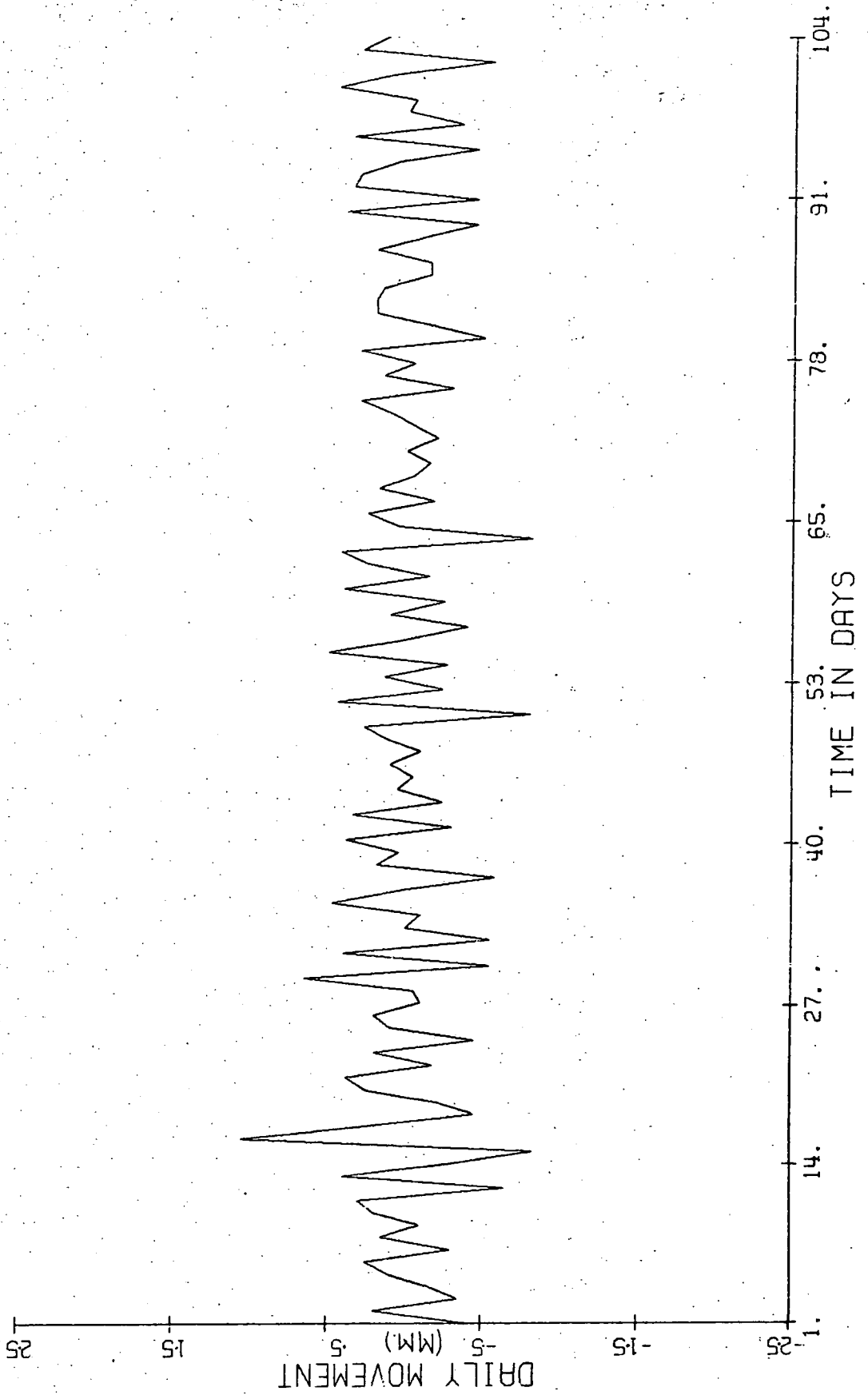


Fig. 6.6C Brandon Plot: Grass Peg 1 Series 1

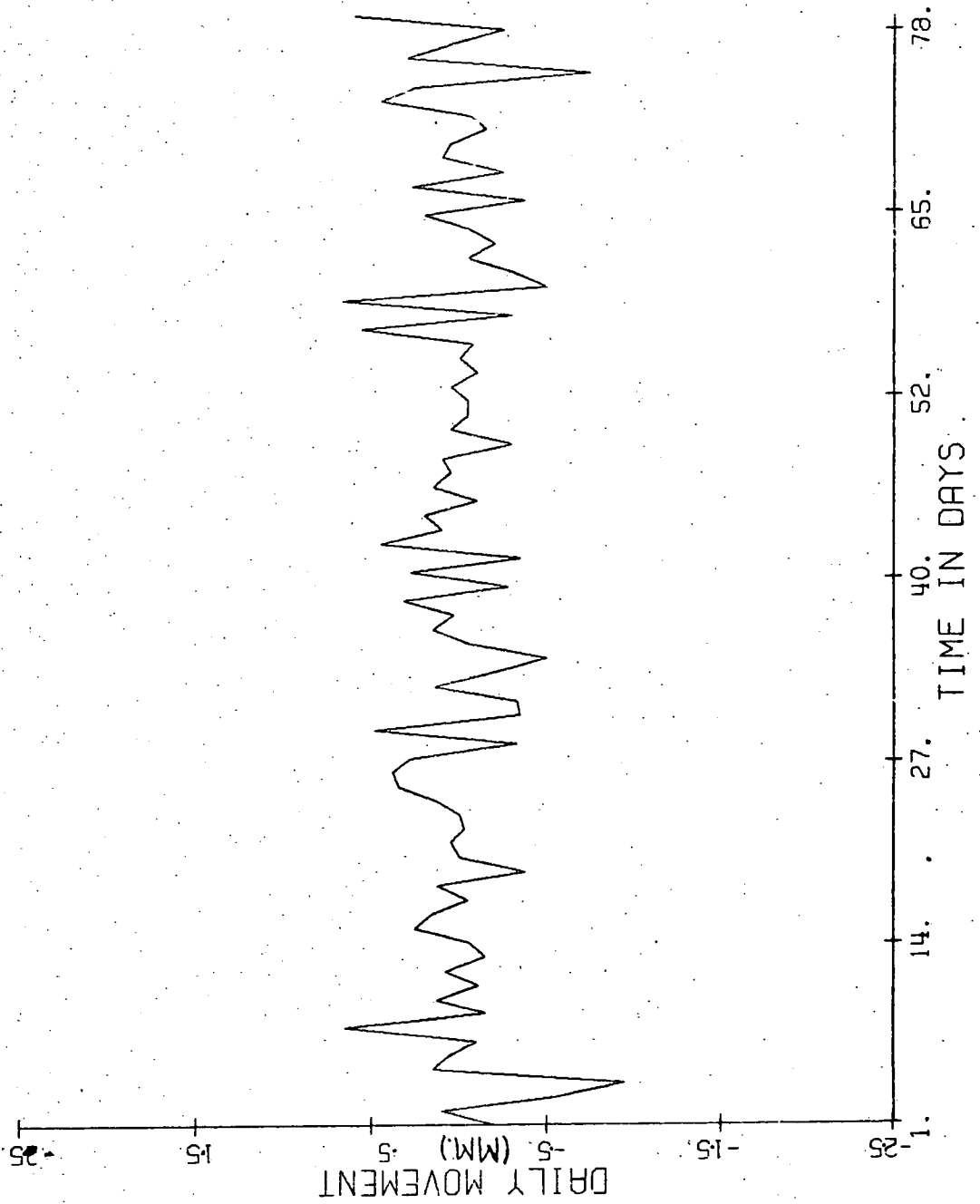


Fig. 6.6D Brandon Plot: Grass Peg 2 Series 2

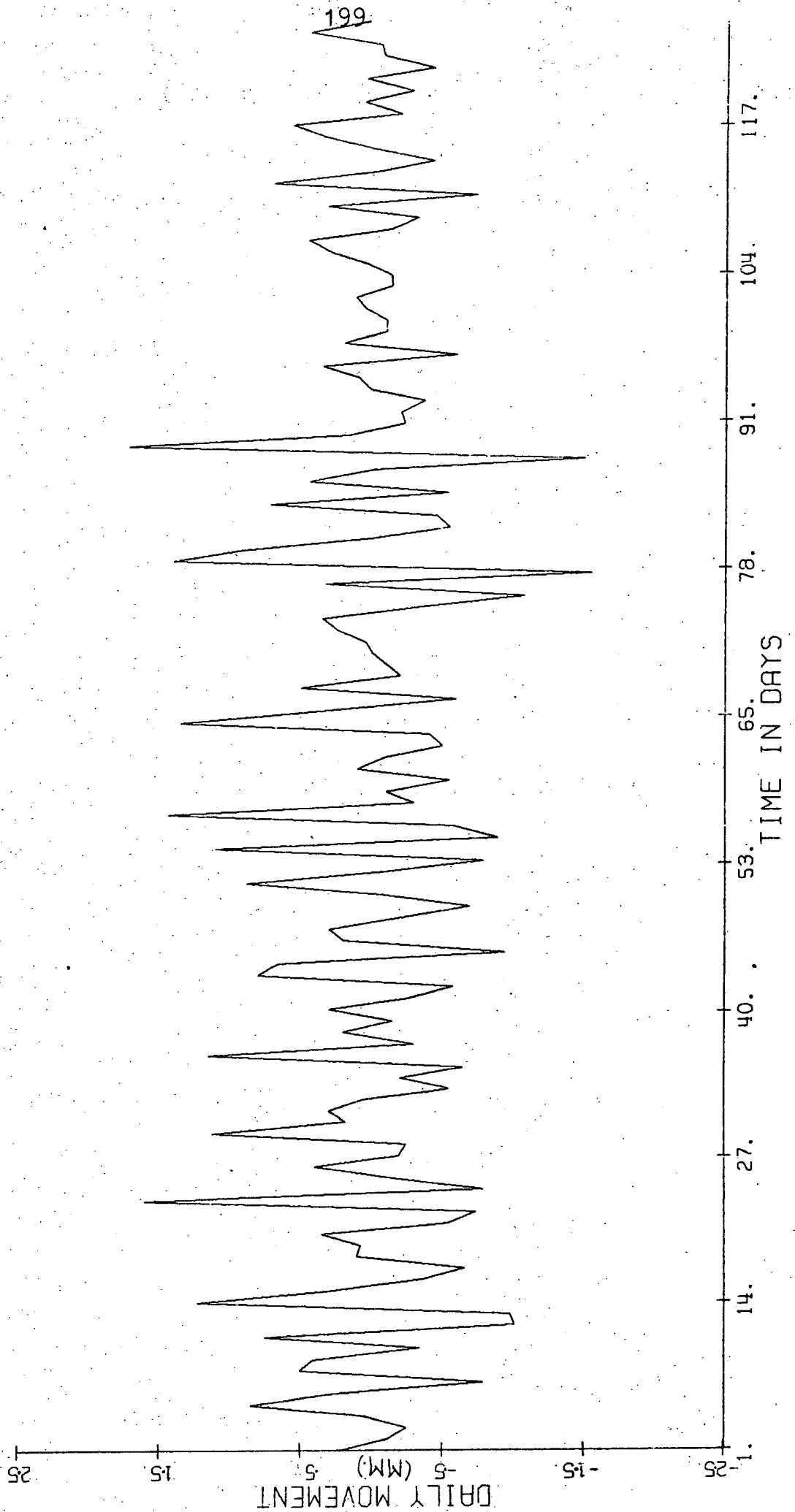


Fig. 6.6E Brandon Plot: Control Peg Series 3

and the remaining ten appear in Appendix 2.

The contrast in the amplitude of movement between the pegs on grass and those on bare earth is most marked. Greater expansion and contraction would be expected where there is no vegetation layer providing a protective influence. Rainfall which could cause wetting and expansion would tend to be partially lost by interception, while drying and possible cracking would be greatly reduced beneath a thick vegetation mat. Thus it can be assumed that soil moisture conditions were more stable in that part of the Brandon plot which was grass covered. Arguments could also be similarly advanced when the effects of freeze-thaw are considered. Frost penetration is known to be three times less beneath grass than beneath bare earth (Bunting, 1967).

All four peg plots also exhibit a definite coincidence in their patterns of peaks and troughs, particularly in the case of the bare earth pegs. The grass pegs show a less uniform pattern, but with local effects such as interception, this is to be expected. With a vegetation layer above the soil, the influence of rainfall is clearly less direct. This is displayed further as a longer lag which causes certain of the grass peg peaks to be displaced one day from the corresponding earth peg peaks.

With regard to the measurement of creep rates, of more significance is the similarity of long term trends. All four plots display clear seasonal tendencies which support the pattern already noticed of generally positive movement in the winter half year and negative in the summer.

These points indicate that the movement of soil is not haphazard but a response to changing meteorological conditions. If creep were a completely random process, the coincidence of peg plot patterns and long term trends could hardly occur. This topic has been discussed in the context of the laboratory programme and will be considered further when the Rookhope results are summarized.

The control peg does, on the other hand, appear somewhat haphazard in its movements, but there is a similarity in parts, particularly to the plot of earth peg 2. In fact this was the nearest peg, and when it is remembered that

soil expansion and contraction will affect the control in the same way as it influences other pegs, the lack of a totally random plot is not so surprising. However, if the plot is examined in detail, major discrepancies do arise.

When rainfall readings are plotted, it can be seen that there is a lag of approximately one day in the case of the earth pegs, but this is extended on occasions with the grass pegs. Of importance here is the exact time when the rain fell and when the readings were taken. As far as possible, all observations were made between 08:30 and 09:00 so that they could be compared with the meteorological results from Durham University Observatory. Furthermore with this as a known consistent factor, it is possible to speculate more easily about the timing of other events. Thus if rain fell at 09:30 there would probably be no time lag when the next day's results were collected from the earth pegs. For this reason, apart from local variations such as soil cracking, an exact lag period would not emerge from regular readings such as these.

The effects of freeze-thaw are less uniform in that the peg may move either way depending on how the frost forms, local vegetation and soil moisture conditions. Frequently, the result is an exaggerated movement and this process accounts for the majority of the extreme peaks and troughs displayed in the peg plots. To isolate more clearly the effects of freeze-thaw, a second series of results was taken on freezing days at 1600, when in most cases thaw had occurred. To maintain the time scale of the plots, it will be noticed that in these cases both points are plotted for the same day. It seems therefore that whereas wetting and drying produce general expansion and interaction with predictable peg responses, freeze-thaw is less specific in its effects, giving rise to a general disturbance which may lead to peg movement in either direction. However, it must be remembered in this connection that most of the frosts recorded were very superficial and their effects on the grass pegs were in many cases extremely marginal.

From a qualitative assessment of the plots, the relationship between meteorological cycles and creep can be

discerned. While it is desirable to confirm such findings statistically before any analysis can take place, there are many factors which militate against producing exact and definitive conclusions, and examples of these must be discussed.

The meteorological variables present a number of problems. With regard to wetting and drying cycles, the intensity of rainfall is likely to affect the length of time lag before any movement occurs. During periods when there is no rainfall, there will be some drying but its rate will depend upon such factors as air temperature, humidity and wind speed. When considering freeze-thaw, the recorded state of the ground gives an idea of freezing, but frost penetration depends upon such variables as soil moisture and vegetation cover.

The exact location of each measuring peg differs, particularly according to soil and vegetation characteristics. Therefore, although the variations are not great, infiltration rates will not be uniform. Results from the study area at Rookhope indicate that within-plot creep rate differences are in fact small, but Carson (1967) has shown that in a similar area infiltration can vary considerably, having in his results a coefficient of variation of 56%.

Apart from these, there are practical experimental problems such as the time recordings are taken compared with the time that changes actually occurred. Furthermore, rainfall is recorded in discrete units while creep movements vary continuously and so relating the two is difficult. This is particularly obvious during drying periods when there is no rainfall but soil movements still occur.

Despite these limitations which must influence any interpretation of results, it was felt that four topics could be investigated in greater detail:

- (a) the daily movement
- (b) the uniformity of movement on the plot
- (c) the relationship with meteorological controls
- (d) the time lag between a meteorological change and a change in soil movement

During the analysis, the five pegs are referred to respectively as: earth peg 1, earth peg 2, grass peg 1, grass peg 2 and control peg. Readings for the period from 20th January until 31st December 1975 provide the data. As explained earlier, there were two breaks in the sequence and therefore three series result.

Table 6.16. Peg Reading Sequence: Details

<u>Series number</u>	<u>Dates of readings</u>	<u>Number of readings</u>
1	20/1/75 - 4/5/75	105
2	22/5/75 - 9/8/75	80
3	25/8/75-31/12/75	127

The daily movement must be examined in the context of the total movement for a particular series. Furthermore it must be remembered that the soil is based on Coal Measure shales which, in a less weathered state have been monitored and shown to be especially active. This may be partially counteracted by the fact that a retaining wall occurs below the plot. Also no Tubes were installed on the plot and bodily movement could not be checked. Linear movement is tabulated for each measurement series using the convention of positive for downslope and negative for upslope movement as employed throughout the study.

Table 6.17. Total Soil Movement

<u>Linear movement (mm)</u>	<u>Series 1</u>	<u>Series 2</u>	<u>Series 3</u>
Earth peg 1	1.5	2.3	2.1
Earth peg 2	0.0	2.7	2.4
Grass peg 1	-0.6	0.5	0.6
Grass peg 2	-0.2	-0.1	1.2

Of the twelve results only three indicate upslope movement and during the complete year grass peg 2 recorded overall movement downslope. The contrast between the rates of movement recorded by the earth pegs and those by the grass pegs is pronounced. It illustrates the enhanced creep reported for bare slopes elsewhere in this study. Bearing in mind the fact that results were not obtained for part of the winter, the grass peg rates are of a similar order to those monitored on the Nardus plots at Rookhope (Chapter 11). However when the daily results are analysed in detail this downslope increment of creep is obscured.

Daily movements were calculated from the Inclinator readings and converted to linear movement in mm at 2.5cm below the surface.

Table 6.18. Soil Movement: Analysis of Daily Readings

<u>Series 1</u>	<u>lower quartile</u>	<u>median</u>	<u>upper quartile</u>
Earth peg 1	-0.50	0.04	0.50
Earth peg 2	-0.41	-0.02	0.40
Grass peg 1	-0.28	0.04	0.31
Grass peg 2	-0.20	0.00	0.25
(Control peg	0.38	0.00	0.50)
 <u>Series 2</u>			
Earth peg 1	-0.50	-0.03	0.63
Earth peg 2	-0.38	-0.04	0.28
Grass peg 1	-0.25	0.00	0.31
Grass peg 2	-0.25	0.00	0.19
(Control peg	0.31	0.04	0.25)

<u>Series 3</u>	<u>lower quartile</u>	<u>median</u>	<u>upper quartile</u>
Earth peg 1	-0.38	0.00	0.34
Earth peg 2	-0.34	-0.04	0.28
Grass peg 1	-0.34	0.01	0.28
Grass peg 2	-0.31	0.00	0.31
(Control peg	0.44	-0.03	0.40)

If the readings are examined it can be seen that in four of the twelve instances the median was displaced slightly upslope. Two of these occurred during Series 2, the measurement period with the lowest rainfall.

The tables show that in each case the distribution approaches normal and that daily movement is on a similar scale to that recorded on the Birkenhead plots and at Rookhope. The earth pegs show greater movement than the grass pegs, a point clearly seen in the plots. The control peg is similar in this respect to the earth pegs, but readings from it are tabulated in parenthesis as it was on a flat surface and therefore upslope and downslope cannot be distinguished.

To investigate uniformity of movement, cross correlations were calculated. The similarity of patterns has already been noted from the peg plots and the problems in examining such a relationship have been considered. Variations in vegetation cover, soil and therefore lag between the reactions of the different pegs would be expected. Thus, particularly when earth pegs and grass pegs are compared, high correlation coefficients could not be anticipated. It was therefore felt that a statistical sampling only would be sufficient to allow comparison with the qualitative assessment. Results were tabulated in groups of twenty readings and for a particular peg one group was selected by random sampling. This was then compared with the corresponding group for the other peg.

Table 6.19. Correlations: Pegs on Same Surface

<u>Series</u>	<u>Pegs</u>	<u>Correlation Coefficient</u>
1	earth peg 1 and earth peg 2	0.59
2	earth peg 1 and earth peg 2	0.73
3	earth peg 1 and earth peg 2	0.62
1	grass peg 1 and grass peg 2	0.54
2	grass peg 1 and grass peg 2	0.89
3	grass peg 1 and grass peg 2	0.60

There is clearly a comparatively high positive correlation between the movement of pegs inserted in similar surfaces. As explained later (Chapter 13) significance levels are not quoted in this study except where the test involved makes this unavoidable. It is felt strongly that throughout the present analysis, it is sufficient to indicate the strength of the relationships. With the number of problems already discussed militating against complete coincidence of movement, the visual assessment must remain crucial.

In each case Series 2 provided the highest value, illustrating the more uniform effect of drying and upslope movement. Regularity of movement in the long term is discussed in detail later in the study, but it can be concluded that, in the short term, the pegs do move together. This statement is supported when the cross correlations between the pegs and the control peg are listed.

Table 6.20. Correlations: Pegs and Control

<u>Series</u>	<u>Pegs</u>	<u>Correlation Coefficient</u>
1	earth peg 1 and control peg	0.00
2	earth peg 1 and control peg	0.00
3	earth peg 1 and control peg	0.00
1	grass peg 1 and control peg	0.00
2	grass peg 1 and control peg	0.00
3	grass peg 1 and control peg	0.00

This complete lack of association is also shown when the two remaining pegs are correlated with the control peg. Thus the control peg, which exhibits much the same range of daily movement as the other pegs does not move in a similar pattern.

When the earth pegs are contrasted with grass pegs, the problem of the lag becomes more acute.

Table 6.21. Correlations: Pegs on Different Surface

<u>Series</u>	<u>Pegs</u>	<u>Lag (days)</u>	<u>Correlation Coefficient</u>
1	earth peg 1 and grass peg 1	0	0.36
1	earth peg 1 and grass peg 1	1	0.35
1	earth peg 1 and grass peg 1	2	0.29
1	earth peg 2 and grass peg 2	0	0.34
1	earth peg 2 and grass peg 2	1	0.28
1	earth peg 2 and grass peg 2	2	0.10

<u>Series</u>	<u>Pegs</u>	<u>Lag (days)</u>	<u>Correlation Coefficient</u>
2	earth peg 1 and grass peg 1	0	0.00
2	earth peg 1 and grass peg 1	1	0.00
2	earth peg 1 and grass peg 1	2	0.00
3	earth peg 1 and grass peg 1	0	0.25
3	earth peg 1 and grass peg 1	1	0.49
3	earth peg 1 and grass peg 1	2	0.27

The correlations are, as expected all low, although a low strength relationship is demonstrated. There is an indication that the lag varies from 0 to 1 day. However it is clear that to calculate correlation coefficients is a coarse method of assessing a complex relationship and, in many ways, a clearer picture emerges from a study of the plotted movements. It seems likely that the complete lack of association during Series 2, the main drying period, results from the problems described and is aggravated by the very different rates of drying on the two surfaces.

Evidence for a relationship with controls has been demonstrated by the uniformity of peg movement. That such controls are meteorological has been indicated elsewhere in the study and has also been shown by the seasonal variations in symmetry noted when the daily movement was discussed earlier. Cross correlations between peg movement and rainfall total, introduce a number of problems. As movement results from expansion which in turn may be caused by wetting, at least during the initial stages of the process, there should be a high positive correlation between creep rate and soil moisture content. Later, if the soil is already very wet, additional moisture will have comparatively little effect. Furthermore the daily rainfall total does not necessarily give an accurate guide to soil moisture since, for example, a high total may have fallen in an intense downpour and been

largely lost in run-off. Therefore it is changes indicating wetting and drying which are important rather than actual rainfall totals. During drying, as mentioned earlier, the pegs are likely to move upslope and this change cannot be related to any change in the rainfall total. Therefore rather than use totals the following numbers were substituted:

- 1 a decrease in rainfall; upslope movement
- 2 static rainfall; no movement
- 3 an increase in rainfall; downslope movement

To help overcome the difficulties associated with drying, periods of twenty days were selected during which there were never more than four consecutive days without rainfall. The other major problem concerns the time lag since, with readings being taken only once each day, this cannot be accurately calculated and allowed in the cross correlation. Examples of the correlation coefficients and lags allowed are listed.

Table 6.22. Correlations: Pegs and Rainfall

<u>Series</u>	<u>Peg</u>	<u>Lag (days)</u>	<u>Correlation with rainfall</u>
1	earth peg 1	1	0.81
2	earth peg 1	1	0.72
3	grass peg 1	1	0.44
3	grass peg 1	2	0.16
3	grass peg 2	2	0.32

While there is a considerable difference between the coefficients, the pattern of correlations does give some indication of a positive relationship between rainfall and creep, with a probable lag of one day.

The effect of freeze-thaw was more difficult to evaluate as the only long term records available were for the state of the ground (Durham University Observatory 1974).

Table 6.23.

State of Ground Code

<u>Surface</u>	
0 Dry	6 Snow or melting snow covering more than half ground
1 Ground moist	7 Snow or melting snow covering ground completely
2 Ground wet	8 Loose, dry snow, dust or sand, covering more than half ground
3 Ground frozen	9 Loose, dry snow, dust or sand, covering ground completely
4 Glaze or ice on ground	
5 Snow or melting snow covering less than half ground	

The only period during which the ground was continuously wet or frozen occurred over eleven days during the early part of Series 1. This period was therefore used for the cross correlations. However it must be remembered that ground state refers to the surface condition while soil expansion is affected by subsurface changes.

Table 6.24.

Correlations: Pegs and State of Ground

<u>Series</u>	<u>Peg</u>	<u>Lag (days)</u>	<u>Correlation with ground state</u>
1	earth peg 1	0	0.42
1	earth peg 2	0	0.63
1	earth peg 2	1	0.21
1	grass peg 1	0	0.11
1	grass peg 1	1	-0.15
1	grass peg 2	0	-0.01
1	grass peg 2	1	-0.10

From this evidence the time lag between meteorological changes and changes in soil movement seems to be approximately one day for wetting and drying cycles while, as would be

expected, there is no discernible lag with freeze-thaw. A further check on lag can be made by calculating the autocorrelation coefficients at increasing time lags for each peg. This technique can be applied since each time series is effectively stationary. Stationarity implies that there is no systematic trend, no systematic change in variance and no strictly periodic variations (Chatfield, 1975). As discussed earlier, any one series for each peg exhibits barely discernible departures from these characteristics.

The autocorrelation coefficients can be plotted against the respective lags to produce a correlogram (e.g. Fig.6.7 ABCDE). If the value of a coefficient falls within the range $\pm 1.96\sqrt{(1/n)}$ it is not significantly different from zero at the 95% level. For the three series of measurements this range can be calculated.

Table 6.25. Autocorrelation Coefficients: Significance Ranges

<u>Series</u>	<u>n</u>	<u>range</u>
1	105	+0.191; -0.191
2	80	+0.219; -0.219
3	127	+0.174; -0.174

From the earlier analysis, the results of the laboratory programme and a consideration of wetting and drying rates (Penman, 1963) it is clear the lag is short. With lag 0, the value is compared with itself giving a coefficient of 1.00. Therefore it is the significant correlations from lag 1 to approximately lag 5 which should be considered when an assessment of the time elapsing between meteorological change and variations in creep rate is being made.

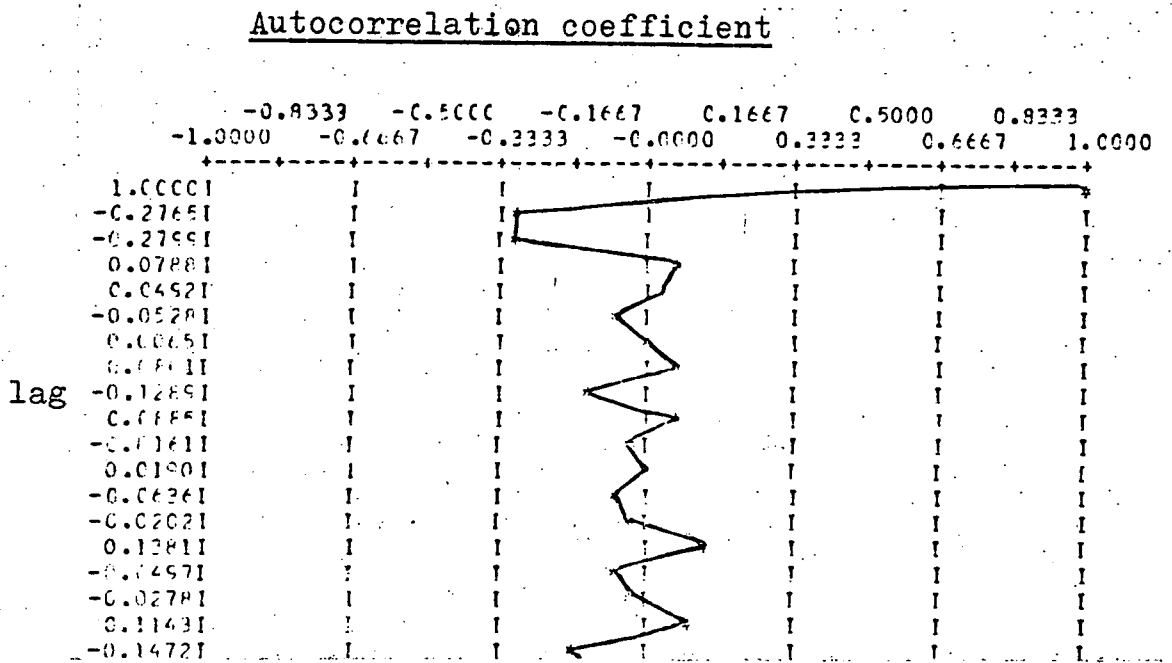


Fig. 6.7A Correlogram: Earth Peg 1 Series 1
 (each coefficient is also listed against the appropriate lag)

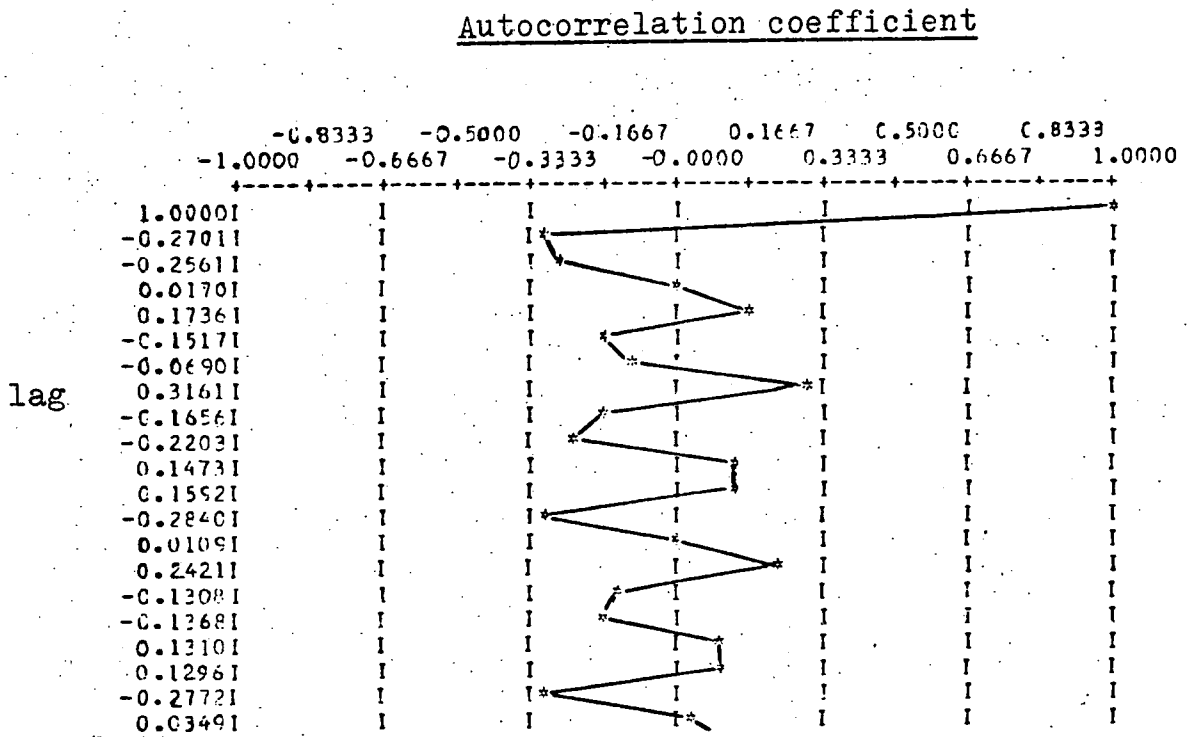


Fig. 6.7B Correlogram: Earth Peg 2 Series 3
 (each coefficient is also listed against the appropriate lag)

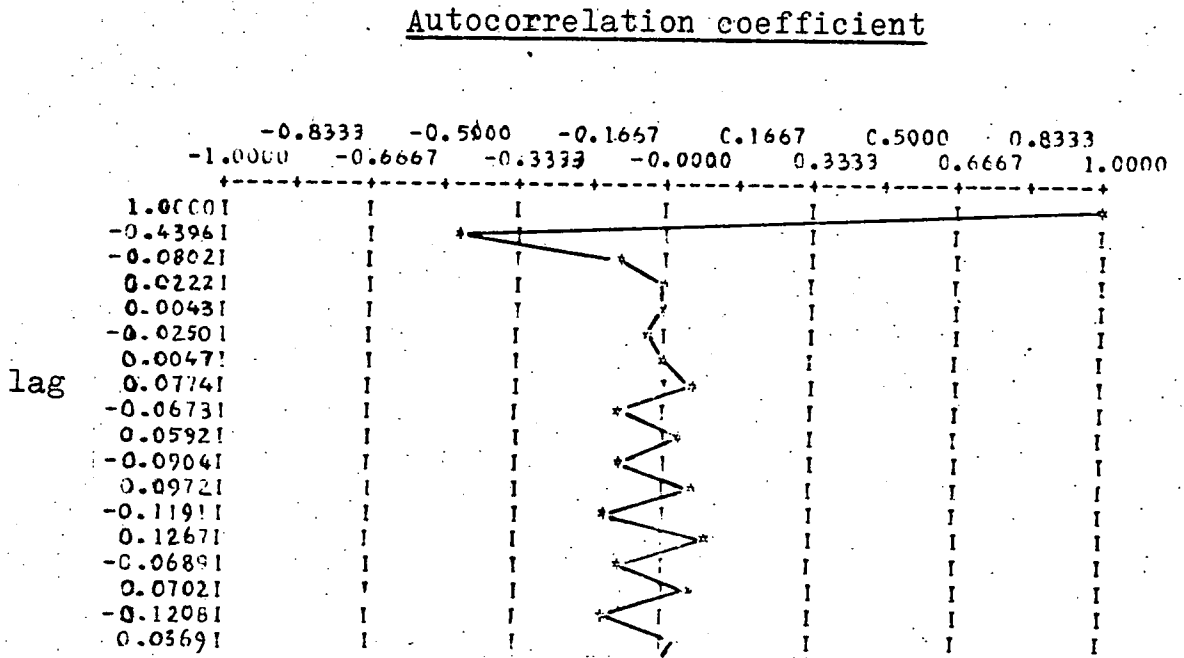


Fig. 6.7C

Correlogram: Grass Peg 1 Series 1

(each coefficient is also listed against the appropriate lag)

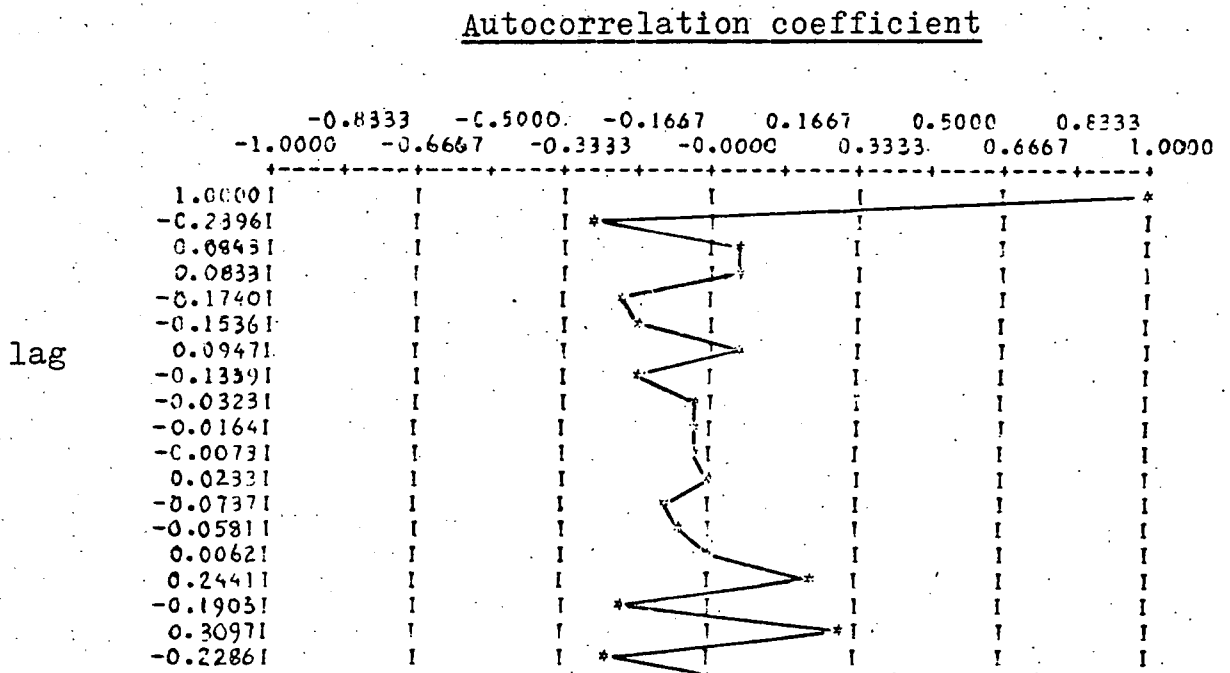


Fig. 6.7D

Correlogram: Grass Peg 2 Series 2

(each coefficient is also listed against the appropriate lag)

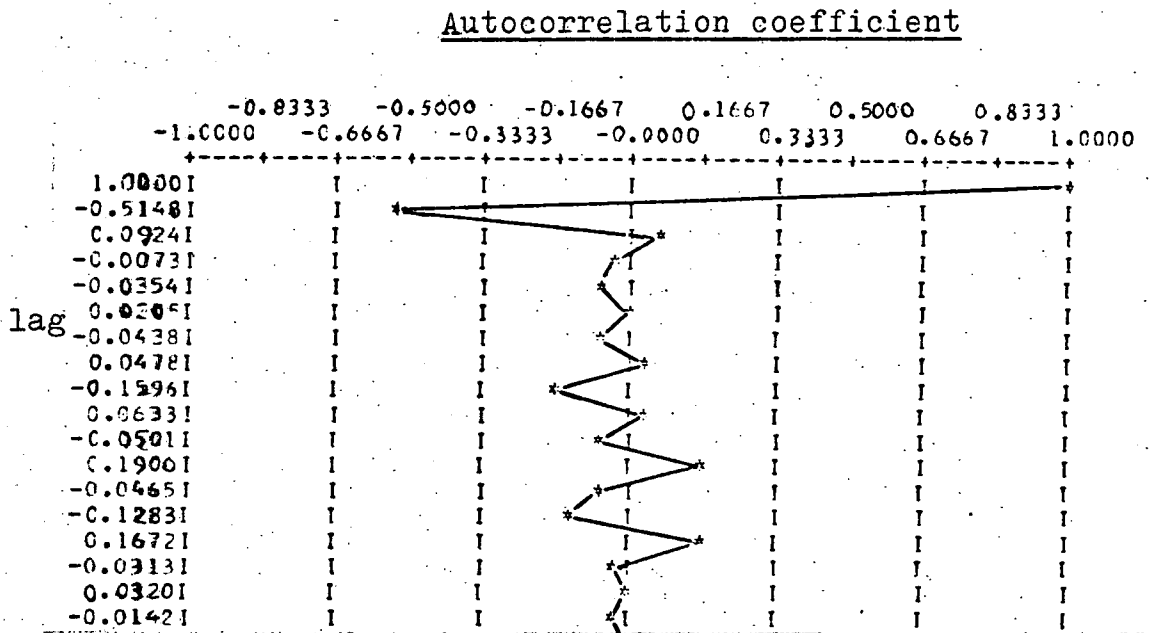


Fig. 6.7E

Correlogram: Control Peg Series 2

(each coefficient is also listed against the appropriate lag)

Table 6.26. Autocorrelation Coefficients and Lags

<u>Series 1</u>					
<u>Peg</u>	<u>Autocorrelation coefficient</u>				
	<u>lag 1</u>	<u>lag 2</u>	<u>lag 3</u>	<u>lag 4</u>	<u>lag 5</u>
Earth 1	<u>-0.277</u>	<u>-0.280</u>	0.079	0.049	-0.053
Earth 2	<u>-0.353</u>	-0.079	-0.079	0.034	0.085
Grass 1	<u>-0.440</u>	-0.080	0.022	0.004	-0.025
Grass 2	<u>-0.444</u>	-0.075	0.055	-0.020	-0.062
Control 1	<u>-0.279</u>	<u>-0.206</u>	-0.131	<u>0.262</u>	-0.048
<u>Series 2</u>					
Earth 1	<u>-0.312</u>	0.015	-0.026	-0.195	0.130
Earth 2	<u>-0.254</u>	0.154	<u>-0.220</u>	-0.066	-0.056
Grass 1	-0.164	-0.215	0.029	0.183	-0.196
Grass 2	<u>-0.240</u>	0.084	0.083	-0.174	-0.154
Control 1	<u>-0.514</u>	0.092	-0.007	-0.035	0.021
<u>Series 3</u>					
Earth 1	<u>-0.224</u>	<u>-0.223</u>	-0.009	0.060	-0.105
Earth 2	<u>-0.270</u>	<u>-0.256</u>	0.017	0.174	-0.152
Grass 1	<u>-0.542</u>	0.071	-0.023	0.016	-0.001
Grass 2	<u>-0.464</u>	0.131	-0.132	-0.110	0.137
Control 1	<u>-0.298</u>	<u>-0.259</u>	0.120	-0.092	0.028

Significant correlations underlined

Interpreting the meaning of a set of autocorrelation coefficients presents difficulties in that a large number of coefficients is likely to contain one or more significant results even when no real effects are present (Chatfield, 1975).

However with these results, when the pattern of significant correlations, underlined in the tables, is considered it shows clearly that the lag is short. These values indicate a sudden and rapid effect. The fact that the coefficients at lag 1 are all slightly negative can be interpreted as meaning that after a particular movement, creep will be less on the next day. Thus a 'pulse' goes rapidly through the system in a period of one or two days, according to the actual lag for each peg. Possible causes of variations in lag have already been discussed and in part, result from problems associated with the times of taking measurements in relation to the times when changes actually occurred.

While it is realised that, apart from local plot factors, the length of lag varies according to meteorological conditions on a particular day, nevertheless it was decided to attempt a more detailed examination by taking very short term readings from earth peg 1. To facilitate interpretation, measurements were made during periods of changeable weather in late May and early June 1976. It was hoped that after two or three days without rainfall, the soil would have dried considerably, then a short period of rainfall would promote a change in the soil movement which could be monitored by the Inclinator peg. Such a change could thus be unambiguously related to that period of rainfall. Furthermore peg readings were taken after short, comparatively intense falls rather than drizzle. However, variations occurred even during one period and no attempt was made to record the actual intensity.

The changes detected by the peg were small and, if these are then converted to linear movement expressed to two places of decimals, discrimination is lost. Therefore to help discern lag, the original Inclinator readings are retained. It should be remembered in this context that 'C' designates 'clockwise' and increases in C values indicates downslope movement.

Table 6.27. Inclinometer Readings and Lag

A.	<u>Time</u>	<u>Inclinometer readings</u>	
	1430	C.5.40	rainfall stopped
	1530	C.5.30	
	1630	C.5.30	
	1730	C.5.45	lag: 3 hours
	1830	C.5.45	
B.	<u>Time</u>	<u>Inclinometer readings</u>	
	0815	C.4.92	rainfall stopped
	0915	C.5.00	
	1015	C.4.95	
	1115	C.5.20	lag: 3 hours
C.	<u>Time</u>	<u>Inclinometer readings</u>	
	0730	C.5.05	rainfall stopped
	0830	C.5.00	
	0930	C.4.92	
	1030	C.4.92	
	1130	C.4.92	
	1230	C.5.15	lag: 5 hours
D.	<u>Time</u>	<u>Inclinometer readings</u>	
	1030	C.5.00	rainfall stopped
	1130	C.5.08	
	1230	C.5.08	
	1330	C.5.09	
	1430	C.5.09	
	1530	C.5.10	
	1630	C.5.25	lag: 6 hours
	1730	C.5.25	

E.	<u>Time</u>	<u>Inclinometer readings</u>	
	1330	C.5.35	rainfall stopped
	1430	C.5.30	
	1600	C.5.00	
	1900	C.5.10	
	2030	C.5.35	lag: 7 hours

In each example the change in the Inclinometer readings is considered to be of sufficient magnitude to indicate the end of the lag period. In cases A, C and E the drying period continued after rainfall had ceased but then a reversal occurred. Example D shows a very slight downslope movement but this is hardly marked enough to constitute an obvious response. In Example E however, it is possible that the lag period is 6 hours after which the reversal was recorded. B illustrates a typical minor fluctuation before the main movement was monitored. Thus in these cases, specifically selected as stated to remove, as far as possible, any ambiguities, lag varied from 3 to 7 hours. With drizzle, longer periods would be expected.

While these results constitute a very small sample, they do provide a further indicator that the response period is of short duration.

This analysis of the readings from the plot at Brandon provides evidence to support that discussed elsewhere in the study that daily movements tend to be uniform, that the relationship between creep and meteorological controls can be demonstrated, and that the time lag involved is short. Since readings were obtained daily and the plot was monitored almost continuously for over a year, the main conclusions on these three points rest very firmly upon the results from Brandon.

Readings were taken daily for the month of February (1974) at the Leaze's House plot but the 5cm soil thermometer recorded no frost cycles. Therefore the meteorological changes add nothing to the record produced at Brandon and are not included. The plot was therefore only significant since, as a lowland

area (66m O.D.) it provided a guide to annual creep rates at such an altitude.

Table 6.28.

Annual Creep Rates

Plot slope	2°	20°
Mean movement (mm)	1.20	1.77
Standard deviation	0.18	0.21

Movement appears rather higher than might have been anticipated but the results do show that rates of creep on lowland plots are of a similar order to those recorded in upland areas.

The other important measurement made was that with the continuous recording peg during 1974. As explained earlier, there were various practical difficulties involved and only one weekly trace is available. The rainfall during this period is given.

Table 6.29.

Rainfall: Leaze's House Plot

Date (May 1974)	7	8	9	10	11	12	13	14	15
Rainfall (mm)	Tr	-	6.7	0.8	-	Tr	0.5	-	-

From this it is possible to see the influence of rainfall and measure the time lag. The amount of movement on the trace is very small but discernible and begins in this case some 24 hours after rainfall ended (Fig. 6.8). This must be viewed as an isolated phenomenon rather than a general rule since it is obviously related to the infiltration rate, itself affected by the existing soil moisture condition and the intensity of rainfall. With complete soil soaking from all sides, as occurred under the laboratory conditions, movement was very much more rapid with a lag of under 1 hour.

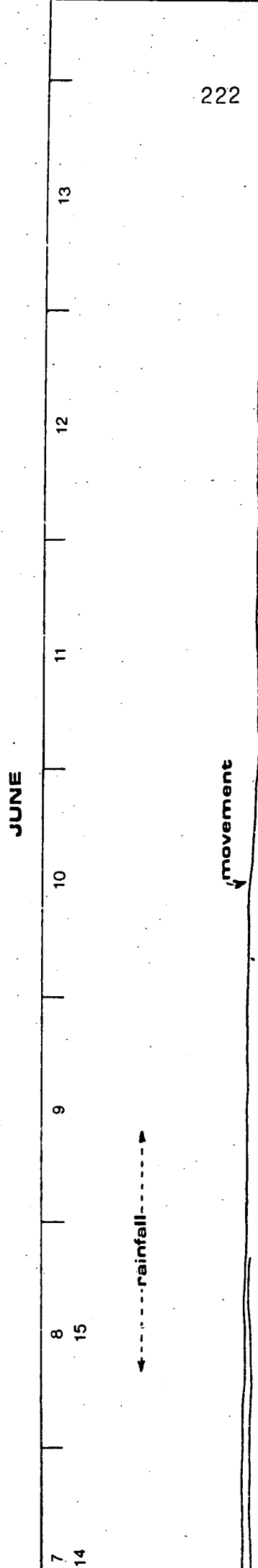


Fig. 6.8

Wetting and Drying Cycle (Leaze's House)

Therefore the results from this one peg record are regarded as valuable, but they must be seen in context.

Pegs on the Sherburn Hill plots were read only four times during the year, and during this time one was removed from each plot.

Table 6.30.

Annual Creep Rates

Plot slope	8°	25°
Mean movement (mm)	0.46	1.62
Standard deviation	0.11	0.23

Results from the 25° slope accord well with those obtained at Leaze's House on a similar slope although in this case there were no bare patches. Movement on the 8° slope is rather low, but this is a very exposed, dry plot, resembling several at Rookhope.

6.8. Summary

Results from the supporting research sites indicate that the Anderson Tube is a valid technique for measuring soil creep. Furthermore, to provide the most realistic assessment of rates, both Tubes and Inclinator pegs should be inserted to a depth of 15cm. The readings show a definite relationship between soil moisture and creep rates while rainfall is less directly related. Increases in soil moisture coincide with downslope movement. Aspect is also important, with north-facing slopes recording greater mean annual movement than south-facing slopes. For transect 1 on the motorway, the estimated mean annual surface movements were 2.86mm and 1.46mm respectively.

The motorway transects also show the very responsive nature of immature soils, which move at twice the rates recorded under conditions of similar moisture and vegetation on nearby mature slopes.

Annual creep rates measured for lowland sites, varying

from 0.5mm to 1.8mm, are of the same order as those measured in uplands. For the Rookhope basin, annual movement ranged from 0.3mm to 2.4mm.

The more detailed results from the Brandon plot, show that the basic pattern of movement recorded by all four pegs is similar. However, daily movement under grass, averaging approximately 0.5mm, is only half that on bare soil. The basic relationship between creep rates and meteorological controls is clearly shown, although it is more obvious with wetting and drying than with freeze-thaw cycles. An increase in rainfall results in a downslope movement.

Finally, it is clearly demonstrated that the time lag between a meteorological change and a change in soil movement is short. Depending on local conditions it varies from approximately three hours to, at the most, two days.

CHAPTER SEVEN

SELECTION OF THE MAIN EXPERIMENTAL AREA

7.1. Introductory

7.2. Stage 1

7.3. Stage 2

7.4. Stage 3

7. SELECTION OF THE MAIN EXPERIMENTAL AREA

7.1 Introductory

The principles underlying the use of drainage basins as suitable landscape units for data collection have already been discussed. Only within the drainage basin can the interaction of factors be seen and quantified so that the inter-relationships, which form the basis of this study can be investigated. However, the lack of control implicit in such a situation hinders the assessment of the contributions of individual variables to the sum total. Therefore it was decided that a compromise was necessary and, while it was highly desirable that results obtained should have as general an application as possible, the selection procedure must isolate not only a representative basin but also one in which a degree of control and experimentation was possible; then both representative unit sources (Amerman, 1965) and experimental plots could be defined and instrumented.

Criteria for watershed selection have been itemised by, for example, Leopold (1962) and by Slaymaker and Chorley (1964) but all are not applicable at the same stage of the process. It would seem that choice must be made on at least four scales producing:

1. The general region for study
2. Basins within that region
3. One particular basin
4. Sites or unit sources within that basin

Not only will the criteria tend to vary but also the technique employed at each subsequent stage. This procedure was applied to the Durham area and stages 1 to 3 are described below. Stage 4 is considered later when problems of instrumentation are discussed.

7.2. Stage 1

The criteria for selecting an appropriate region were taken to be:

- (a) the occurrence of small defined watersheds with surface drainage
- (b) cultural effects with associated problems for regular access and measurement
- (c) distance from Durham which should not involve more than approximately two hours' travelling time if adequate readings are to be obtained during one visit.
- (d) the area should be sufficiently remote to ensure that vandalism is improbable

With Ordnance Survey maps, scale 1:63360, western Durham comprising essentially the eastern slopes of the Pennines dissected by several river valleys, was selected as the most likely region. Within this area is a range of catchments of various sizes, many of the first and second order basins being in areas of free grazing with a uniform land use which was unlikely to change during the course of the study. However, access can be difficult within the region owing to the sparse road network, and it was decided that, bearing this in mind, together with the other factors listed, the site selected should be within the watersheds of the upper Wear within a limited distance of a major road. Furthermore, such aspects as the geology, pedology and geomorphological history of Upper Weardale are well documented, and research within the area would complement that already being undertaken by the Durham University Geography Department in connection with the hydrology of the Wear system.

7.3. Stage 2

Using Ordnance Survey maps of scale 1:63360 and 1:25000 together with a geological map and aerial photographs, the possible basins within Upper Weardale were distinguished. Cultural effects on a smaller scale were still important but the main criteria at this stage were:

- (a) small size so that the site could be mapped in one day (Slaymaker and Chorley, 1964)
- (b) a simple self-contained first or second order network

- (c) stream permanence
- (d) a limited variation in lithology
- (e) easy access facilitating the use of apparatus and the removal of specimens
- (f) a possible variation of aspect
- (g) a limited altitude range of some 60m to 90m

As a result, ten small basins were selected for examination in the field (Fig. 7.1): (1) Ireshope Burn, (2) South Foul Sike, (3) Waskerley Beck, (4) Stanhope Burn 1, (5) Stanhope Burn 2, (6) Black Burn, (7) Bollihope Burn 1, (8) Bollihope Burn 2, (9) Middlehope Burn, (10) Bolts Burn.

7.4. Stage 3

The selection criteria listed were checked in the field and using these and the following points, the main experimental area for the study was chosen:

- (a) a clearly defined watershed
- (b) clearly distinguishable slope facets at a variety of angles
- (c) a small number of well defined vegetation associations
- (d) a limited range of soil types
- (e) the availability of meteorological data locally

It was realised that each small basin has its own functional identity and integrity (England and Onstad, 1968), and consequently it was considered vital that each of the ten basins was visited and examined. The limitations and advantages of each were noted, taken into account, and then summarized in a table.

Table 7.1 lists with a series of scales, the presence or absence of the key factors, the place of the basin on the scale being shown by an asterisk.

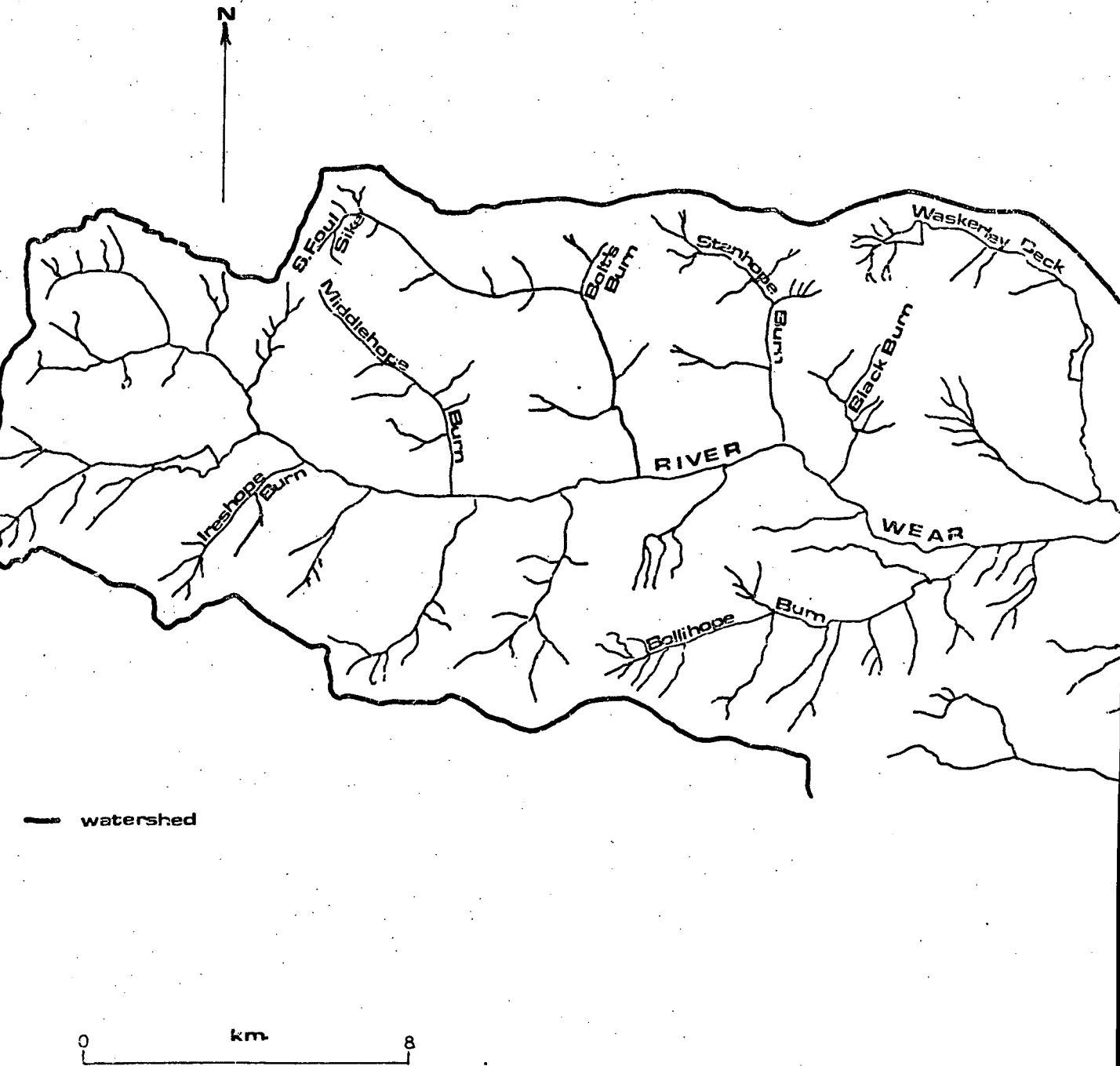


Fig. 7.1 Upper Weardale: Drainage Basins

<u>BASIN</u>	<u>ACCESS</u>	<u>DEFINITION</u>	<u>SLOPE FACETS</u>	<u>VEGETATION ASSOCIATIONS</u>	<u>MET. DATA AVAILABLE</u>
Waskerley Beck	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Stanhope Burn 1	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Stanhope Burn 2	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Black Burn	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Bollihope Burn 1	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Bollihope Burn 2	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Middlehope Burn	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *
Bolts Burn	easy----difficult *	good----poor *	many----few *	several----one *	very near----none *

Table 7.1

Drainage Basin Characteristics

Eventually the small Bolts Burn drainage basin situated in an area known as Bolts Walls, approximately 0.7km to the north of Rookhope village, was selected (Plate 7.1). It satisfied all the main criteria except that the watershed on the western side lacked clear definition. However, this problem was overcome in the later choice of individual plots for instrumentation, and in any case, there were compensating advantages. The basin is drained by two small permanent streams, one flowing from north to south and the other from east to west, giving two nested sub-systems with a slope facing each of the cardinal points. The interfluvium between is extremely uniform laterally but longitudinally it displays a series of clear slope elements in repeated assemblages, and since it faces south-west, is well exposed to the predominant rain-bearing winds but allows considerations of aspect to be neglected. The eastern and north-eastern boundary is provided by a quarry railway embankment which has been in existence since 1850. Therefore the interfluvium bounded by a sharp watershed to the north and north-west, the railway embankment and the two streams form a totally self-contained unit on which variations in creep rates can be studied. At its edges are active and inactive slopes together with several man-made mounds. The mounds resulting from the embankment construction are vegetated and have areas of level surface which are particularly suitable for the establishment of control points, while a shale tip near the mouth of a mining tunnel provides an interesting contrast with the natural slopes (Fig. 7.2). The Weardale Lead Company in Rookhope village maintains a rainfall recording station and the Castle School at Stanhope in Weardale itself is also a Meteorological Office recording centre.

It was therefore felt that this basin offered a suitable variety of factors possibly affecting soil creep rates and provided particularly good opportunities to establish control experiments.

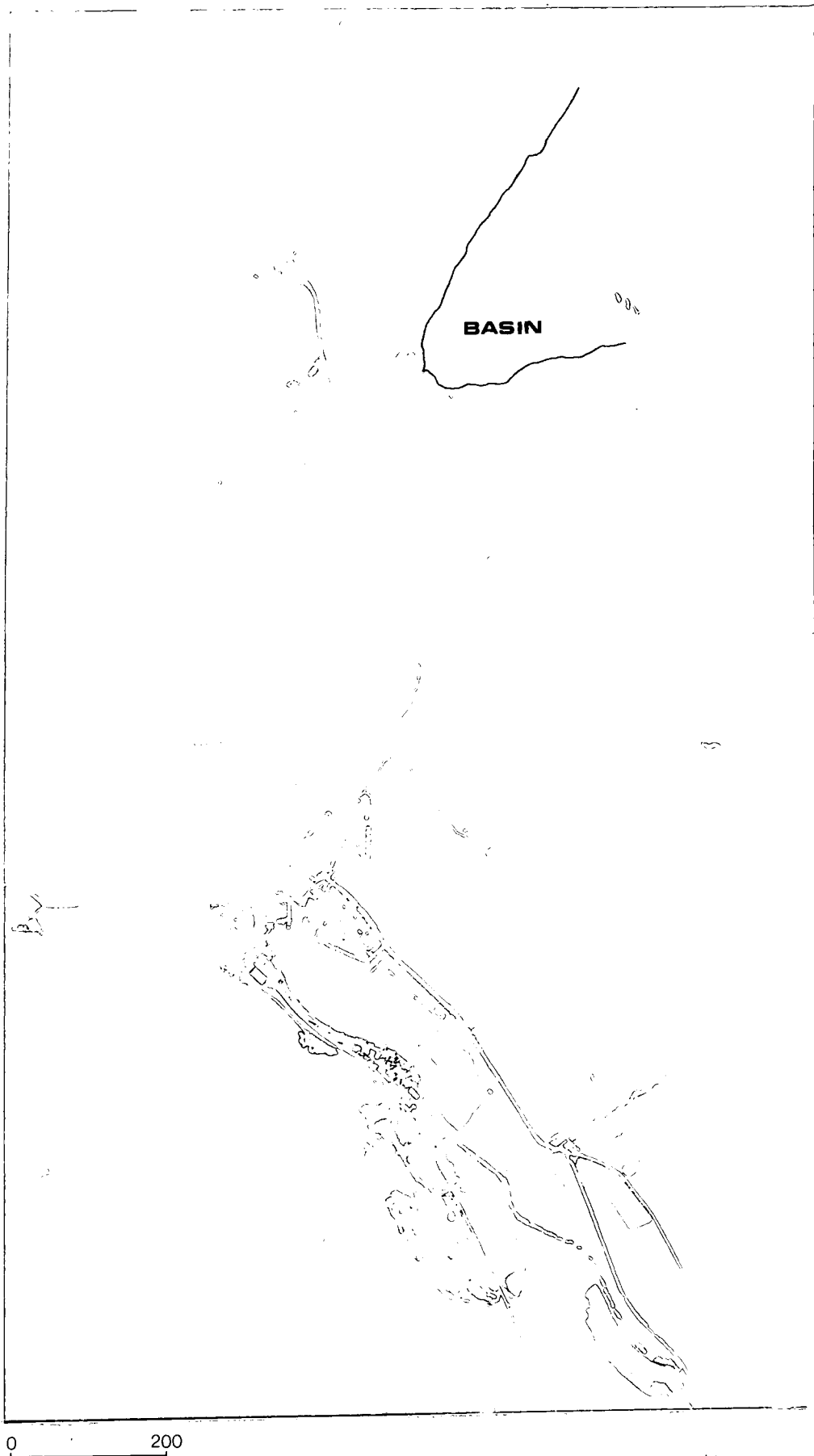
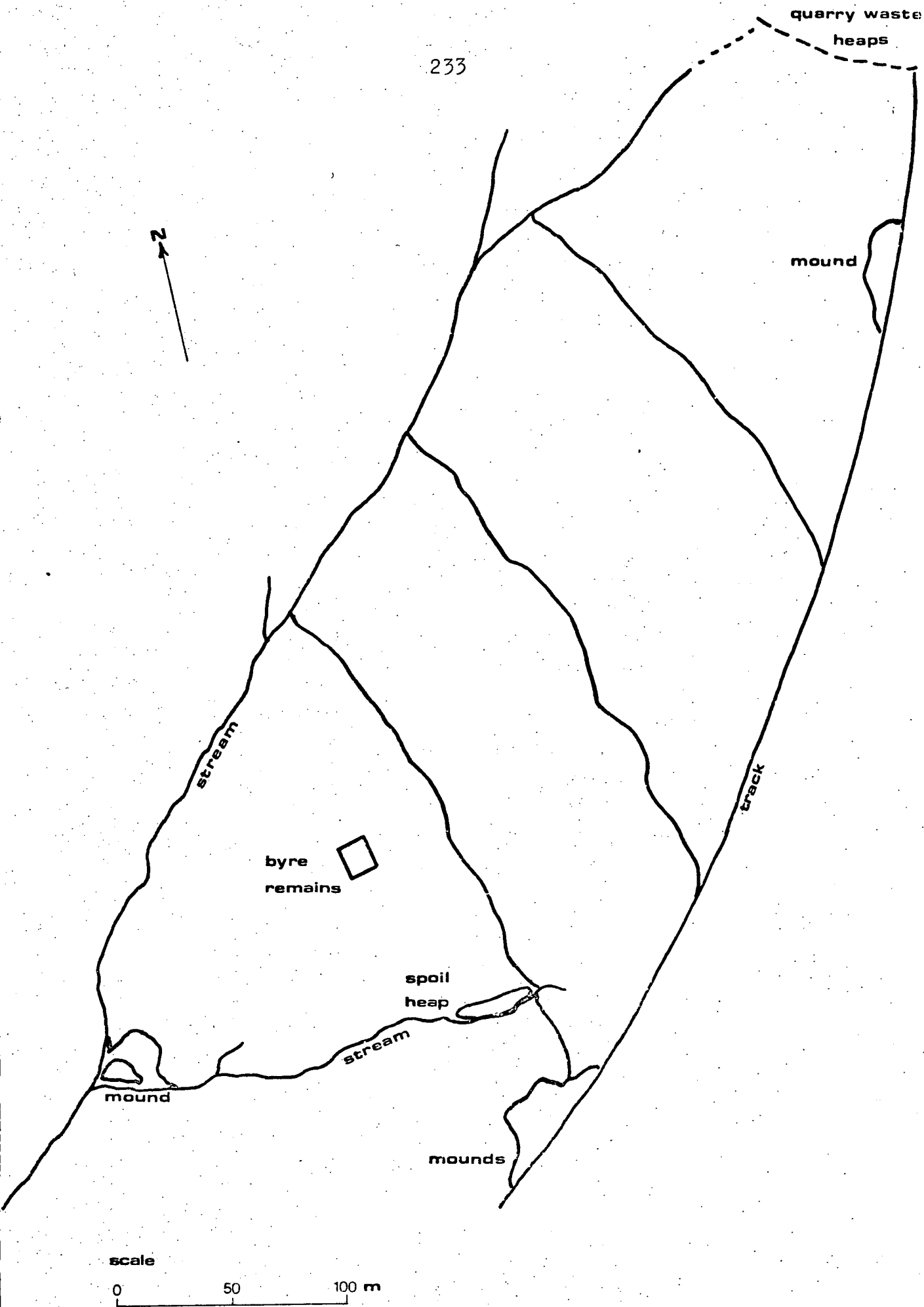


Plate 7.1

Rookhope Village and Rookhope Basin



scale
0 50 100 m

Fig. 7.2 Rookhope Basin: Boundaries and Main Features

CHAPTER EIGHT

BACKGROUND TO UPPER WEARDALE AND THE BASIN
AT ROOKHOPE

- 8.1. Introductory
- 8.2. Geology
- 8.3. Geomorphological Development
- 8.4. Soils
- 8.5. Climate
- 8.6. Vegetation
- 8.7. Rookhope Basin

8. BACKGROUND TO UPPER WEARDALE AND THE BASIN AT ROOKHOPE

8.1. Introductory

The drainage basins identified during the sampling procedure leading to the selection of the study area at Rookhope are all located in what has become known as Upper Weardale. This particular delimitation of the dale section, within the Wear valley, has been used by Atkinson (1968) and Falconer (1970). The boundaries are taken to be the watershed to the north, west and south and easting of the National Grid ($1^{\circ} 50' 50''$ W) to the east 410,000. This gives a maximum east-west length of 28km and an average width of about 11km.

Upper Weardale has received comparatively little attention from geomorphologists (Falconer, 1970) and the few important works (Dwerryhouse, 1902, Maling, 1955, Atkinson, 1968 and Falconer, 1970) are widely spread both in time and also in the main topic of study. If there is a general trend, it is concerned with the history and effects of glaciation and, in this context, the area is mentioned in several more general surveys including those of Trotter (1929), Raistrick (1931) and Hollingworth (1932). The subject of the present study, mass movement, has merited scant attention in any of this literature although the re-establishment of sub-aerial processes after the retreat of the ice is discussed.

The geomorphological character of Northern England is strongly dependent upon the rock type and the structural elements (King, 1976). In the case of Durham County, the dominant feature is the gently warped mass of Carboniferous sediments of the Alston Block. The River Wear drains eastwards through a basin opening from the centre of this feature. Therefore if the Rookhope experimental area is to be placed in its geomorphological context, it is necessary to discuss the geological background to Upper Weardale.

8.2. Geology

The geology of the region has been described in detail by Dunham (1948) and Johnson (1970), while summaries have been included in the studies of Maling (1955), Atkinson (1968), Vincent (1969) and Falconer (1970). However it is felt that a short description of the major aspects is necessary in the present work.

The chief structural element is the Alston Block, a well defined unit bounded on the north, west and south by major fault-systems. Eastwards the block inclines gently beneath younger strata, although an eastern boundary off the coast has been identified (Bott, 1961). There is evidence that the faults, even within the same system, were active at different times (King, 1976), while the timing of the main diagenesis is controversial. Trotter (1953) considered the main uplift to be of Tertiary age while Wells and Kirkaldy (1966) and Dunham (1952) concluded that the major movement occurred during the Hercynian orogeny. The complete structure is best illustrated by a schematic cross section after Bott and Johnson (1967) (Fig. 8.1).

The lithology has been summarized (Atkinson, 1968).

Table 8.1. Alston Block: Geological Succession

<u>Group</u>	<u>Main Strata</u>
1. 'Local' Millstone Grit	Coarse grits, sandstones and shales with ganisters between the groups
2. Upper Limestone Group	Coarse grits, sandstones, ganisters, thin coals, limestones and shales
3. Middle Limestone Group	Rhythmic alternation of limestones, shales, sandstones and thin coals (e.g. Fig. 8.4)
4. Lower Limestone Group	Massive limestone overlain by alternating limestones, shales and sandstones

A more detailed stratigraphic column for Upper Weardale is included (Fig. 8.2) and the continuation of this downwards can be illustrated (Fig. 8.3) from the Rookhope boring (Johnson, 1970).

Within Upper Weardale the higher interfluvial watersheds are composed of Upper Carboniferous strata distinguished broadly as sandstone beds. The Lower Carboniferous rocks, ed

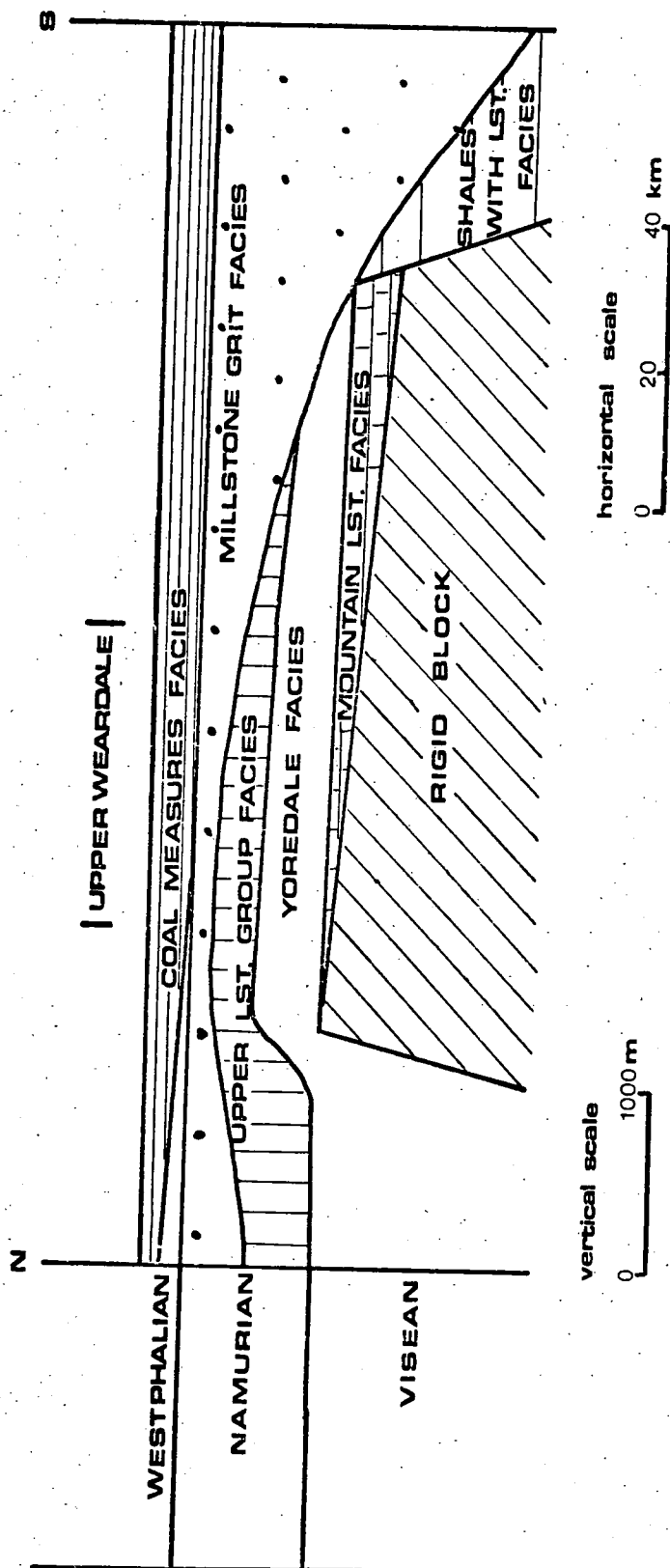


Fig. 8.1 Northern Pennines: Schematic Cross Section
(after Bott and Johnson 1967)

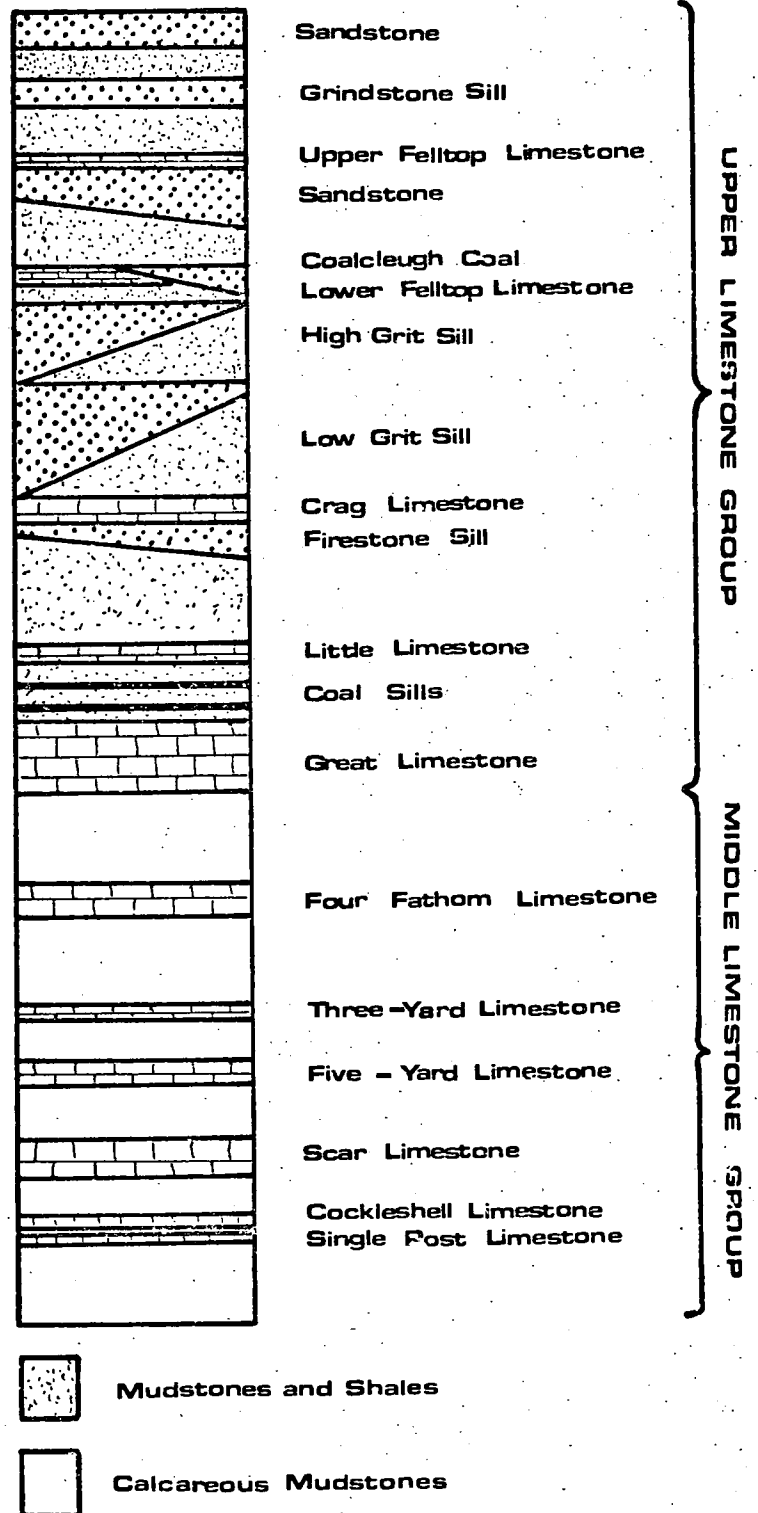


Fig. 8.2

Upper Weardale: Stratigraphical Column
 (based on Dunham^{et al} 1965)

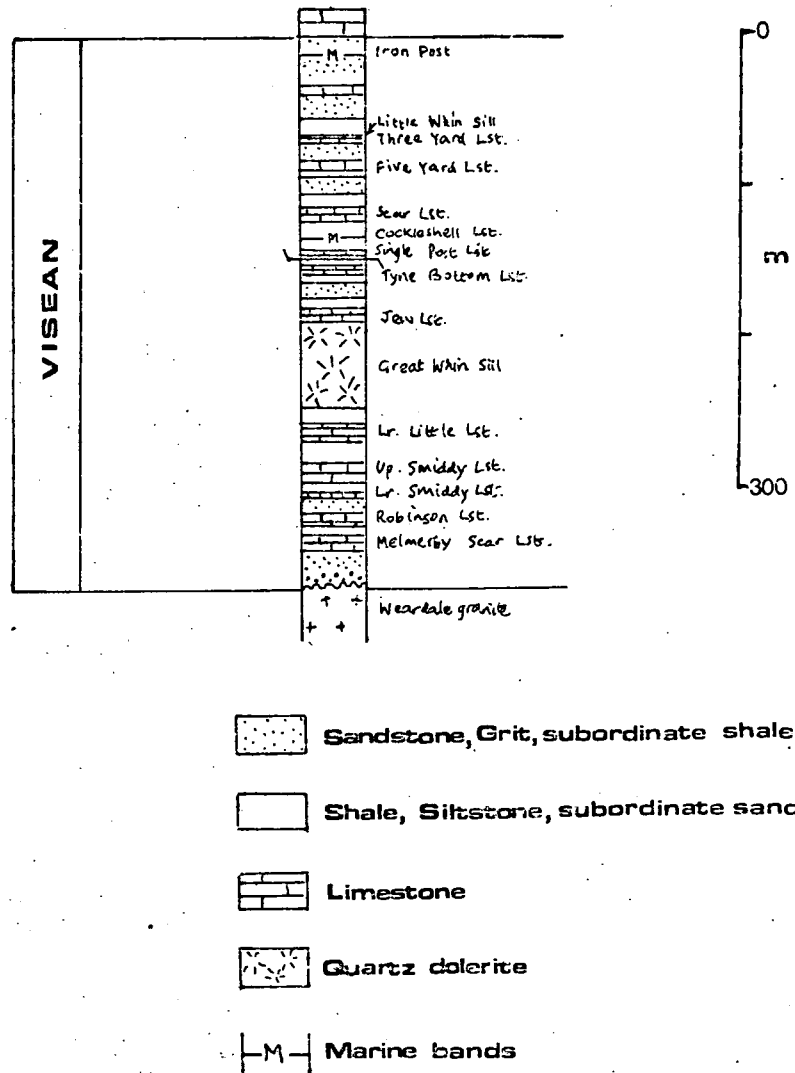


Fig. 8.3

Rookhope Boring: Stratigraphical Column
(Dunham et al 1965)

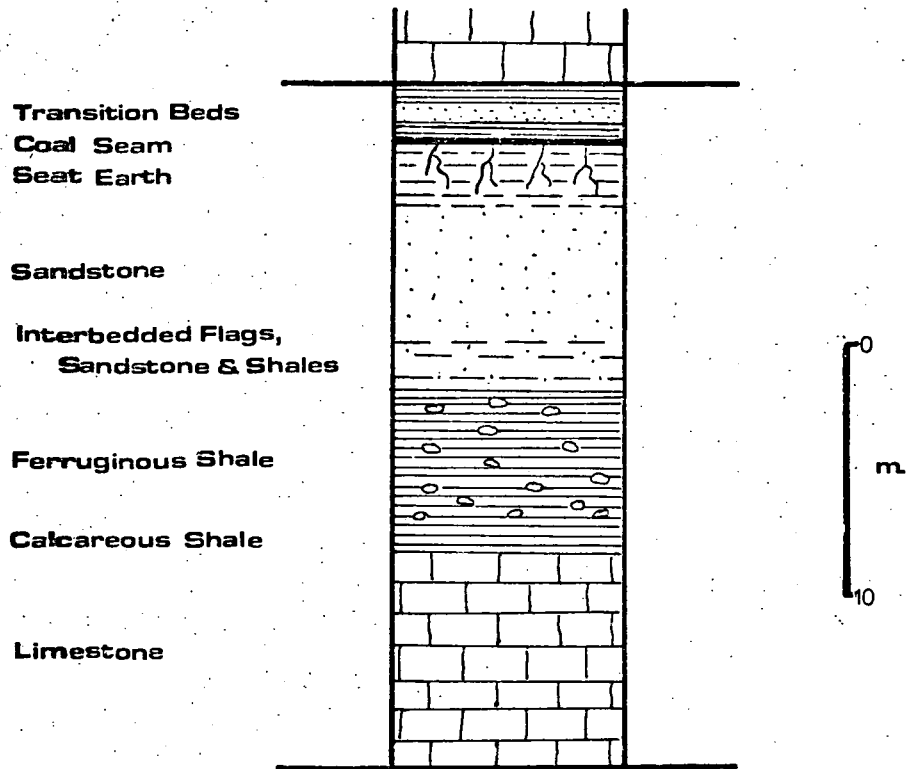


Fig 8.4

Yoredale Cyclothem

mainly limestones, shown in the Rookhope boring column, outcrop on the valley sides. This distinction can also be appreciated in the short geological section (Fig. 8.5) of the Rookhope Burn area. The section also illustrates the relatively undeformed nature of the strata although this simplicity of structure is balanced by a complexity of lithology. The basic picture is, however, of Carboniferous strata laid on a stable Palaeozoic floor and then gently upwarped by the granitic intrusion.

8.3. Geomorphological Development

The overall form of the landscape following this uplift can be reconstructed through the identification and plotting of erosion surfaces (Maling, 1955, Sissons, 1960) and also through the technique of trend surface analysis.

However, a more complete overall impression can be gained from the analysis by King (1967) who concluded that a quadratic surface best described the summit shape of the Alston Block. This result has been subsequently confirmed by Beaumont (1970) who described the form as a ridge trending west-south-west to east-north-east. If contours are constructed on this, it can be seen that Upper Weardale follows a line basically orthogonal to them and can therefore be considered an original consequent (Fig. 8.6). Furthermore, with uplift, incision would have occurred and the pattern would have become fixed. Thus the evidence suggests strongly that the position of the dale section of the Wear Valley has altered little since the emplacement of the granite.

The other contribution to the evolution of the Tertiary landscape involves the possible effect of sub-aerial weathering (Atkinson, 1968) but as yet this must be largely speculative.

However, a more profound influence was exercised by the Pleistocene glaciation. The published research on this aspect of the geomorphology of the area is limited and is discussed in detail by Vincent (1969). It is not proposed therefore to trace the history of glacial research but to indicate certain relevant ideas and conclusions.

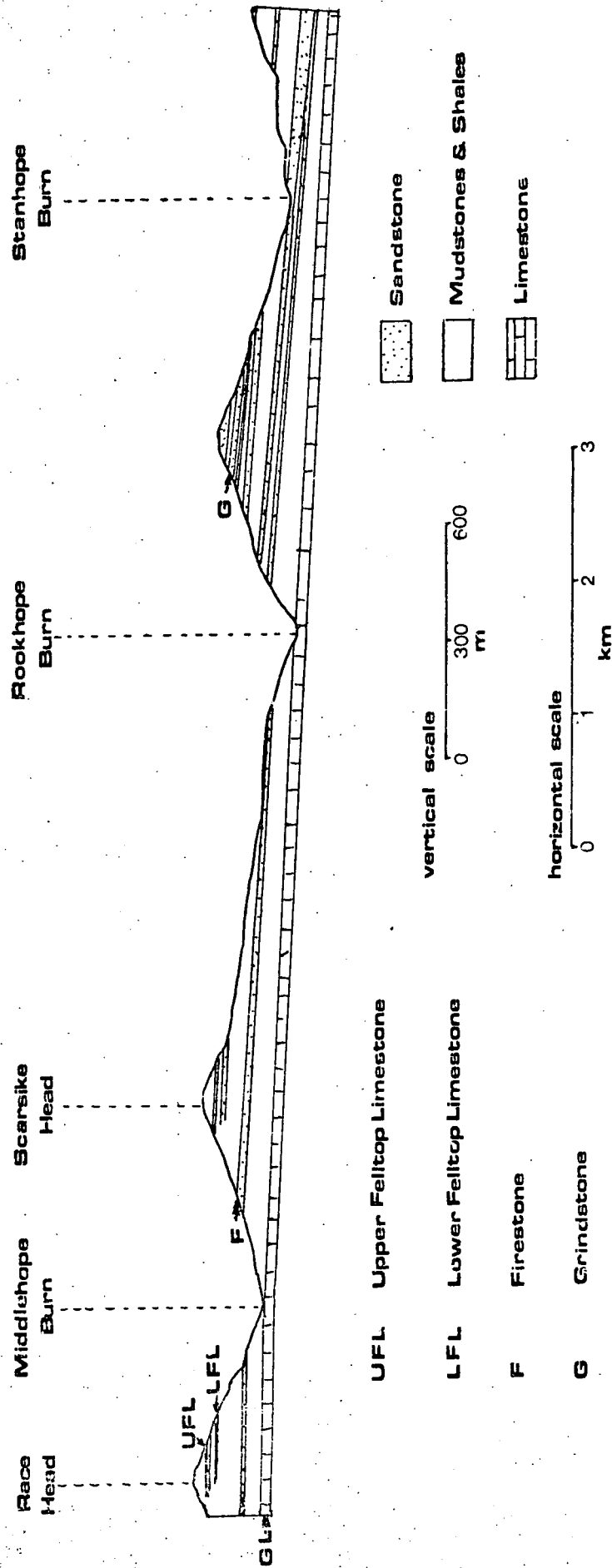
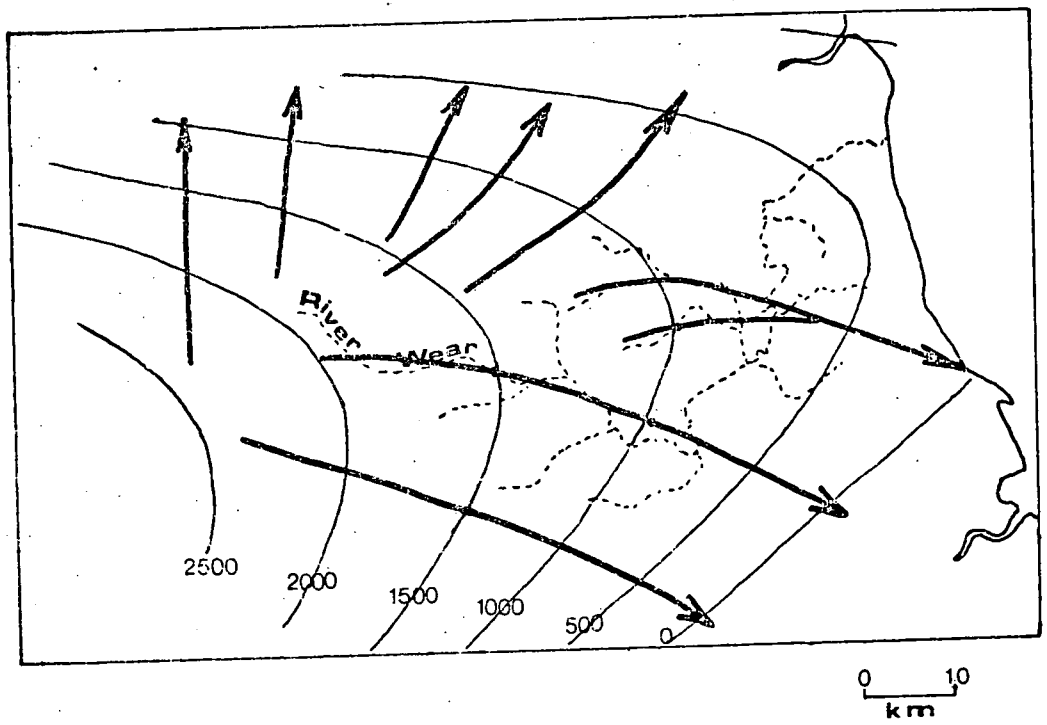


Fig. 8.5 Rookhope Basin Area: Geological Section



- quadratic trend surface contour lines (ft)
- - - - present river courses
- original consequents

Fig. 8.6 Quadratic Surface

Upper Weardale lay within the limits of the Saale* and Weichselian** glaciation of Britain (West, 1968) and there is clear evidence that ice has been present, but as yet multiple glaciation cannot be confirmed. Glacial action is shown by the presence of till deposits and striations but there are none of the major depositional landforms considered characteristic of glaciated valleys.

The general pattern of glaciation envisaged by Dwerryhouse (1902) (Fig. 8.7 A,B) is still accepted although, with more evidence from recent work, controversies have arisen. Basically, it is considered that Upper Weardale was occupied by a local glacier and the main watersheds remained exposed as nunatak ridges even during the period of maximum glaciation. There is disagreement about the height of ice cover, particularly as the field evidence is difficult to interpret. Raistrick (1931) (Fig. 8.8 B) supported the idea of nunataks and Trotter (1929) placed the ice shed during the main glaciation near the Upper Weardale watershed (Fig. 8.8 A), but Vincent (1969) considered that diffluence could have occurred at the western end of

*Wolstonian

**Devensian

(Mitchell, Penny, Shotton and West, 1973)

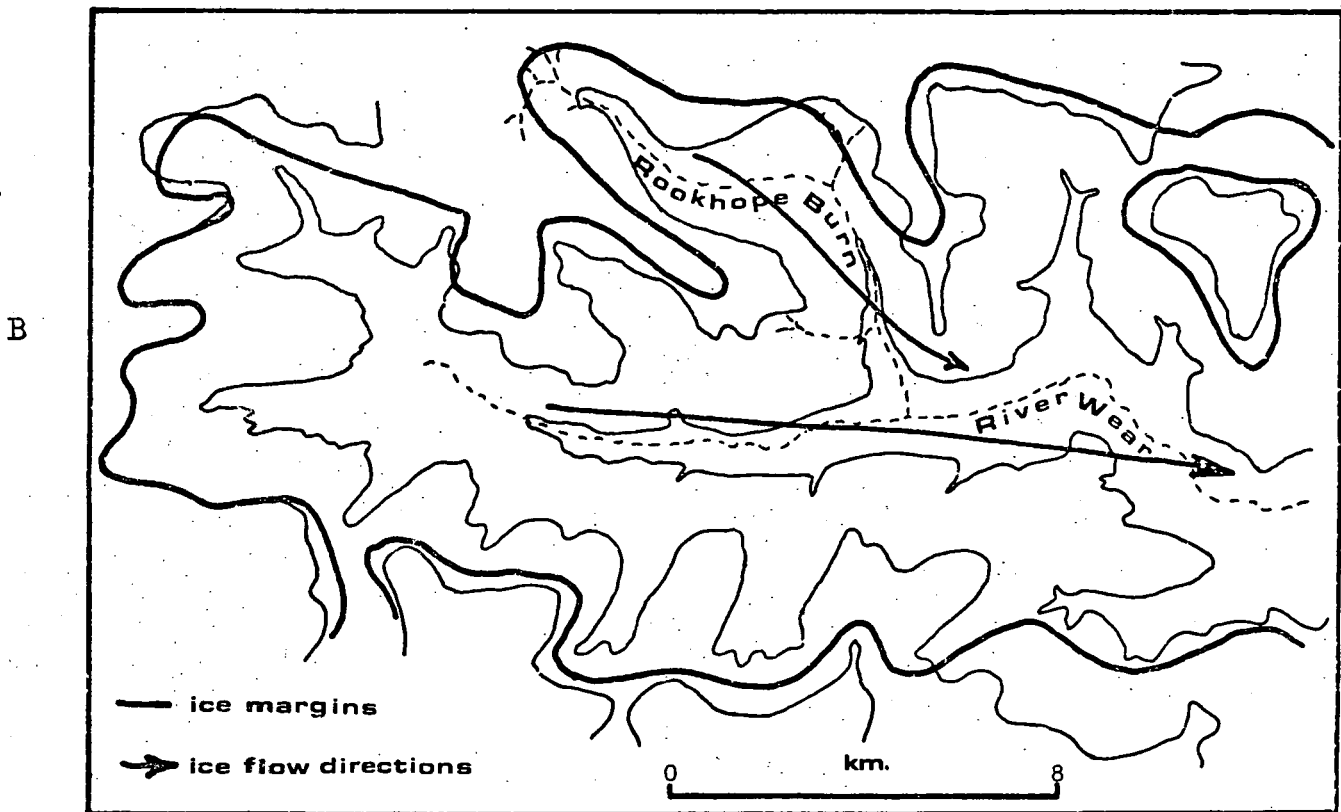
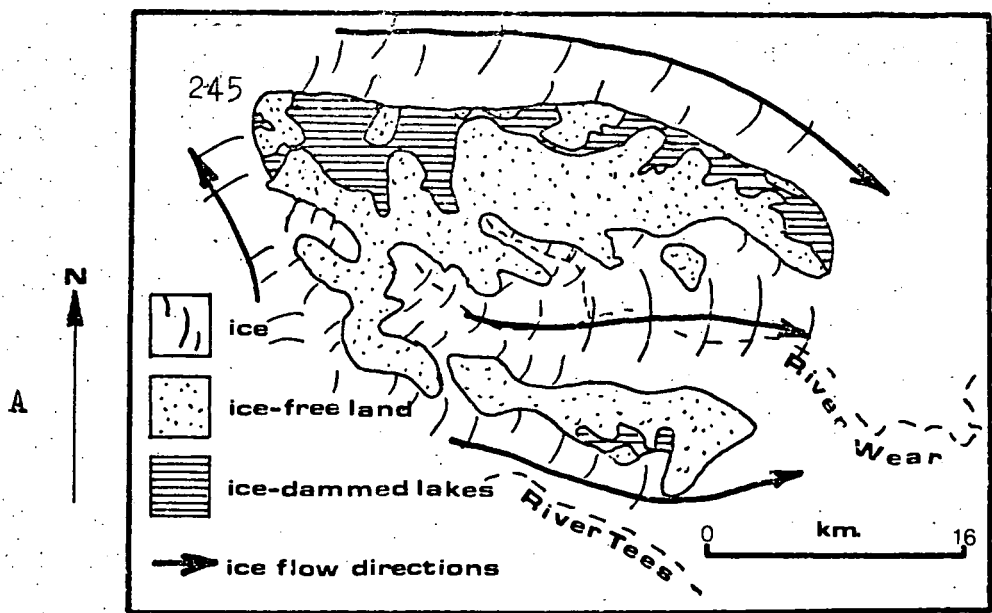


Fig. 8.7 Upper Weardale: Pattern of Glaciation
(after Dwerryhouse 1902)

- A Regional
B Local

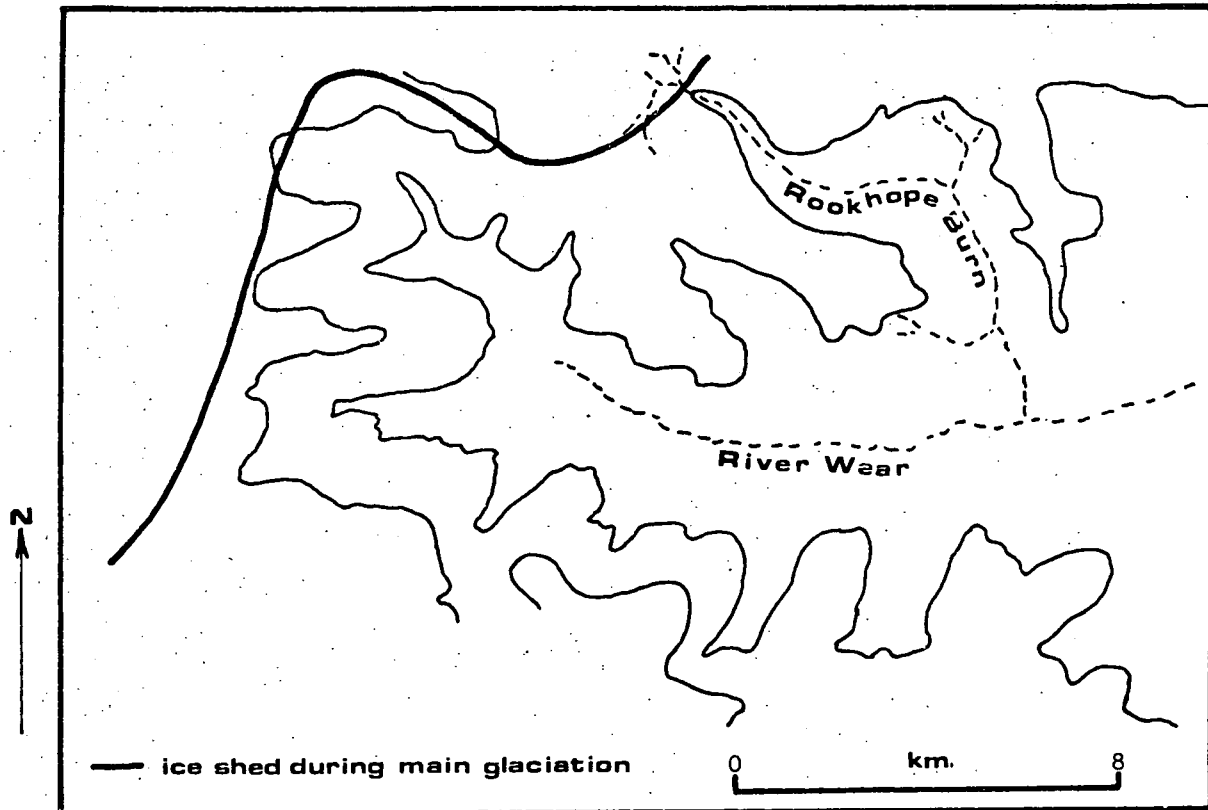


Fig 8.8A Position of Ice Shed (Trotter 1929)

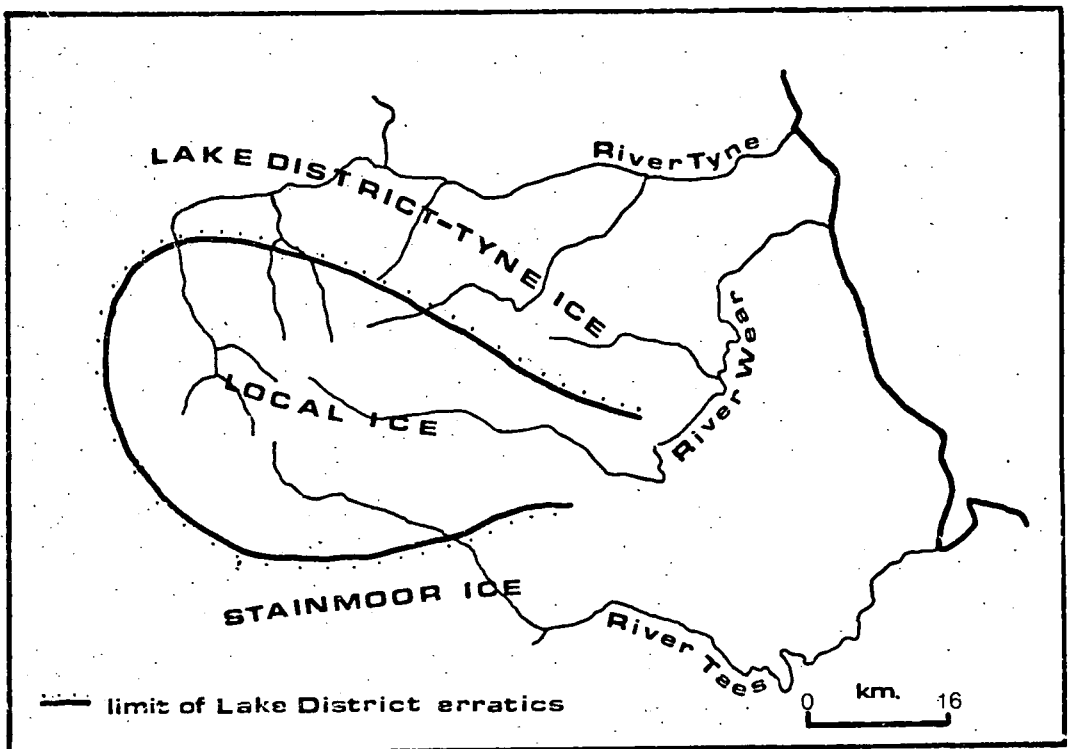


Fig. 8.8B Limit of Lake District Erratics (Raistrick 1931)

Weardale.

While Upper Weardale exhibits no landforms resulting from severe glacial erosion, the pronounced valley side benches are thought to have been accentuated by ice action (Trotter, 1929, Falconer, 1970). Atkinson (1968) described these features as dominant in the cross valley profiles and they illustrate clearly the geomorphological significance of the Carboniferous cyclothem. The interbedding of comparatively thin strata of resistant sandstones and limestones with less resistant shales and mudstones produces this characteristic relief.

During the late-glacial and post-glacial periods, intense periglacial activity must have prevailed in Upper Weardale, and Atkinson (1968) cited evidence of cryoturbation and solifluction. Using the dating for zones suggested by Godwin (1956), Atkinson tabulated the post-glacial chronology of Weardale.

Table 8.2. Weardale: Post-glacial Chronology

<u>Zone</u>	
VIII	Peat Erosion
VII	Peat Formation
V-VI	Birch 'Forest'
IV	Cryoturbation
III	Nivation Field
II	Cryoturbation
I	Cryoturbation

Two periods of cryoturbation were separated by intense nivation activity. Later, as the climatic conditions ameliorated, the development of birch forest and peat deposits attests to fluvial action.

Subsequent to this mass movement, colluviation and stream erosion have combined to modify the surface of Upper Weardale. The area is defined as a zone of 'active

frost' by Radforth (1962) and minor landforms resulting from slope instability are obvious throughout the area. Thus, a study leading to the assessment of rates of soil creep in such an environment is considered significant not only in itself but also in aiding the more detailed interpretation of the development of the Upper Weardale landscape.

Finally, the effects of man should be mentioned. In Weardale, mining and quarrying are particularly evident but the influence of grazing and changing patterns of land use must also be considered.

8.4. Soils

Since, even during the Pleistocene period, Upper Weardale was virtually a self-contained unit with little outside influence, the soil parent materials are local in origin. While stressing the intermingling and mixing which has occurred, Atkinson (1968) recognised five major categories of parent material: weathered rock, solifluction deposits, till, alluvium and spoil. Although spoil is not related to topography, the other four categories have a definite geographical distribution. The weathered rock, or upland regolith, is located on the higher ridges and interfluvies, solifluction deposits are found on slope sides, while till and alluvium are restricted to the lowest slopes and valley bottoms.

The upland regolith typically comprises two distinct layers: at the surface sub-angular rock fragments in a sandy matrix and below this fine sandy or silt loam with smaller angular fragments. Solifluction deposits exhibit variable characteristics over short distances, but consist essentially of a greyish silty clay matrix containing locally derived stone-sized fragments. It is severely gleyed either uniformly or in the form of ochreous mottling. The till is described as basically blue boulder clay with striated stones, but it is rarely uncontaminated. It is massive in structure becoming brown coloured and prismatic on drying.

Falconer (1970) has criticised this classification

as being limited in its geomorphological significance and too exclusive in distinguishing between solifluction deposits and till. However, his main concern was with the Pleistocene geomorphology of Upper Weardale and, as a basis for discussing soils, the categories described are particularly appropriate.

The soils developed in Upper Weardale have been classified and discussed in great detail by Atkinson (1968) and his remains the authoritative work on the subject. However, the completeness and complexity of the study militate against meaningful sampling, and for a background summary the synopsis provided by Stevens and Atkinson (1970) is preferred. It is sufficient to list Atkinson's taxonomic units.

Table 8.3. Weardale Soils: Taxonomic Units

<u>Division</u>	<u>Major Soil Group</u>
Organic Soils	a. Bog Peats b. Flush Peats
Sub-peat Soils	a. Podzolic sub-peat Soils b. Gleyed sub-peat Soils
Gley Soils	a. Ground-water Gleys b. Surface-water Gleys
Leached Soils	a. Podzols b. Brown Earths
Calcareous Soils	
Alluvial Soils	
Ranker Soils	

Using altitudinal and morphological limits similar to those governing the distribution of parent materials, the soils of Upper Weardale can be briefly described. Above approximately 615m, on the flatter watersheds and interfluves,

blanket peat predominates, varying in depth from 30cm to 270cm. Below this two sequences of mineral soil are recognised. On heavy textured, poorly drained deposits, the blanket peat is succeeded by Peaty Gley soils. These display a thinnish amorphous peat upper horizon and a gleyed blue-grey or grey mineral horizon which is commonly mottled. At about 431m Surface-water Gley soils replace the Peaty Gleys. These have a thin organic layer overlaying a saturated and intensely gleyed upper mineral horizon and a better drained, mottled lower horizon. In the valley floor Ground-water Gleys and Basin Peat occur.

The second sequence is developed on material with a high sandstone content and therefore free or imperfect drainage. Brown Earths, showing little differentiation between horizons are characteristic of the lower slopes while podzols exhibiting clear evidence of leaching occur on the freely drained slopes above. The dry Calluna heathlands are underlain by Humus-iron Podzols. These soils have an acid humus layer above a bleached Ae horizon and a dark B horizon enriched by iron and humus. Under the Calluna-grass association, Iron Podzols with an iron rich B horizon are typical, while around the margins of the organic and gley soils, Peaty Podzols occur.

The other soils, developed on drift-free limestone strata are Rendzina and Brown Calcareous soils. However, since the outcrops are linear and generally thin, most are mantled by superficial deposits, and such soils are not common in Upper Weardale.

Jenny (1941) formulated five independent variables in soil formation and these can be used as a summary. In such a small area, there are unlikely to be significant variations in time, particularly as there is no evidence of relic soils. It can be assumed therefore that development has occurred over the last 12000-15000 years (Manley, 1942). Parent material has been discussed in some detail and the main impression must be of complexity, with a range of surface deposits on a series of contrasting and generally thin rock outcrops. These deposits are largely controlled by topography, and clearly there is a relationship between

drainage and slope angle. Variations in the thickness and characteristics of the organic horizons have been noted but with such an acid environment the activities of soil fauna must be limited. Finally, while the overall climate must be similar throughout Upper Weardale, precipitation and wind speed will increase with altitude. Bryan (1967), referring to the Central Pennines, considered climate to be the most important factor and under similar drainage conditions it is possible to envisage a climosequence from Sol Brun Acide through Brown Podzol to Iron Podzol and Humus-iron Poszol.

8.5. Climate

Since the climatic variable is considered so significant, a short summary of regional characteristics should be included and the three elements: precipitation, temperature range and wind speed, provide an appropriate framework. Data for the area are scanty, but evidence suggests that Upper Weardale shows sharp contrasts over short distances, depending upon altitude, aspect and exposure. Records are kept at Moor House (556m), the Nature Conservancy Station, on the eastern side of Cross Fell beyond the head of Weardale and these may be contrasted, where necessary, with those from the Durham University Observatory (102m). Atkinson (1968) also quoted results obtained at the Laneheads Field Centre during the 1960-61 season.

The effects of altitude and exposure to the prevailing south-westerly winds, are apparent from the distribution of precipitation. On the higher parts of Upper Weardale totals approach 1650mm falling to approximately 875mm at the eastern end of the dale section. Distribution tends to be even throughout the year although there is a discernible maximum. The number of raindays varies from approximately 220 in the west to 180 in the east. The heaviest snowfall occurs with northerly and easterly winds so that Upper Weardale is particularly susceptible. The snow-cover gradient again shows a marked correlation with altitude, averaging some 80 days in the west and 30 days in the east.

Temperature records for the area are even more sparse and it is only possible to make general observations. Statistics available indicate a pattern of cool summers

and cold winters which can be illustrated by recordings made at Nenthead (450m):

Mean January 0.5°C

Mean July 12°C

It has been shown that temperatures at Moor House are similar to sea level values recorded some 10° of latitude further north (Smith, 1970). Certainly on the higher slopes of Upper Weardale minimum air temperatures can fall below freezing point in every month of the year. The growing season, delimited by a mean monthly temperature of 6.1°C , lasts for some 7.5 months in lowland Durham but is reduced to 5.5 months at a height of 500m. The differences can be seen by comparing the mean monthly soil temperatures at 30cm depth (1963-68) for Durham and Moor House.

Table 8.4. Mean Monthly Soil Temperatures (depth 30cm):
Durham and Moor House

$^{\circ}\text{C}$	<u>January</u>	<u>February</u>	<u>March</u>	<u>April</u>	<u>May</u>	<u>June</u>	<u>July</u>
Durham	2.5	2.8	4.5	7.1	10.6	14.2	15.2
Moor House	1.3	1.3	1.8	3.6	6.6	10.3	11.4

$^{\circ}\text{C}$	<u>August</u>	<u>September</u>	<u>October</u>	<u>November</u>	<u>December</u>	<u>Year</u>
Durham	15.3	13.8	11.0	7.0	3.9	9.0
Moor House	11.5	10.0	7.8	4.5	2.4	6.0

Atkinson (1968) related length of growing season to altitude quoting a decrease of 10 days for every 75m. Mean wind speeds also reflect altitude, velocities being recorded in Upper Weardale which can be twice those of the lowlands to the east. This can be illustrated if the monthly readings for Moor House and Durham are contrasted.

Table 8.5. Mean Monthly Wind Speed: Moor House and Durham

<u>knots</u>	<u>January</u>	<u>February</u>	<u>March</u>	<u>April</u>	<u>May</u>	<u>June</u>	<u>July</u>
Moor House 556m	16.2	15.9	16.0	13.5	13.2	11.9	11.1
Durham Obs. 102m	8.8	8.8	9.4	8.3	7.1	6.1	5.8

<u>knots</u>	<u>August</u>	<u>September</u>	<u>October</u>	<u>November</u>	<u>December</u>	<u>Year</u>
Moor House 556m	11.6	12.3	13.5	13.7	15.7	13.7
Durham Obs. 102m	5.9	6.0	6.6	7.2	8.8	7.4

Thus the increasing severity of climate with altitude is demonstrated by the three elements described. It affects pedogenesis through such aspects as leaching and rates of organic breakdown and a climosequence of soils has been suggested. It is also reflected in the vegetation pattern and since the distribution of the different communities is important in the present study, this aspect of the background must be discussed.

8.6. Vegetation

Climate and vegetation both exercise an influence on soil formation (Jenny, 1941) and in a study of soil creep both must therefore be considered. While it is realised that no total understanding of vegetation distribution can be achieved without recourse to the past, Atkinson (1968) and Bellamy (1970) provide detailed coverage of this subject. It is proposed therefore to describe briefly the present pattern which in common with soil and climate displays marked changes over short distances.

The vegetation of Upper Weardale belongs to an Oak-Scots Pine-Birch Heath and/or Moor association and occupies a regional site which would, under natural conditions, show

a sequence from oak woodland to montane peat and wind-eroded heath (Atkinson, 1968). This present pattern is influenced by a number of factors, particularly the sharp changes of relief and differences in microclimate, together with variations in slope, parent material and drainage.

Based on a simple four-fold division (Pearsall, 1950) the major communities as given by Atkinson (1968) are listed.

Table 8.6. Weardale Vegetation: Major Communities

1. Grasslands	1. Meadow Pastures
	2. Agrostis - Festuca
	3. Nardus
2. Woodlands	1. Mixed Deciduous
	2. Betula
	3. Pinus
	4. Spruce
3. Heaths	1. Calluna-Eriophorum-Vaccinium
	2. Calluna-Eriophorum
	3. Calluna-grass heath
	4. Calluna-Juncus squarrosus
	5. Calluna-Nardus
	6. Pteridium
4. Moorland	1. Sphagnum Bog
	2. Juncus squarrosus Bog
	3. Juncus effusus Bog
	4. Cotton grass Bog
	5. Molinia Bog
	6. Mixed Wet Bog
	7. Molinia-Cotton Grass
	8. Cotton Grass-Vaccinium
	9. Erosion Complex

The other major influence on the vegetation mosaic is that of man, indirectly through such factors as air pollution and directly through agriculture, forestry and extractive industry. In fact the level of air pollution over Durham City has declined noticeably throughout the 1960's (Smith, 1970) and its influence on vegetation is probably less marked than in the Central Pennines (Edwards, 1962). Grazing is significant not only in its relationship to erosion but also in promoting leaching (Pearsall, 1950). Furthermore parts of Upper Weardale higher slopes are being drained and reclaimed for agriculture or forestry.

Thus the vegetation pattern can be seen as dynamic, altering in response to a number of complex and interrelated factors.

8.7. Rookhope Basin

The experimental area comprises a comparatively low and regular interfluvium between two small streams which drain into Bolts Burn (Fig. 8.9). It covers an area of 15 hectares measuring 600m from the watershed to the outlet. In altitude it rises from 367m to 487m, giving a range of 120m (Plate 8.1).

The area is mainly underlain by Carboniferous mudstones although the dominant features are three small but well defined scarps (Plates 8.2 A,B,C,D). On the Institute of Geological Sciences Sheet 25 (1965) these are shown as being composed of sandstone, while above them the conjectured position of the Upper Fell top Limestone is marked. At the lowest point of the basin the Firestone Sill sandstone occurs (Plate 8.3). According to Holland and Lambert (1970), who include a map of the solid geology at Rookhope in their discussion on Weardale Granite, the Upper Fell top Limestone is included but between this and the Firestone Sill sandstone, near the basin outlet only one outcrop of sandstone occurs, the Lower Slate Sill sandstone (Fig. 8.10). Field evidence from the sandy nature of the deposits would seem to indicate that the three clear scarps are formed from sandstone.

The resulting slope profiles therefore provide obvious instances of the benches so typical of Upper Weardale, which

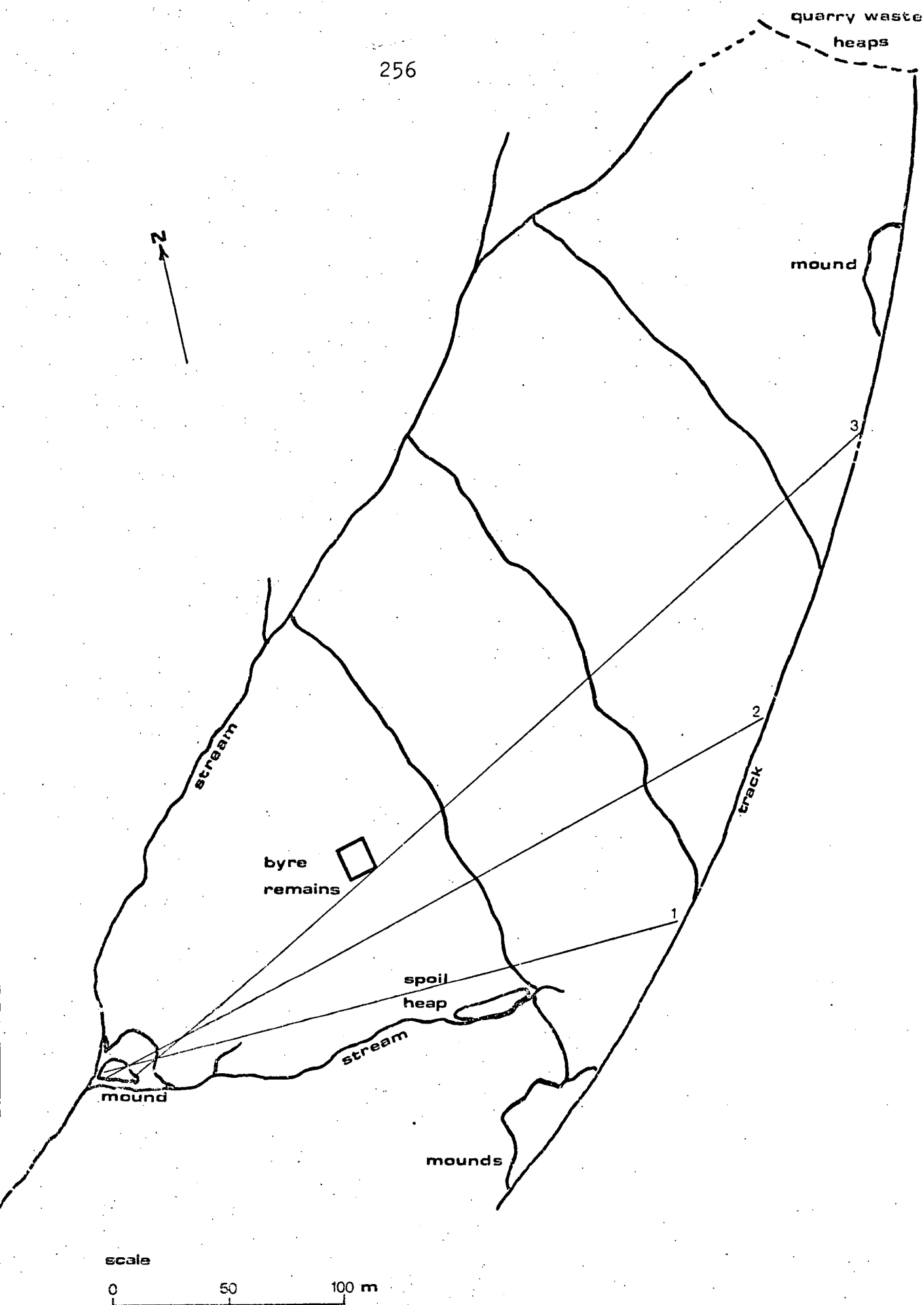


Fig. 8.9 Rookhope: Main Features and Profile Lines

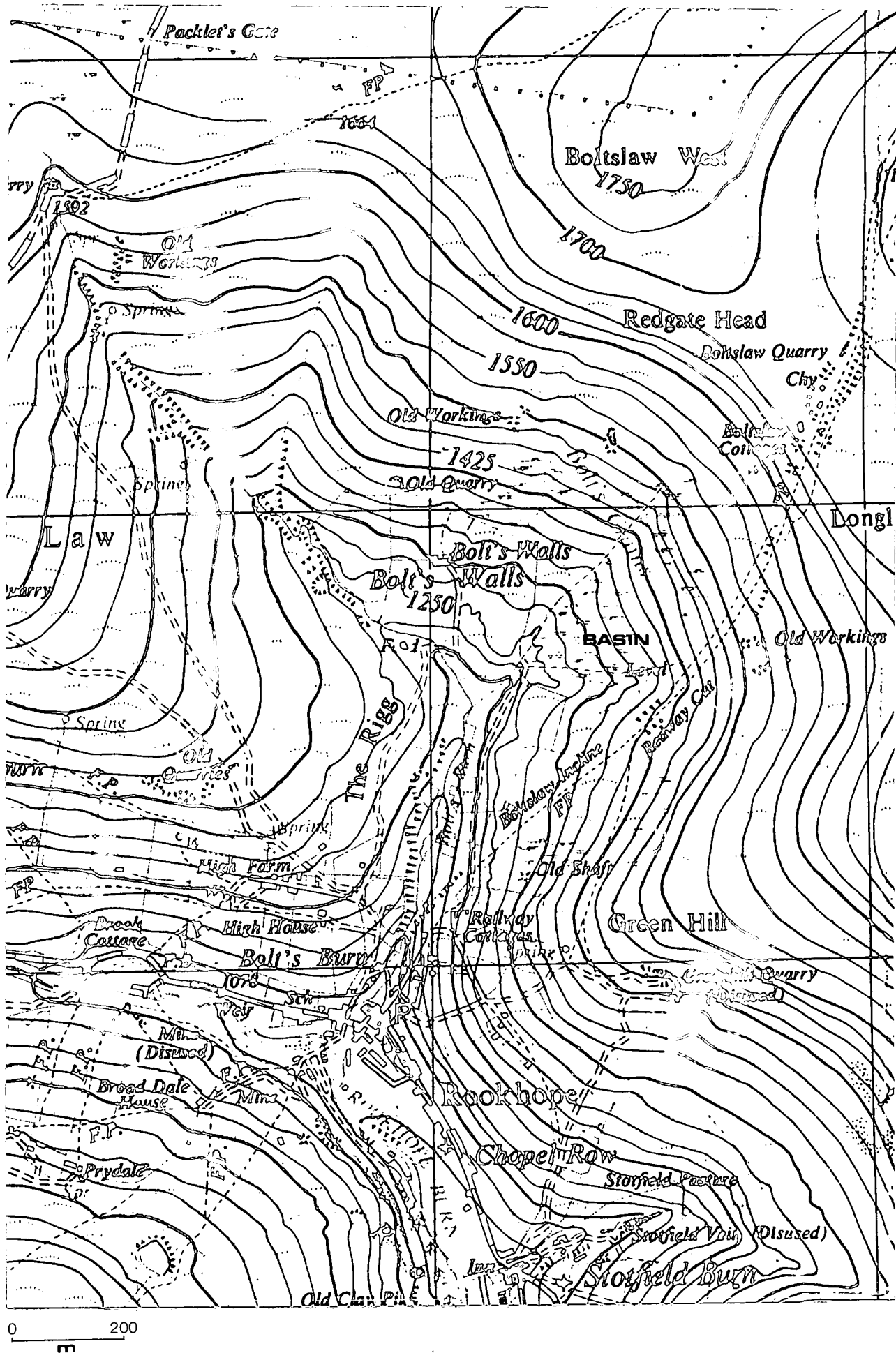


Plate 8.1

Rookhope Basin: Topographical

A



B



Plate 8.2

Rookhope Basin from:

A the west

B the south-west

C



D

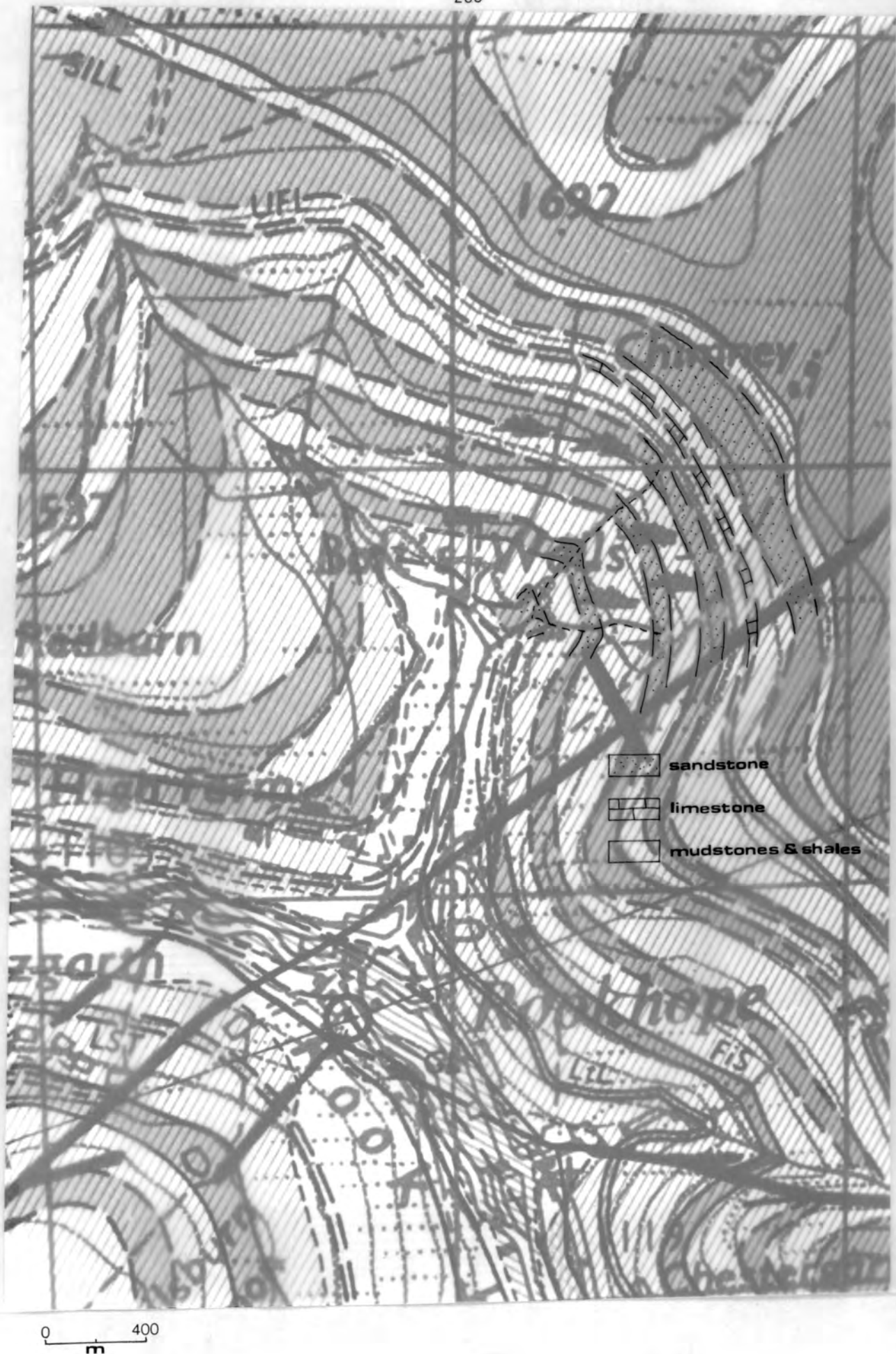


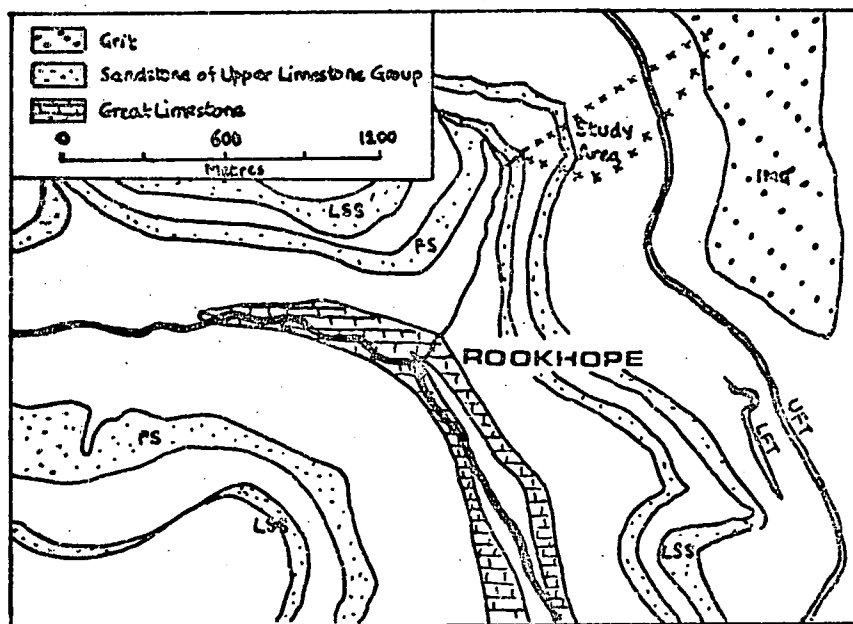
Plate 8.2

Rookhope Basin from:

C the south-east

D the east





UFT	Upper Felltop Limestone
LFT	Lower Felltop Limestone
LSS	Lower Slate Sill Sandstone
FS	Firestone Sill Sandstone
IMG	1st. Millstone Grit

Fig. 8.10 Rookhope: Solid Geology
(after Dunham et al 1965)

were discussed earlier. The more resistant sandstones form the scarps while the gently sloping tops are based on shale. To illustrate this, three profiles were measured from the mine railway embankment to the outlet (Fig. 8.9) each comprising angular readings made over a ground surface length of 1.52m using an adapted Pitty pantometer.

Table 8.7. Rookhope Basin: Slope Profiles

<u>Profile number</u>	<u>Number of readings</u>	<u>Mean slope angle ($^{\circ}$)</u>
1	265	10.6
2	312	10.8
3	390	10.6

It can be seen that the mean slope angle is very uniform and, to compare the profiles, it was decided to plot them using a dimensionless Y co-ordinate and 200 equal increments in the X co-ordinate so that they were the same length (Fig. 8.11 A,B,C). Finally, the similarity is again obvious in the histograms illustrating the relative frequency of slope angle classes (Fig. 8.12 A,B,C). Thus, topographically, the experimental area appears extremely uniform transversely across the basin, facilitating control in the layout of plots and other experiments.

Since the area is an interfluvium rather than a basin, other morphometric variables concerned with shape (Gregory and Walling, 1973) are not considered appropriate.

From its position, mean slope and altitude, the area is within the zone categorised by Atkinson (1968) as having solifluction deposits. It also exhibits areas of poor drainage and sandstone outcrops and therefore a marked variability of soils would be expected. Characteristics of the soil types affecting rates of soil creep are discussed in detail later and it is sufficient to state that examples from both sequences occur. The altitudinal range of the basin places it across the boundary indicated as dividing Peaty Gley soils from Surface-water Gleys (Plate 8.4) and

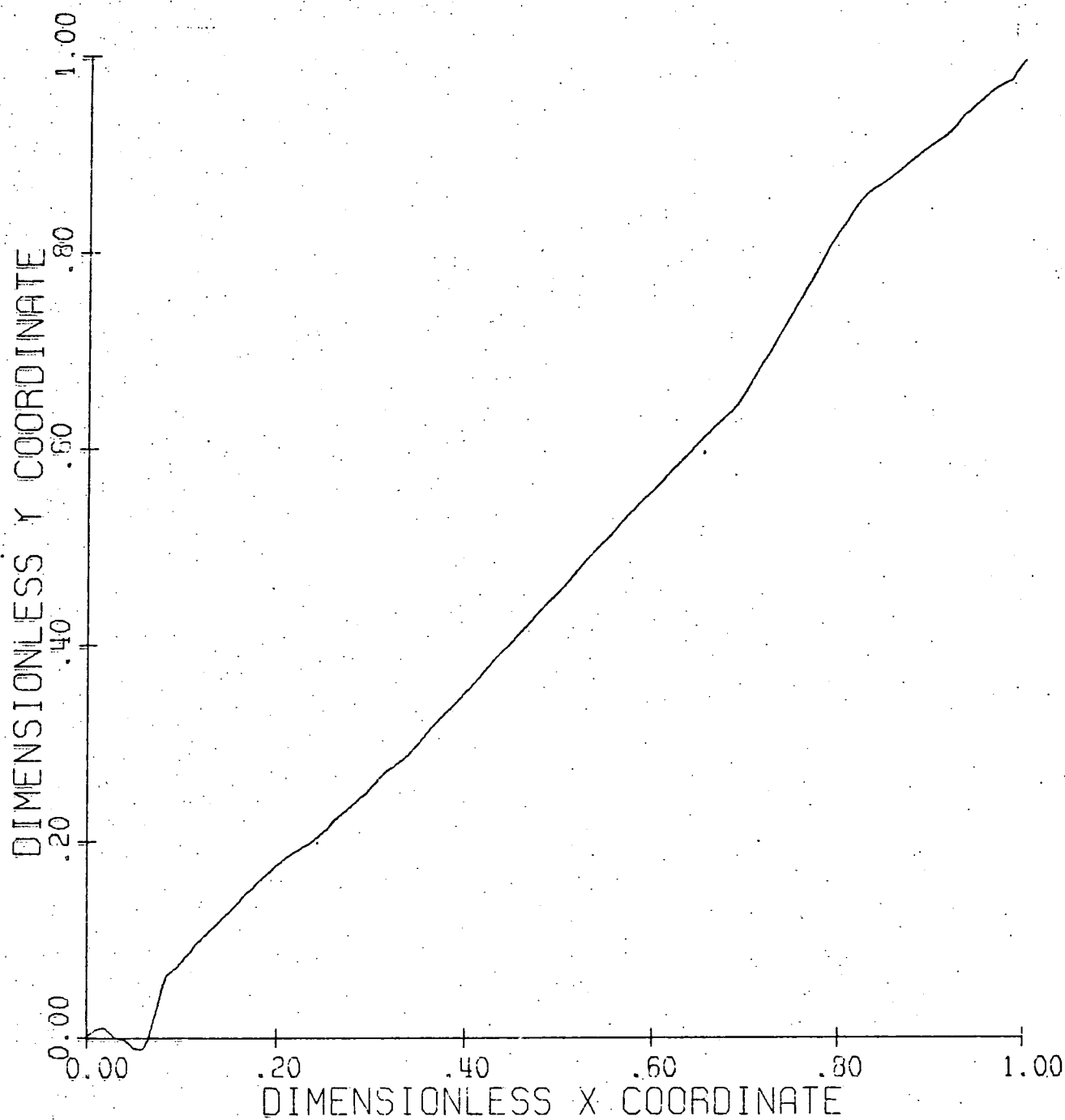


Fig. 8.11 A

Slope Profile 1

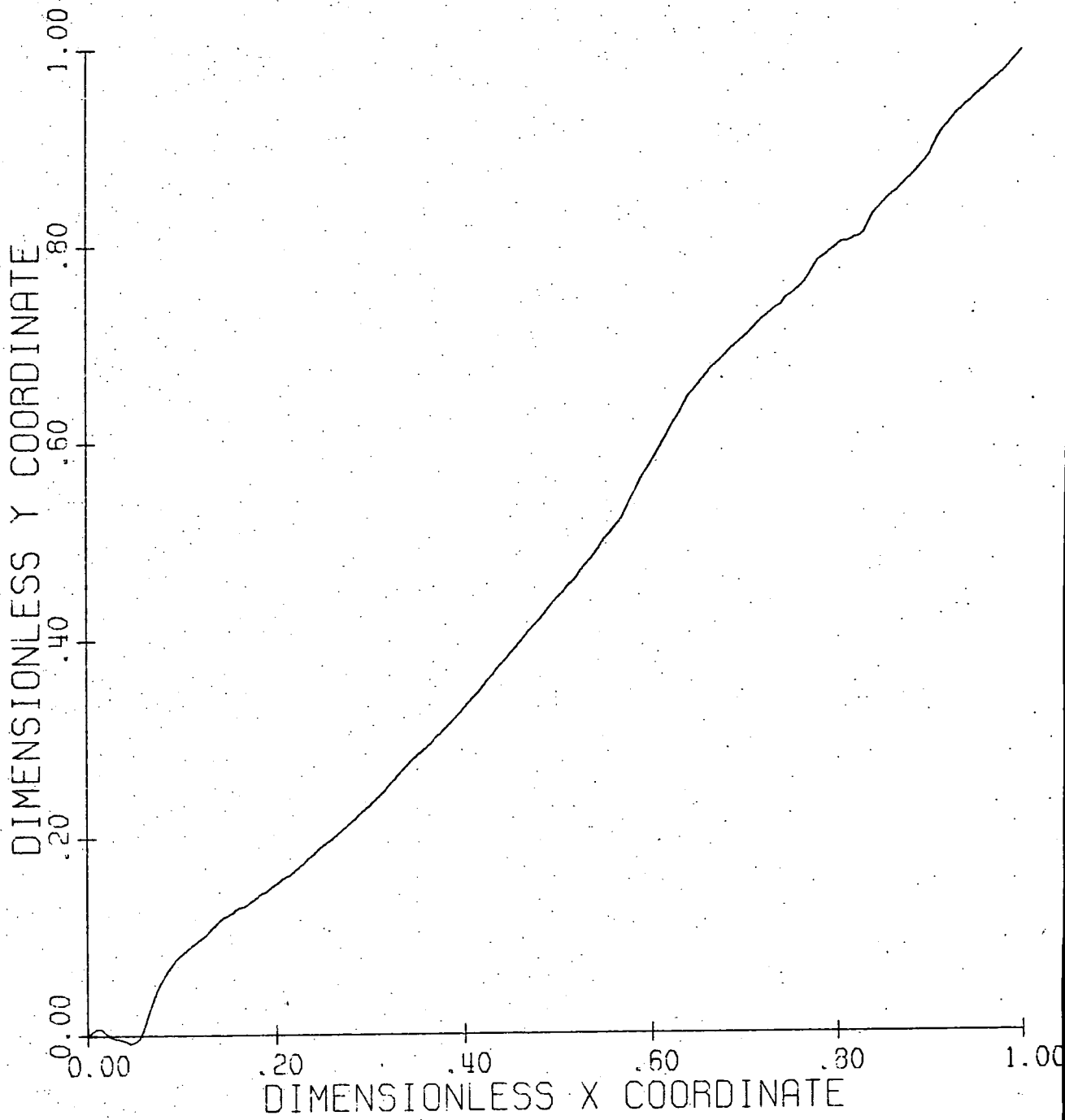


Fig. 8.11 B

Slope Profile 2

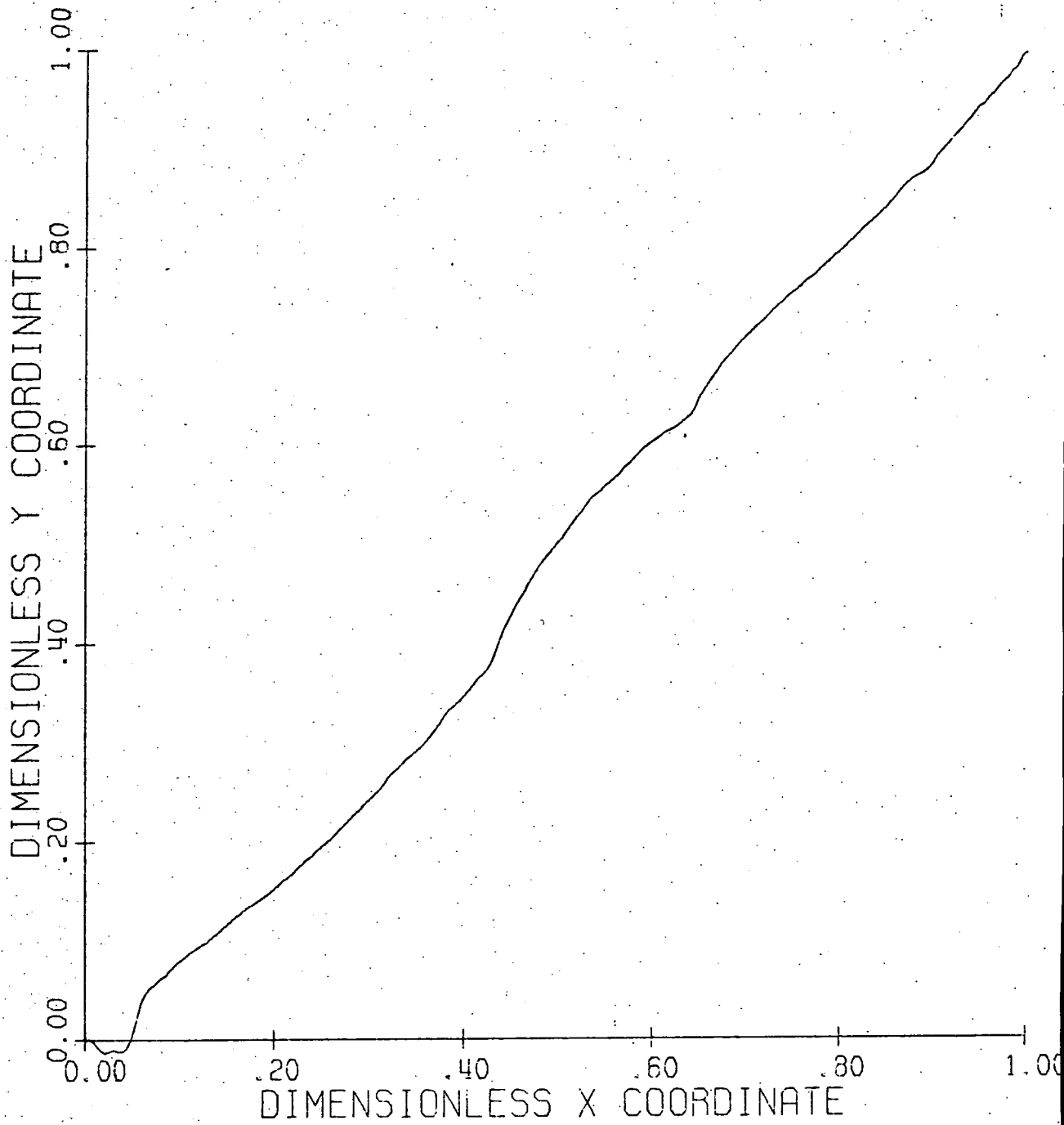


Fig. 8.11 C

Slope Profile 3

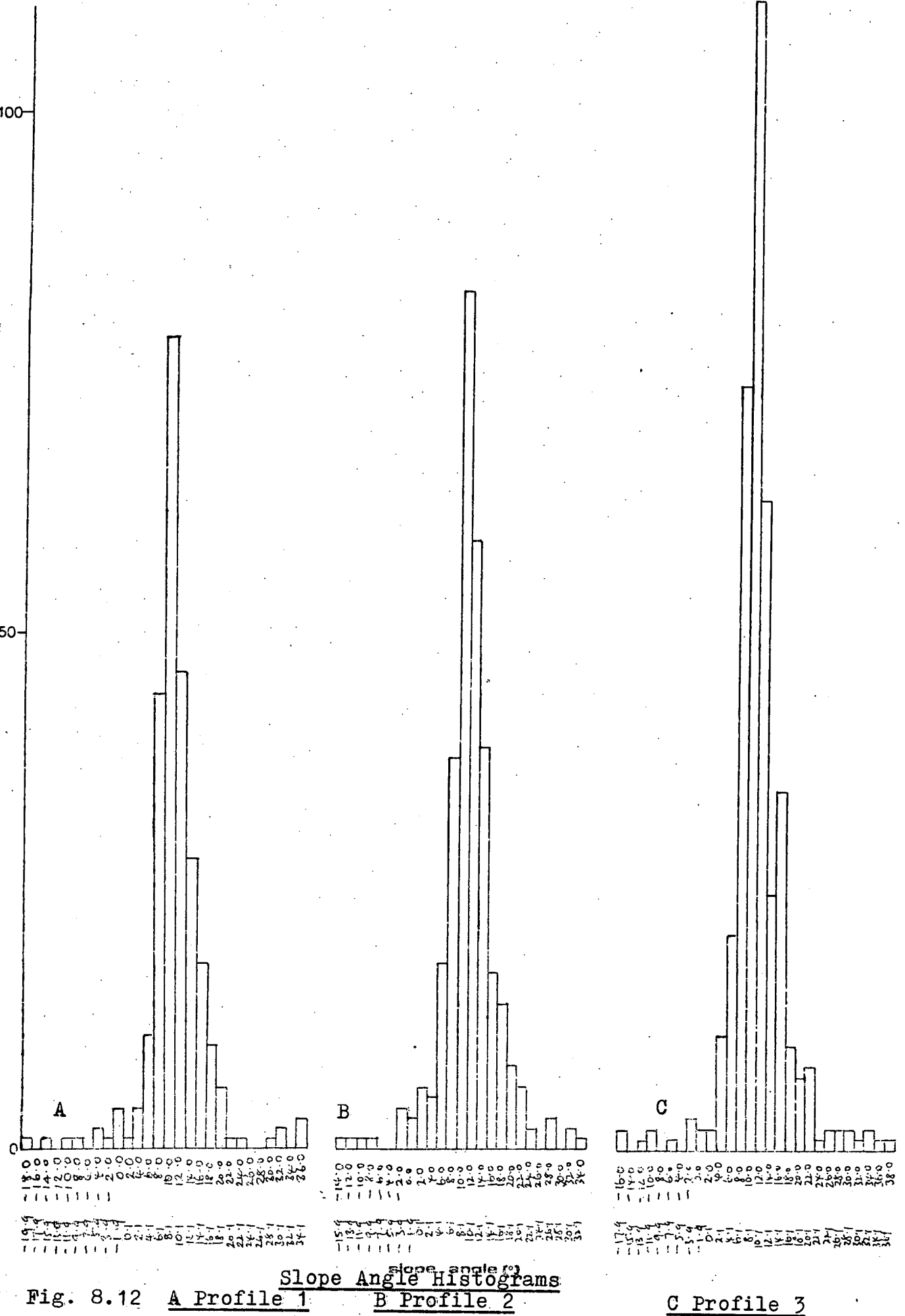




Plate 8.4 Surface-water Gley



Plate 8.5 Iron Podzol



Plate 8.6 Peaty Podzol

these types can be distinguished. On the drier areas Iron Podzols (Plate 8.5) and Peaty Podzols (Plate 8.6) are developed.

In the present study, involving particularly the effects of soil moisture, the important point would seem to be the organic proportion in the profile rather than any refinement of classification; for humus is capable of absorbing large quantities of water thus increasing the water holding capacity of soils (FitzPatrick, 1971). Therefore, in the field measurements, emphasis is placed upon the variation in this proportion, as shown by organic depth and organic percentage. It is realised that the properties of the different types of organic matter in the basin will vary (Farnham and Finney, 1965) but it is intended to measure in each case the characteristics of relevance to this study rather than infer them from a classification.

Finally, mention must also be made of spoil as a parent material, since measurements of creep rate were made on the tip within the basin (Plate 8.7).

Since climatic data relating to wetting and drying and also freeze-thaw were available locally and are examined in the study, it is not necessary to include details in this background summary.

The vegetation communities represented in the basin also form a major element in the analysis of factors affecting creep rates. With local variations in soil type and drainage, there are sharp changes in the mosaic over short distances, but basically three communities can be discerned: Nardus, Pteridium and Juncus squarrosus bog. (Plate 8.8, Fig. 8.13). All three occur on the gentlest and on the steepest slopes, but the Nardus grassland shows the greatest tolerance of drainage conditions. On drier sites it is associated with Iron Podzols and shows a sparse admixture of Calluna while in wetter areas it is underlain by Peaty Podzols and even Surface-water Gleys and is accompanied by mosses and sometimes Sphagnum. The Pteridium heath occurs everywhere on dry slopes with thin Iron Podzols while the Juncus squarrosus bog is limited to the wetter parts of the basin in which the Peaty Gleys are also developed.



Plate 8.7

Spoil Heap



Plate 8.8

Rookhope Basin: Aerial View showing Vegetation

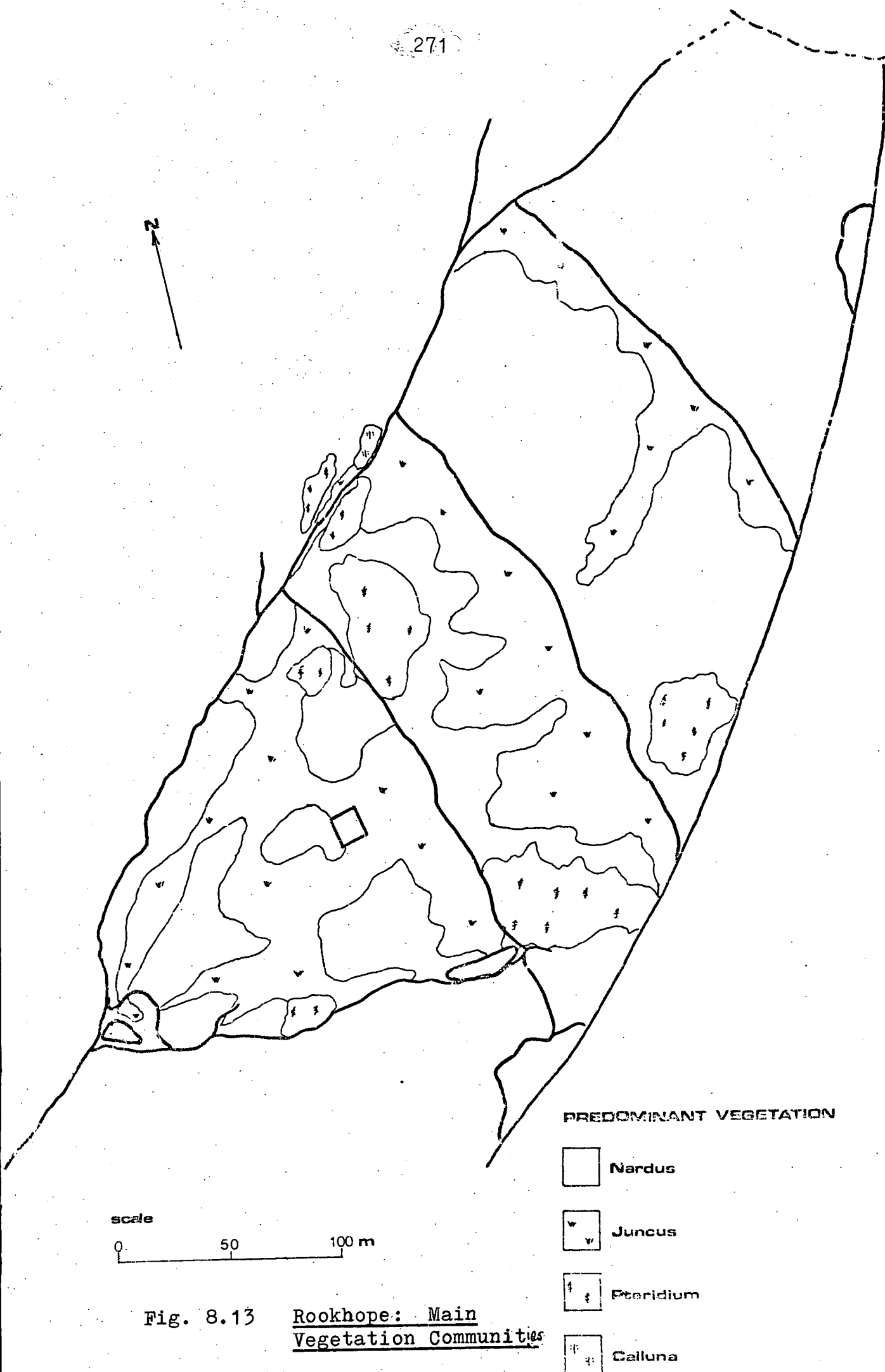


Fig. 8.13

Rookhope: Main
Vegetation Communities

It can be concluded that the Rookhope Basin contains within a small area a marked variety of topography, soil and vegetation. However there is, as explained, a clear uniformity within the diversity and therefore it is possible to exercise some control while monitoring the required variables.

CHAPTER NINE

INSTRUMENTATION OF ROOKHOPE BASIN

9.1. Introductory

9.2. Pilot Programme

9.3. Main Study Programme

9.4. Procedure

9.5. Plot Disposition

9. INSTRUMENTATION OF ROOKHOPE BASIN

9.1. Introductory

The implementation of an experimental design involves testing conceptual models in the field. This includes the initial sampling of selected variables to allow an assessment of their importance in the overall system. Once this has been completed, plots and patterns of instrumentation can be selected in a more meaningful manner. Therefore, although there may be several stages, instrumentation can be seen as a complete process, developing during a study. Thus, rather than describe the arrangement of instruments and the results obtained for each experiment separately, it is felt that a clearer picture can be presented if the complete instrumentation procedure at the Rookhope basin is discussed in detail.

Before instrumenting the basin fully, it was decided that a pilot study should be completed together with a number of subsidiary plot investigations. It was felt that there would be several advantages in such a procedure:

- (a) A preliminary assessment of creep rates and their possible variations could be made.
- (b) The multi-variate problem of controls could be simplified by evaluating some factors separately.
- (c) Different methods of instrumentation could be used and compared.

9.2. Pilot Programme

The incised upper valleys of the two small streams provided suitable contrasting sites (Fig. 9.1). Both approximately 30m long and 5m deep with valley sides sloping at angles of between 15° and 32° . Also as soil depth averages 17.5cm in both basins and in each case exhibits a high sand content, it can be assumed that apart from the effects produced by differences of aspect and

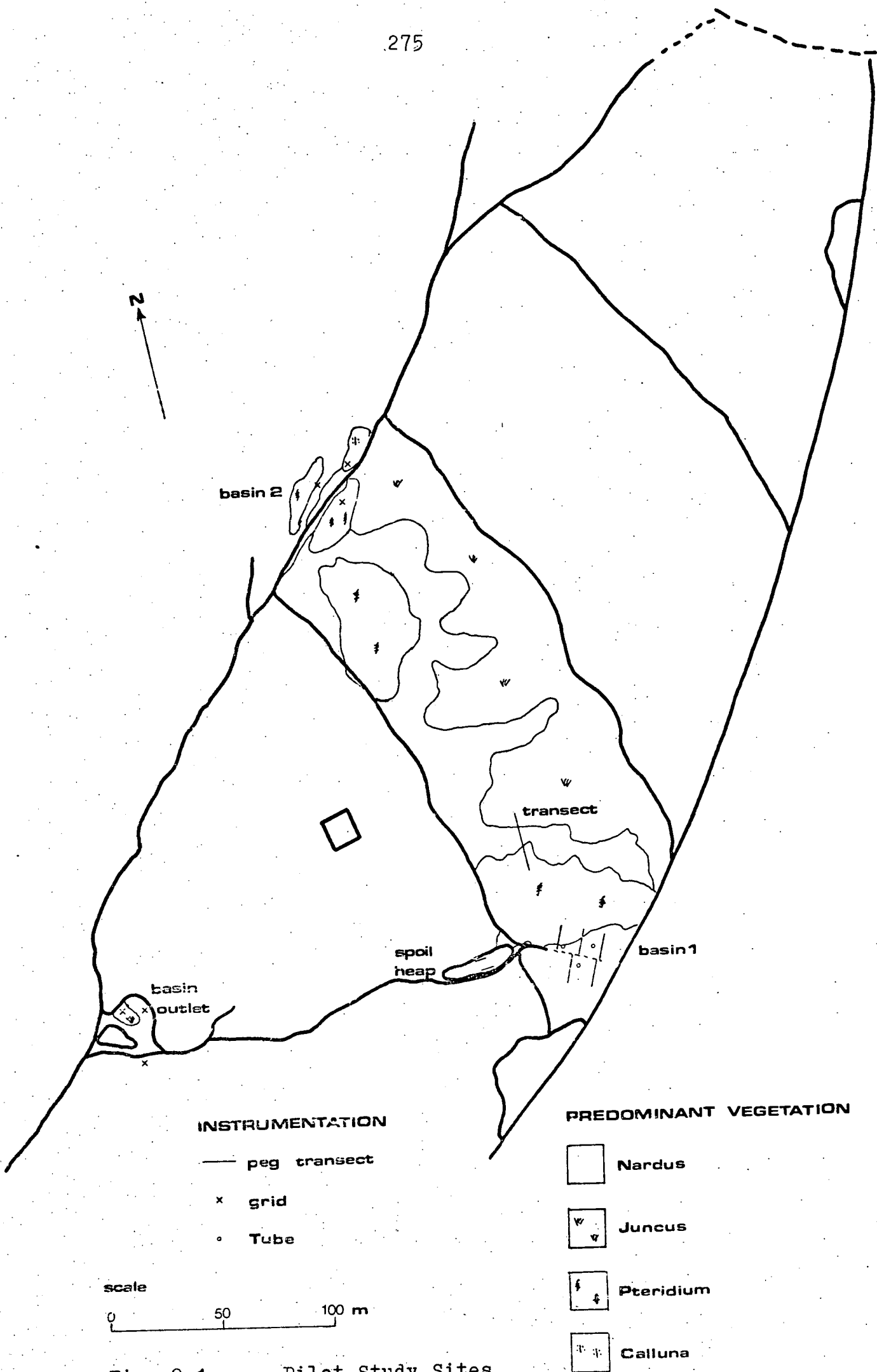


Fig. 9.1

Pilot Study Sites

vegetation, drainage characteristics will be similar.

Basin 1 lies in an east-west direction and has a narrow almost horizontal floor (Plate 9.1). The slopes are inactive at the base as the stream has been diverted underground into a former mining tunnel. The vegetation consists of a generally uniform covering of bracken (Pteridium aquilinum) with areas of mat grass (Nardus stricta). The aspect, allowing a comparison to be made between a north-facing and a south-facing slope, and the lack of significant variation in vegetation were important factors in the pilot study design. Furthermore the angle of the inactive valley floor was particularly suitable for the establishment of control points.

Basin 2 lies in a north-north-east to south-south-west direction and possesses a broader marshy floor some 6m wide, across which the stream flows (Plate 9.2). The slope bases are therefore more active and the vegetation consists of distinct associations of bracken (Pteridium aquilinum), mat grass (Nardus stricta) with a sparse admixture of bracken, and ling (Calluna vulgaris).

Bearing in mind the generally homogeneous nature of Basin 1, it was decided to select five random transects, divide each into three equal sections and insert a peg in the centre of each section. This resulted in three transects on the south-facing slope and two on the north-facing. A control peg was placed in the valley floor on as level a facet as possible at the end of transects 1, 2 and 4. Three Tube sites were also selected randomly, producing two south-facing and one north-facing Tube, one near the slope crest, one in mid slope and one at the slope base. One further addition was a set of six experimental flange pegs arranged 15cm apart in a line along the contour on a randomly selected site. The flanges, constructed of flat aluminium rod 6.3cm long, 2.5cm wide and 1mm thick, were bolted horizontally to the pegs, each at a different depth down the blade. Therefore it was possible to obtain a reading of the exaggerated creep rate at 2.5cm intervals from the soil surface to the peg base.

As Basin 2 exhibits clearly defined vegetation patterns, three unit sources or plots were selected by



Plate 9.1

Basin 1



Plate 9.2

Basin 2

stratified random sampling. Within each main association, the centre point of the plot was chosen, using random number tables. A grid was then constructed round this point and the positions for four pegs and a Tube allocated randomly. As the valley floor is clearly mobile, no control points were established.

While these two basins allowed some preliminary comparisons of aspect, vegetation control and sampling design, it was thought essential that measurements should be obtained for certain of the other variables. Furthermore as the study is concerned with rates of mass movement, a guide as to losses at the base of the main study watershed, as near as possible to the outflow point, was considered necessary (Plate 9.3). Therefore a series of three plots was selected using the procedure which had been employed for Basin 2. The area includes slopes with angles of between 15° and 30° , a soil depth of between 17.5cm and 27.5cm and a variety of vegetation and drainage conditions. It was therefore possible to locate one grid on a predominantly heath-rush (Juncus squarrosus) covered slope, one on a mat grass (Nardus stricta) and one on an actively undercut bare slope. In each case four pegs were installed in a random pattern on the grid.

The lightly vegetated shale tip already mentioned as a factor in the site selection, lies east-west and slopes at 32° . Four pegs were installed centrally, two on the north-facing and two on the south-facing slope. It was intended that these, being at approximately the same angle as those described earlier, would provide an interesting comparison between creep rates on natural and on artificial slopes. Furthermore they represented a situation similar to that on the Etherow valley slopes and in the quarry in North Wales (Chapter 6).

Finally, to obtain a direct indication of the variation of movement with vegetation association on the main south-west facing interfluvial constituting the major experimental area, a transect was installed. This consisted of six pegs placed along the contour centrally on a 15° facet of distinct vegetation groups. Two pegs were inserted on the Pteridium association, two on the



Plate 9.3

Basin Outlet Site

Nardus and two on the Juncus. Thus it was hoped to obtain a contrast which eliminated slope angle and aspect factors (Fig. 9.1).

The establishment of this pilot programme extended over a period of almost six months, so that after the problems had been clarified and sufficient readings obtained, there remained some eighteen months for the main part of the study. The dates when readings were first obtained, together with a description of the main variables in each case, are given later (Chapter 10). In fact results continued to be taken from all but one of the pilot study plots until the end of the fieldwork period.

With this pilot programme it was felt that the main interfluvium could be instrumented more efficiently and effectively. Approximate rates of creep varying with such factors as vegetation type, slope angle and position on the slope would have been obtained and would provide a guide to the weightings necessary in the main experimental design. At the same time, this could also be improved by results from the various plot preliminary experiments.

9.3. Main Study Programme

Before the main interfluvium at Rookhope could be instrumented, it was necessary to examine carefully the available evidence. This consisted of the pilot study results produced over a rather limited time period together with readings obtained during the work on the preliminary plots. However, of equal concern was the theoretical approach in such an experiment, as it was realised that the effort in designing new techniques would be wasted by poor field application.

Readings from the plots on Bidston Hill and in North Wales indicated a direct relationship between creep rates and soil moisture. The possible controlling influence of vegetation was evidenced by results from the Rookhope pilot study. Contrasts between rates measured on the three plots near the basin outflow point at Rookhope clearly seemed attributable in a large measure to vegetation differences. However it is difficult to distinguish

between the effects of vegetation, soil and drainage, as the main plant associations studied tend to occur on distinct areas of soil with particular soil moisture characteristics. Slope angle does not appear as a discernible dominant factor on any plot or site, but as its relationship with creep rates is well documented, it was decided that it should be investigated further. Therefore from the fieldwork evidence it seemed that instrumentation should be directed towards an appraisal of the following factors: vegetation, distance from the watershed and slope angle. In addition, it was intended to evaluate overall basin losses by soil creep so that comparisons could be made with the results of other workers (Evans, 1974, Morgan, 1974, etc.). From sampling, it was established that there was a clear coincidence between vegetation and soil type, but at certain boundaries an overlap existed and could be instrumented in an attempt to separate these two variables. The other factor to emerge from this preliminary work was the marked similarity between the mean results from Basin 1 and those from the comparable plots in Basin 2. Although it is clearly a very small sample it was felt that the indication was sufficiently plain to allow the use of plots for the main interfluvium.

With this evidence, it was possible to begin constructing an experimental design bearing in mind the importance of:

- (a) obtaining as much information as possible for the work done
- (b) avoiding as far as possible non-orthogonality
- (c) avoiding designs which cannot be analysed (Gilbert, 1973)

If an attempt is made to separate the factors involved so that a two row matrix is produced, then with the differences in vegetation coverage and slope distribution, the result must be non-orthogonal. If however as a result of the close inter-relationships of the measured variables, each plot is regarded as a cell, then the proposed design does not contravene criterion (b).

The importance of considering the future analysis cannot be overstressed particularly as the likely problems are compounded by the notoriously heterogeneous nature of soil. This involves specifically the sampling pattern and the sample size. With regard to the pattern it is clearly desirable to employ a degree of randomization to lessen the significance of unpredictable variation. However there are many advantages in a design based on unit sources (Amerman, 1965). A unit source or plot is defined as a subdivision of a complex watershed which 'has a single cover, a single soil type and is otherwise physically homogeneous'. Ackermann(1966) based his work on elemental blocks 3m by 3m which were in no way isolated, while in the Hubbard Brook Experimental Forest, plots complement basin readings. With these basin units it is possible to exercise a greater degree of control and in a complex environment such as that of a watershed, distribution may well be considered more important than overall density. Therefore it was decided to use the randomized block method which has been described as the most generally useful and flexible experimental design (Heath, 1970). The area is divided into blocks, each as uniform as possible in respect of attributes considered important, and treatments are applied randomly within each block. A further aspect of control was the provision of specially sited control pegs at the head, middle and foot of the basin.

Consideration of ideas on sample size tended to reinforce the choice of this experimental design. There can clearly be no definite fixed density for instrumenting such an area and this must depend upon the research objectives. However the inherent lack of control already discussed can be overcome to a large degree by extensive replication, although constraints such as expense and time must also be taken into account. In the present study, with its accent on short term measurement, it was thought to be essential that all the instruments could be read during the limited time available on a winter day. The variations within the basin further accent this theme since the more heterogeneous the

population, the more intense the sampling rate should be (Reynolds, 1975B).

The basic problem was essentially one of assessing, within the constraints mentioned, the number of samples necessary to estimate the true mean within certain limits. Furthermore, as the statistical methods envisaged were based on the normal distribution, normality was also considered vital. With regard to the sample size, the accuracy of point measurements of creep rates must be considered at least limited (Reynolds, 1968), and therefore it is necessary to obtain a mean value for each reading. An added advantage of this procedure which covers the second point is that even when the distribution of individual values is not normal, the distribution of means of grouped values tends towards normality as the group size is increased (Heath, 1970). In fact if there are four or more readings within each group it may be assumed that the distribution of means will be near enough to normal for statistical methods based on the normal distribution to be used. These considerations would seem to vindicate the application of a design based on small sampling areas or plots selected by the randomized block method. With regard to actual numbers, Leopold (Evans, 1974) has stated that for accurate results at least 20 T bars would be necessary and this number served as a useful guide during the actual sampling procedure.

When a measuring instrument is placed in a system, there is likely to be a period of adjustment before consistent and valid readings can be obtained. Replication in time must also be borne in mind therefore, and it was decided that after an initial period, further instruments should be inserted to provide a guide as to the length of this period.

The procedure adopted can be summarized broadly in three stages:

- (a) Division of the watershed into blocks.
- (b) Random selection of a sampling area within each block.
- (c) Random siting of instruments within each sampling area.

9.4. Procedure

The basin was mapped by plane table intersection survey using three base lines. The ends of each base line and thirty other significant points indicating slope or vegetation changes were permanently marked by coloured pegs. Three regularly spaced transects were then measured down the basin using a Pitty pantometer, and from the resulting profiles histograms were constructed (Fig. 8.12). Using the map and profiles supplemented by evidence from aerial photographs the slopes were grouped into three broad angular categories and the approximate coverage of each main vegetation association calculated. Detailed sampling was then undertaken to check these details and also to assess the degree of coincidence between vegetation and soil type distribution.

As a result, it was decided that the sampling areas should be selected according to vegetation association, slope angle and distance from the watershed. The constraints on a free selection were the occurrence of a particular combination and the need to ensure comparability between the vegetation associations.

The following matrix resulted (Fig. 9.2).

Table 9.1. Plot Distribution according to Slope Angle and Vegetation Association

<u>Slope ($^{\circ}$)</u>	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
1-8	2	4	2
9-16	4	2	2
17-24	1	1	2

As was appreciated during site selection, the basin provides opportunities for paired blocks since the basic structure in the upper part is repeated in the lower. Furthermore this allowed the factor of distance from the watershed to be included virtually automatically. In fact consideration of this variable led to the selection

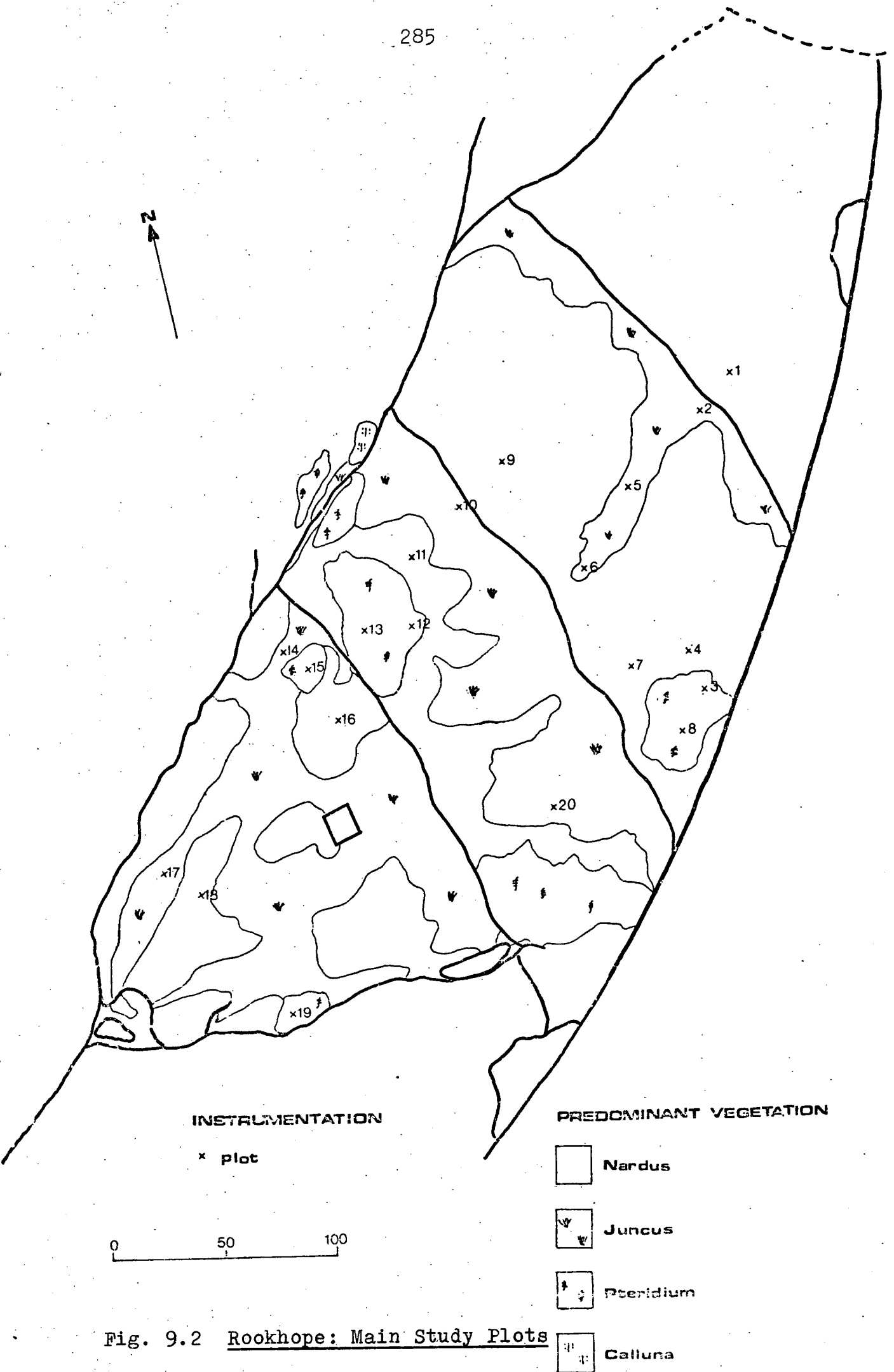


Fig. 9.2 Rookhope: Main Study Plots

of one extra area.

With the appropriate blocks for each cell chosen, the central point sampling area within each block was located randomly on the map and this position was translated into a field location using the coloured survey pegs and a tape. These locations were then checked by a resurvey.

A square grid of nine points was constructed round each surveyed central point leaving 60cm between each column and each row. This distance was taken as a compromise between the need for obtaining consistent results from as homogeneous an area as possible and the necessity to stand on the block and take readings from one instrument without disturbing neighbouring apparatus. This grid allows the installation of nine measuring devices in sufficiently close proximity that they can be considered as a sampling point, and it therefore facilitated an assessment of 'within-sample' variation. For investigating factors which involve the disturbance or removal of soil, a zone 120cm in width was measured round the basic grid on all but the upslope side. It was considered that random selection could be achieved on three sides and disturbance upslope would adversely affect the grid instruments. For example, drainage is obviously a vital factor and this is considerably altered locally when a soil pit is excavated. In fact this zone was used principally for soil pits and also for the installation of Young's Pits.

For the installation of instruments on the grid, the following procedure was adopted at each plot:

- (a) The nine sampling points were numbered with the top row (numbers 1, 2 and 3) being on the upslope side.
- (b) The sampling points were ordered using random number tables.
- (c) Pegs were inserted into the first four positions.
- (d) An Anderson's Tube was placed in the fifth position.
- (e) Two dowelling pillars, one for short term and one for long term measurement, were installed in points 6 and 7.
- (f) Point 8 was used for a Cassidy's Tube.

- (g) Point 9 was retained for the addition of one more peg which was later inserted to give a guide to the adjustment time, already mentioned.
- (h) Aluminium pillars were emplaced approximately 20cm upslope and downslope from the central rod of the Anderson's Tube (Plates 9.4 A,B,C.).

In the 120cm wide zone reserved round the grid, positions were generated by the random number tables, using as a basis all the grid points except that in the centre (number 5). The new positions were taken to be 60cm from the grid point located by the random number tables. Positions for points 1, 2 and 3 were measured upslope, and those for points 7, 8 and 9, downslope. Positions for points 4 and 6 were marked to the left and right respectively (Fig. 9.3). With these new positions identified, an aluminium peg and a sand pillar were placed in each plot. Using the same method, the three sectional tubes already mentioned were installed, one each in plots 14, 15 and 16. These particular plots were selected as they are close together and of similar slope angle but differ in vegetation cover. Instrumentation was completed by the addition of a Young's Pit in each plot, located approximately 60cm to the left or right or on the downslope side, the direction being determined by a die. It was felt that these pits should not be excavated on the upslope side as local drainage conditions might be altered.

During the latter part of the pilot study, three transects forming a series primarily designed to help evaluate the effect of slope angle were established. For this an area of Nardus interspersed with Carex spp extending across the major slope elements of the main watershed scarp was selected. The transects, each consisting of four pegs equally spaced at 30cm intervals along the contour, were located one on the 2° slope above the convex break, one centrally on the 20° scarp facet and one on the 8° slope below the concave break. Later the line was extended by adding two dowelling pillars, an aluminium peg, a Cassidy's Tube, a sand pillar and a further wooden peg, each inserted 30cm from the neighbouring device. The actual position, to left or

A



B



C



Plate 9.4

Instrumented Plots

A Plot 2; B Plot 3; C Plot 4

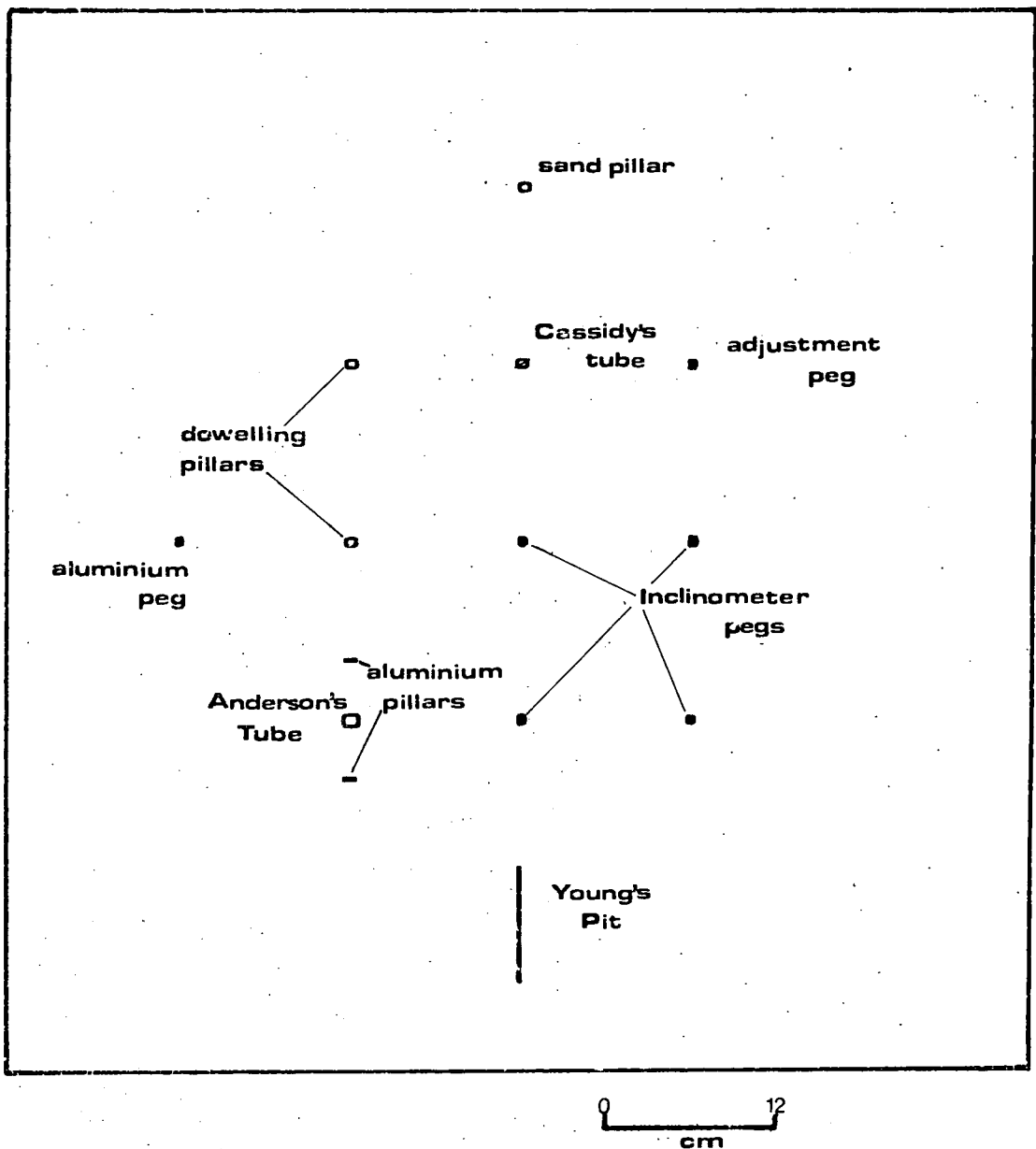


Fig. 9.3 Example of Instrumented Plot (plot 15)

right of the existing instruments was determined by die. On one extremity a Young's Pit was excavated while in the middle transect, across the steepest slope, an Anderson's Tube was also installed. On approximately the same line as the middle and upper transects, three Open Tubes were sited, one in each major vegetation association. Near each of these six positions, an area of vegetation measuring 20cm by 60cm was removed and two pegs were inserted in each of the resulting bare patches (Plate 9.5).

The total design was then completed by measuring devices placed away from the main blocks and transects. Three of the rods with associated 15cm nails were used to measure soil bulging immediately beyond the sharp break of slope at the lower end of the basin. It was thought that results from these might be compared particularly with those obtained from the Open Tubes. Nine 'boundary' transects, each consisting of from three to six pegs, were established across zones of sharp vegetation change to help separate certain of the factors affecting creep rates. Finally three summit facets with slope angles of under 1° were selected as control points and pegs were installed in each. These facets were located on small mounds selected to give altitudinal variation; at one of the highest points, at approximately the middle point and near the outflow of the watershed (Fig. 9.4).

Apart from the aluminium pegs, the wooden pegs used to indicate adjustment time and the transects previously established, instrumentation of the basin was completed in a period of approximately six weeks. The original sets of four wooden pegs required two sessions, but each of the remaining categories was totally installed in one day. The method of insertion has been described and the procedure for locating each device within the basin has been fully discussed. It should be noted that the only departure from this procedure occurred when pieces of rock in the soil prevented emplacement at a particular point. This occurred on blocks 3, 9 and 15 and the instruments were then placed as near as possible to their correct grid positions.



A



B

Plate 9.5

Excavated PlotsA Nardus plotB Pteridium plot

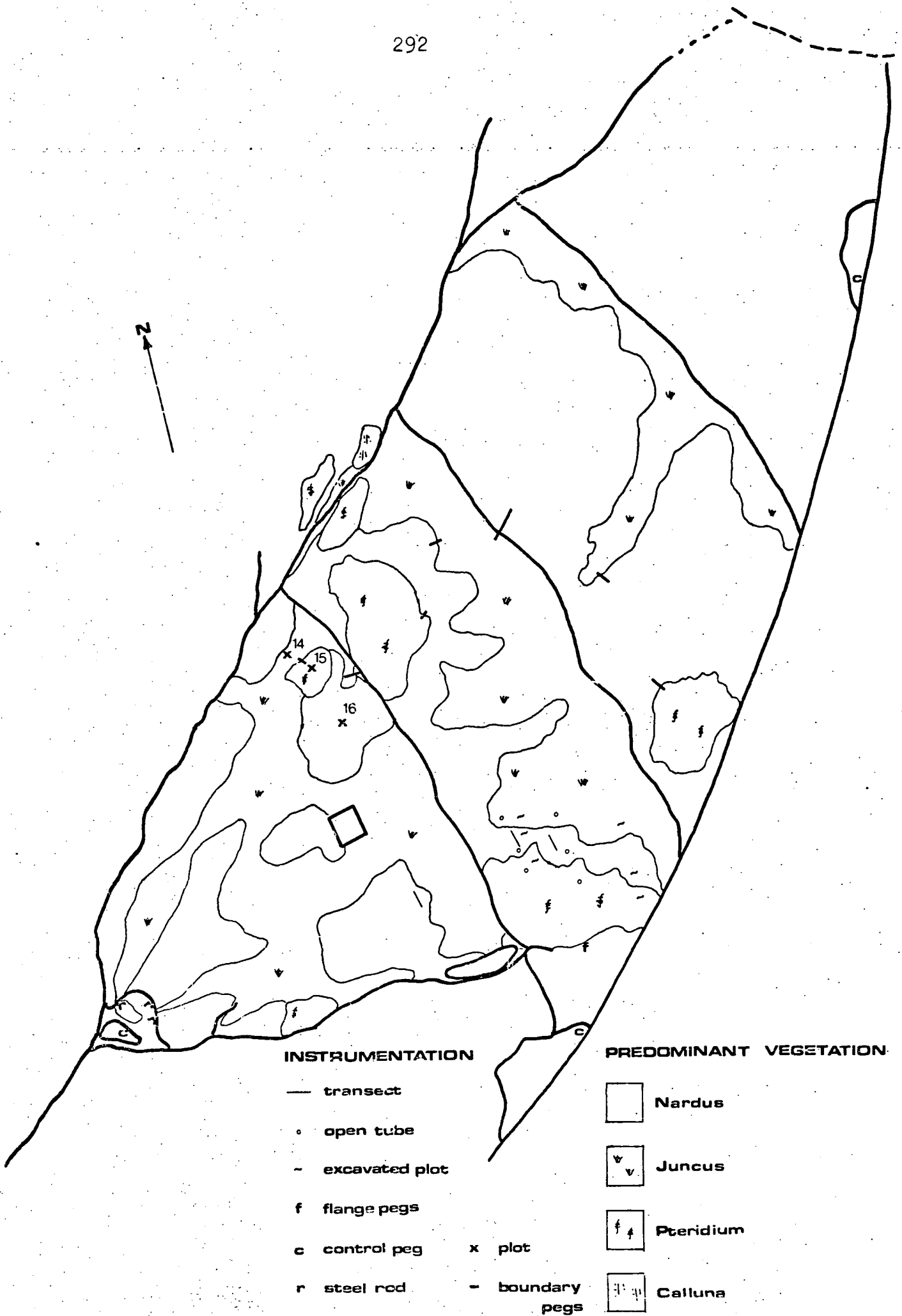


Fig. 9.4

Rookhope: Supplementary Study and other Experimental Sites

9.5. Plot Disposition

Rather than describe each individual block in detail, it seems more appropriate to indicate groupings with possible sources of comparison and contrast. The details of variables measured on each block are tabulated and analysed later and in this section it is intended to use only broad categories of morphology and dominant plant genera to illustrate the finalised experimental design.

From the watershed at its apex to its outflow point, the basin can be divided into four major transverse morphological units (Fig. 9.5). The highest area, unit A, consists of a gently convex element with only minor changes of angle. Below this, unit B is a well developed convex element grading from a clearly defined flattish facet at about 6° to a scarp of approximately 22° . Unit C is a somewhat larger scale repeat of unit B with much the same angular variation. Unit D comprises a faintly concave element ending at the final short scarp which has been largely influenced by man in its formation.

Unit A is almost entirely Nardus covered and consequently plot 1 was selected in isolation as the most exposed area. Plots 2, 3 and 4 were established on the upper facet of unit B and provide a contrast in vegetation since each of the dominant genera is represented. Below plot 2 and on a steeper angle but with the same Juncus cover plot 5 was laid out. The two therefore form a longitudinal pair, the transect being completed down the unit by plot 6 which is on the scarp. This plot is also matched transversely with plot 7 (Nardus) and plot 8 (Pteridium). Plots 7 and 8 can thus be paired respectively with plots 4 and 3. Plot 9 being at an approximately similar angle is intended as a contrast with plot 1 which is very much closer to the watershed but is also Nardus covered.

Unit C is almost horizontal at its upper end and plot 10 was established to take advantage of this fact. At a slightly steeper angle plots 11 (Nardus), 12 (Pteridium) 20 (Juncus) and the upper transect (Nardus and Carex) may be compared. On the scarp of unit C are plot 13, on a

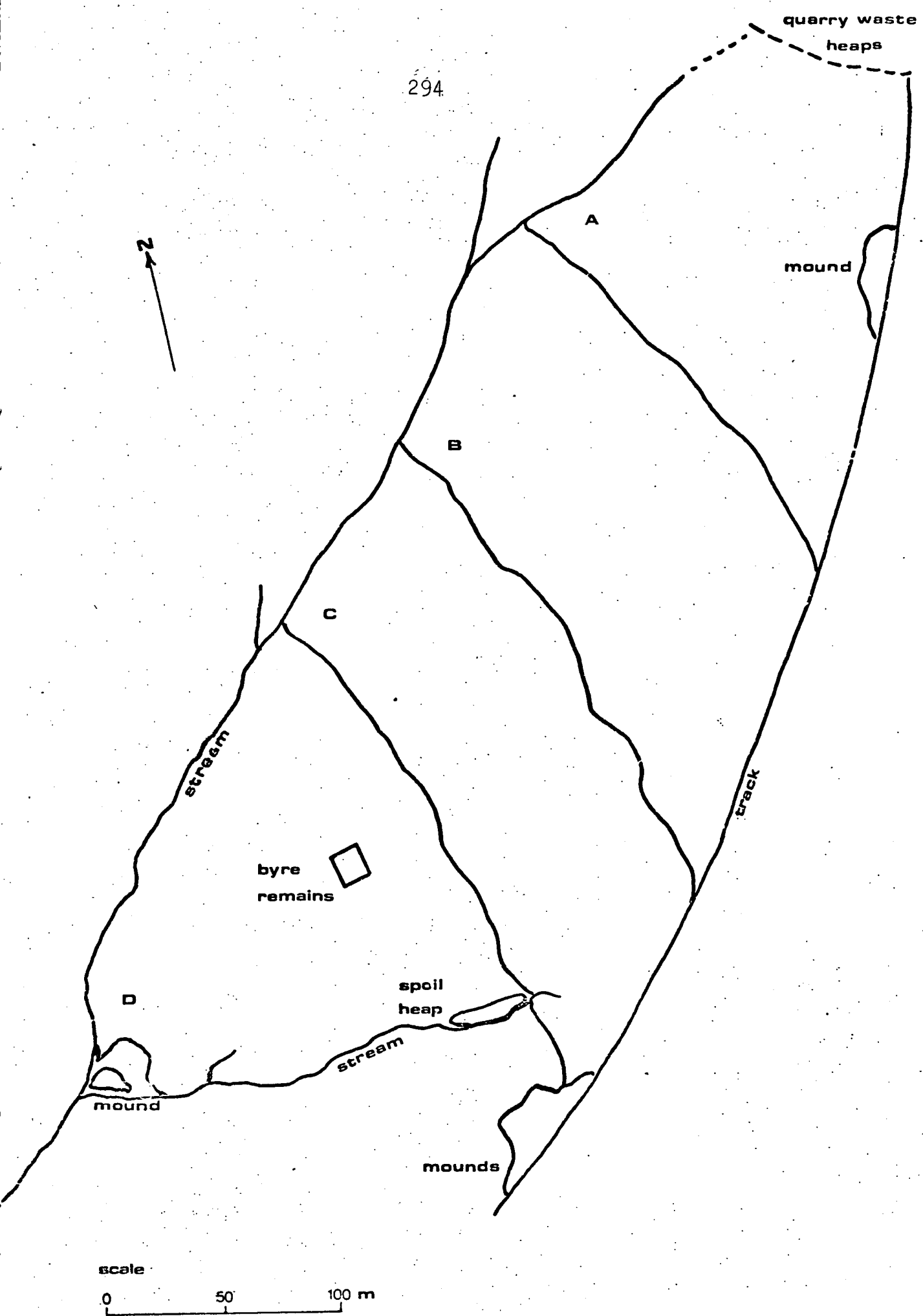


Fig. 9.5 Rookhope Morphological Units

Pteridium slope and the middle transect, but it was not possible to site a Juncus plot. Plot 13 forms a matched pair with plot 12 above it.

Along the scarp foot zone below unit C which forms the higher part of unit D, plots 14, 15 and 16 were all located in close proximity, each at approximately the same angle but with a different dominant vegetation cover. Plots 17, 18 and 19 are similarly matched at the lower end of unit D although plot 19 is necessarily somewhat removed as the Pteridium cover is extremely limited in extent. The lower transect allows comparisons with the other two Nardus and Carex transects.

If the basin is viewed longitudinally across the dominant structural axes, it can be seen that several transects are available for analysis. For example, the Juncus plots, 2, 5, 6, 10, 14 and 17 form one such transect stretching almost the entire length of the watershed. The Nardus plots, 1, 4 and 7 together with the three original transects are similarly arranged. Furthermore, plot 1 can also be linked with plots 9, 11, 16 and 18. The Pteridium plots also form two transects, 12, 13 and 15 in the lower part of the basin, and 3, 8 and 19 stretching almost throughout its length.

It is felt, in conclusion, that this pattern resulting from the stratified random sampling process described, gives maximum opportunity of making comparisons and, as far as possible, attempting to evaluate the effect of individual factors within a complex multivariate system.

CHAPTER TEN

THE PILOT STUDY AND SUPPLEMENTARY WORK AT ROOKHOPE

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- 10.2. Pilot Study
 - 10.2.1. Basin 1
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 - 10.2.3. Basin Outlet Plots
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10. THE PILOT STUDY AND SUPPLEMENTARY WORK AT ROOKHOPE

10.1. Introductory

An important factor in helping finalise the experimental design for the main site at Rookhope was the pilot study. It was hoped that by an initial planned analysis of what appeared to be significant controls, it would be possible to instrument the major watershed and complete the fieldwork programme without the necessity of many adjustments or changes. In particular it was felt that a preliminary assessment of the effects of the vegetation community, the slope angle and the position of a peg on the slope might be made. However, other aspects of the pilot study were not duplicated later. For example, the influence of aspect could only be evaluated on basin 1 and using the spoil heap both of which provided slopes of the required orientation. Also since several of the measuring devices provided evidence about the velocity profile, the experiment with flange pegs was not extended on to the main site.

Since many of the relevant conclusions reached as a result of the pilot study were incorporated in the final design and have therefore already been mentioned, it is important to examine the fieldwork results on which these were based. A brief description will therefore be given of each experiment within the pilot study irrespective of whether it merely provided background ideas for the main study or led directly to conclusions for the whole programme. All readings of linear creep refer to a depth of 2.5cm.

10.2. Pilot Study

10.2.1. Basin 1

Five transects of three pegs each were established in basin 1 as already described with three control pegs on horizontal facets in the virtually level valley floor. Transects 1, 3 and 5 were on the south facing slope while 2 and 4 faced north. Otherwise slopes were similar, soil depth was shallow throughout averaging 17.5cm, and the

vegetation consisted of a comparatively uniform cover of Pteridium with Nardus. While ideas about possible controls could be formed after about four months, for comparative purposes the annual rates were measured. The slope angles, included as a guide, are those of the facet in which the control peg is installed.

Table 10.1. Annual Creep Rates (Inclinometer Pegs):

Basin 1

Transect	1	2	3	4	5
Slope angle ($^{\circ}$)	29	26	21	32	32
Mean annual movement (mm)	0.52	1.68	0.48	1.37	0.74
Standard deviation	0.09	0.24	0.18	0.25	0.08

It can be seen that the north facing pegs registered very much higher readings than the south facing, and if individual pegs are considered, only one facing south exceeded the lowest reading of those opposite. Although the standard deviations of transects 2 and 4 are among the larger recorded for annual movement in the entire study, the difference between the results is still clear cut. The point-biserial correlation coefficient is 0.97 which is significant at the 95% level for five values. However, this significance value is included only as an indication, for reasons explained in the main analysis (Chapter 13). While it must be conceded that evidence from five transects cannot be definitive, when allied to other indications in this study, the fact that creep rates are affected by aspect seems a reasonable conclusion.

The control pegs remained comparatively static and in no case approached the lowest transect peg reading.

Table 10.2. Control Peg Readings: Basin 1

Control peg (transect number)	1	2	4
Annual movement (mm)	+0.15	-0.02	+0.11

Again, as with any such preliminary study, the small sample involved can only show possible trends which need further examination. In this case, the pegs were singularly stable and provided further confirmation that the peg movements registered in the basin were not haphazard. Furthermore they illustrate the importance of using controls and the possibilities for establishing such pegs within the main watershed.

Initial conclusions about the significance of aspect are supported by the Tube readings. Three Tubes were installed, numbers 1 and 3 south facing and number 2 on the opposite side. Tube 3 was damaged after approximately six months, but by matching it with the subsequent movement of Tube 1, an estimated reading is given.

Table 10.3. Annual Creep Rates (Anderson's Tubes):
 Basin 1

Tube	1	2	3
Annual movement (mm)	0.6	1.2	(0.8)

Apart from displaying the same trend according to aspect already discussed, these results also show the same order of movement as the peg readings. The rates recorded on the spoil tip also appeared to be related to aspect although the evidence was less clear since, in each case the range between the results from the two pegs was comparatively large.

Table 10.4. Annual Creep Rates: Spoil Tip

Plot	<u>North facing</u>	<u>South facing</u>
Mean annual movement (mm)	4.01	2.39
Range	0.85	0.56

Both rates and ranges indicate unstable surface debris with excessive response to changing weather conditions. They are in fact very similar to those obtained from the bare marl slope in North Wales.

From the results it seems that creep rates are higher on north facing slopes, a conclusion which supports evidence provided by the study of the M53 slopes (Chapter 6). Certainly from field evidence, frosts penetrate deeper and last longer on slopes of this orientation. On several occasions one side of the spoil tip was frozen while the other had already thawed and dried.

Apart from a general study of likely creep rates in this environment, the other factor which it was hoped might be clarified by the work in basin 1 was the importance of peg position on the slope. This seemed relevant bearing in mind the effect of the distance down slope upon soil factors advanced by Furley (1971). On all five transects the pegs were proportionately spaced with one on the convex upper slope, one on the scarp and one near the base.

Table 10.5. Annual Creep Rates according to Slope Element:Basin 1

Peg position	<u>Upper</u>	<u>Middle</u>	<u>Lower</u>
Mean movement (mm)	0.61	1.02	0.74
Standard deviation	0.22	0.39	0.21

With the differences according to aspect already noticed, it would be expected that standard deviation

would be large. As a result, variations of rate cannot be related to position in the transect and creep rates do not appear to increase downslope. In fact only transect 5 recorded such a pattern of movement. However, the maximum rates were measured on the steepest part of each slope and the possible relationship between creep and slope angle was obviously a factor to be examined in the main study.

10.2.2. Basin 2

Basin 2 with gentler slopes than basin 1 was instrumented on a plot pattern, with the three plots being located in a different vegetation community. Plot 1 was established on a Calluna covered slope, plot 2 on a slope predominantly Nardus covered but with an admixture of Pteridium and plot 3 on a Pteridium slope. Each contained four pegs complemented by one Tube. During the course of the study, two pegs were removed from plot 2 but one of these survived long enough for a realistic measurement of the annual movement to be made.

Table 10.6. Annual Creep Rates (Inclinometer Pegs):

Basin 2

Plot	1	2	3
Mean slope angle ($^{\circ}$)	23	22	21
Mean annual movement (mm)	0.30	0.89	0.42
Standard deviation	0.12	0.06	0.18

While there was a degree of variation on the Pteridium plot, readings from the predominantly Nardus covered slope were consistently high and those from the Calluna slope low. This pattern is summarized by the standard deviations which indicate a high degree of uniformity on the Nardus plot. Although this can only give a broad indication, differences of creep according to vegetation community can be seen to be worthy of further study, and again this helped provide evidence for the design

of the main study. As with basin 1, Tube results supported the initial conclusions and also gave some confirmation of the peg measurements.

Table 10.7. Annual Creep Rates (Anderson's Tube):
Basin 2

Plot	1	2	3
Annual movement (Tubes) (mm)	0.4	0.9	0.5

10.2.3. Basin Outlet Plots

However, to examine the possible significance of vegetation further, and also to investigate rates of creep at the basin outlet, three more plots were established. One was sited on the only totally bare slope in the whole basin, where stream undercutting was extremely active, and the other two in the same small slope complex, one Nardus covered and the other a Juncus slope. All three were situated at the extreme lower end of the watershed with only the bottom control peg, on a small eminence, between them and the confluence. Four pegs were inserted in each plot but one was removed from the bare slope and one damaged on the Nardus plot.

Table 10.8 Annual Creep Rates (Inclinometer Pegs):
Basin Outlet Plots

Plot	1	2	3
	<u>no vegetation</u>	<u>Nardus</u>	<u>Juncus</u>
Mean annual movement (mm)	2.92	1.05	1.93
Standard deviation	0.42	0.12	0.14

These results fit well into the pattern being established. The creep rate measured on plot 1 is high and the standard deviation large, both indicating an unstable and responsive surface. It therefore tends to accord with the results from the spoil tip although soil would be expected to display greater cohesion than loose weathered shale. Thus despite the fact that plot 1 faced north, the rates were not so excessive as those monitored on the spoil tip slope of the same aspect. The result for plot 2 is similar to those for plot 2 in basin 2, while the Juncus plot, being extremely wet in winter, might be expected to register higher rates.

10.2.4. The Transect

To provide further evidence and also to link this part of the pilot study with the main study, a transect of six pegs was established centrally on the interfluvium extending 15m from a Pteridium, through a Nardus to a Juncus association. In this area of the main watershed, all three communities were in close proximity and it was considered particularly suitable for a comparison.

Table 10.9. Annual Creep Rates (Inclinometer Pegs):
Transect

Transect community	<u>Pteridium</u>	<u>Nardus</u>	<u>Juncus</u>
Mean annual movement (mm)	0.78	1.27	1.50
Range	0.02	0.04	0.38

The rates registered are in the expected order although movement in the Juncus area seems somewhat restricted. However it must be remembered that there were only two pegs within each community and in fact, only one of the Juncus pegs indicated a low reading. The extremely small range between the two pegs in each of the other two communities should also be noted.

10.3. Discussion

The results from this part of the pilot study suggest strongly that there is a relationship between vegetation community and creep rates. In fact, from the evidence, an order of susceptibility to movement might be tentatively advanced: Calluna, Pteridium, Nardus, Juncus and bare soil. However, it must be stressed immediately that vegetation represents a response to many environmental factors, for example, soil type and particularly drainage conditions. Therefore, apart from bare soil, this list might also be the order of soil moisture content at certain times of the year. Furthermore it is also realised that vegetation exercises an influence on its environment and therefore, at this stage of the study, it is taken to be merely a convenient grouping of possibly significant controls.

A further aspect, mentioned when the pilot study design was discussed, is the importance of basal activity. The slopes of basin 2 were classified as active since a stream runs through the valley and rapid removal of material can occur, while those of basin 1 with no stream, were considered inactive. It can be seen from the results that no conclusions are possible as the rate for the one similarly vegetated slope in basin 2 was higher than the south facing slopes of basin 1 but lower than the north facing. Furthermore, any undercutting is likely to be a local effect and there would be obvious difficulties in comparing the rates between basins. However, it may be because the stream in basin 2 seldom covers the valley floor and therefore, despite the fact that they are technically active, the slope bases undergo very little erosion. The only clearly active slope is the bare slope near the basin outlet which was undergoing obvious undercutting. In this case the lack of vegetation is a complicating issue since the rate of creep cannot be assessed against that of any other slope within the watershed.

These five experimental areas, the two basins, the spoil tip, the complex of three plots near the confluence and the transect formed the basis of the pilot study design. The general conclusions, previously discussed, must be

evaluated bearing in mind the primary constraint of a limited number of measuring devices. However, this was counteracted to a certain extent by the close monitoring which involved reading all the pegs on 21 occasions during the year and taking 7 sets of measurements from the Tubes over the same period. Thus the changes occurring and the patterns of movement could be carefully scrutinised and as a result, vegetation community was added to slope as a major factor in the design for the main study. One limitation was found later when it was discovered on measuring a quadrat that no predominantly Calluna covered plot could be located in the watershed.

10.4. Supplementary Studies

10.4.1. Transects

It has already been mentioned that during the pilot study, evidence about the possible relationship between creep rates and position on the slope was not as clear as that concerning the other two basic controls examined. As this fact became increasingly obvious, it was decided to establish three transects on a Nardus and Carex spp slope across the convex upper part, the middle scarp and the concave lower element respectively. Each consisted of four pegs which were read on 17 occasions and a Tube was added to the middle transect from which 6 sets of measurements were obtained. During the year one peg from the middle transect was damaged and as it was not possible to make a realistic estimate from the readings taken at that stage, results for that transect refer to three pegs only.

Table 10.10. Annual Creep Rates (Inclinometer Pegs):
Transects

Transect	<u>Upper</u>	<u>Middle</u>	<u>Lower</u>
Slope angle ($^{\circ}$)	6.5	22.5	8.5
Mean annual movement (mm)	1.23	1.59	1.52
Standard deviation	0.14	0.14	0.21

The annual rate for the Tube was 1.7mm, which agrees well with the peg average for the middle transect. While the movements are all of the same order, the differences do indicate that there could possibly be a relationship with slope angle. The most rapid rates occur on the scarp, which is a similar pattern to that occurring in basin 1. However the standard deviations, while not particularly large, do militate against any clear-cut distinctions according to rate being made. This particular experiment continued into the period of the main study as did several other more minor investigations.

10.4.2. Flange Pegs

The line of six flange pegs was installed along the contour next to transect 3 in basin 1. They were intended to provide a guide to the variation of movement with depth. It should be noted that in the table, the depth refers to the distance of the upper edge of the flange from the top of the pegs.

Table 10.11. Annual Creep Rates: Flange Pegs

Peg	1	2	3	4	5	6
Flange depth (cm)	12.5	10.0	7.5	5.0	2.5	0
Annual movement (mm)	0.53	0.28	0.44	0.36	1.27	1.19

The most rapid rates were recorded by pegs 5 and 6.

Bearing in mind the standard deviations and ranges measured elsewhere in the pilot study, it seems probable that these are distinct from the rates measured by the other pegs. Therefore this experiment lends some support to the theory that creep declines with depth from a maximum at about 2.5cm. Below this depth creep rates appear lower and are likely to be inhibited by the flange. As stated earlier, it was not considered necessary to replicate this type of peg further as three of the other measuring devices used on each plot in the main study, also gave depth profiles. While any soil measurements from only one set of pegs must be treated with caution, it should be noted that measurements were taken on 11 occasions during the year.

10.4.3. Sectional Tubes

A further experiment to investigate the same factor was conducted during the main study period using sectional Tubes, sited on plots 14, 15 and 16. The Tube on plot 15 was damaged while the upper section of that on plot 14 was moved and the lower sections could not be measured owing to the water level. The only readings obtained therefore are for plot 16.

Table 10.12. Annual Creep Rates (Sectional Tubes):
Plot 16

Depth (cm)	2.5	5.0	7.5
Annual movement (mm)	0.7	0.5	0.2

While these results illustrate a decrease with depth similar to that measured elsewhere, the rates are very low and it is likely that the sections do not move sufficiently freely. The movement is in fact approximately half that recorded by the pegs on plot 16.

10.4.4. Excavated Plots

As a different method of examining the same problem,

six small excavated plots were laid out, two for each main vegetation community one of each pair on a steep slope (22.5°) and one on a flatter slope (4°) (Plate 9.5). The vegetation mat was removed together with the upper 5cm of soil so that creep rates for profiles lacking what was probably the most mobile layer, could be measured. However, it is appreciated that this is a totally artificial situation in that the lower soil layers, being uninhibited, will move more than normal. Moreover a small patch surrounded by undisturbed vegetation cannot be expected to show changes typical of a larger bare area. Furthermore, these results cannot be compared with those for either the bare slope or the spoil tip since the surface in those cases was loose and broken, while with the excavated plots it was still compacted and certainly contained root systems. Each plot was instrumented with two pegs, one 15cm from the upper end and one 15cm from the lower.

Table 10.13. Annual Creep Rates (Inclinometer Pegs):
Excavated Plots

Slope 4°			
Community	<u>Pteridium</u>	<u>Nardus</u>	<u>Juncus</u>
Mean annual movement (mm)	0.30	0.47	0.50
Range	0.10	0.11	0.18
Slope 22.5°			
Community	<u>Pteridium</u>	<u>Nardus</u>	<u>Juncus</u>
Mean annual movement (mm)	0.25	0.30	0.65
Range	0.01	0.21	0.28

Despite the many limitations of this experiment, it is worthy of note that the rates are approximately one third of those normally recorded on the respective community plots. However, particularly on the steeper slope, the ranges for

the Nardus and Juncus communities were large and so the means must be treated with caution. This might be taken as an indication of the instability which characterises results from other unvegetated plots. There appears to be no indication of a relationship between slope angle and movement. The most obviously depressed results are those for the Juncus plots, and a further reason for this may well be that they remained saturated, as far as could be ascertained, throughout the period. Thus there was no drying cycle to produce vertical movement.

10.4.5. Summary

These four experiments included among the subsidiary studies were, apart from the transect study, on a small scale providing only guidelines. In fact, considered together, the three concerned with velocity profiles give a reasonable indication that rates decline with depth, reaching a maximum at about 2.5cm from the soil surface.

10.5. Boundary Transects

After the twenty plots in the study basin had been instrumented, using a design based primarily on slope angle and vegetation community, with aspects of distance included as already described, it was decided that more factor discrimination should be introduced. Since there was a marked coincidence between vegetation association and broadly grouped soil type, it was realised that while any separation of these might not add significantly to the number of possible correlations, it would provide some guide to the relative importance of the vegetation and the soil complexes of variables in controlling rates of soil creep. The most likely places for any mismatch would appear to be near the edges and consequently a series of 7 transects was installed across a number of vegetation community boundaries within the watershed. It was hoped to detect positions where the rate of creep measured did not accord with the general trend exhibited by neighbouring plots in that particular vegetation community. However it must be remembered that a vital element in the experimental design for this study has been

replication to take account of the inherent heterogeneity of soil and therefore most creep rates reported have been means. In the case of the boundary pegs, since point measurements were required, no replication was possible and the readings listed are for individual pegs. It was felt that despite this limitation, the results obtained in each case would be clearer than would the mean taken from a series of pegs inserted as accurately as possible but probably rather differently placed with regard to the boundary. It was considered that if the peg in each vegetation community registered a rate similar to the average for that community and the boundary pegs installed between them gave a result approximately to the mean of those two rates, no discrimination between possible vegetation and soil effects would be possible. If on the other hand the rate recorded by the boundary peg was similar to that found in a neighbouring community, this would provide evidence that soil rather than vegetation factors were more significant in controlling creep. Each peg was read four times during the year and the annual movement in mm is given. Each transect was located as near as possible to a plot and it is listed according to the number of its plot.

Table 10.14. Annual Creep Rates (Inclinometer Pegs):
Boundary Transects

Plot 6	<u>Juncus</u>	<u>boundary</u>	<u>Nardus</u>		
Annual movement (mm)	2.35	1.60	1.07		
Plot 7	<u>Pteridium</u>	<u>boundary</u>	<u>Nardus</u>		
Annual movement (mm)	0.12	0.52	1.03		
Plot 9	<u>Calluna</u>	<u>boundary 1</u>	<u>Nardus</u>	<u>boundary 2</u>	<u>Juncus</u>
Annual movement (mm)	0.65	0.52	(0.75)	(1.80)	1.40

Plot 11	<u>Nardus</u>	<u>boundary</u>	<u>Juncus</u>
Annual movement (mm)	1.26	1.04	(2.85)

Plot 12	<u>Pteridium</u>	<u>boundary</u>	<u>Nardus</u>
Annual movement (mm)	(1.07)	0.39	1.29

Plot 15	<u>Juncus</u>	<u>boundary</u>	<u>Pteridium</u>
Annual movement (mm)	1.47	1.91	0.66

Plot 16	<u>Pteridium</u>	<u>boundary 1</u>	<u>boundary 2</u>	<u>Juncus</u>
Annual movement (mm)	(0.93)	2.02	(2.51)	2.46

Altogether six pegs were removed, two from plot 9, two from plot 16 and one each from plots 11 and 12. All disappeared after three of the four readings had been taken and therefore realistic estimates could be made. However, in interpreting the result, this point must be borne in mind.

It can be seen that the boundary pegs in plots 6 and 7 indicate annual rates of movement which approximate to the means of their respective neighbouring communities. Therefore it can be concluded that there is a probable relationship between vegetation and soil type. On the other hand, in the remaining plots there seems a likelihood that some mismatch exists. In plot 9, although the reading for the boundary 1 peg does not show any very strong tendency, it is low and points towards a continuation of the Calluna soils. However, boundary 2 peg illustrates a rate typical of Juncus plots. Plot 15 and both boundary pegs in plot 16 show similarly an extension of the soils characteristic of the Juncus community. In plots 11 and 12, the boundary peg readings are both lower than either of their respective neighbours and therefore that in plot 11 indicates an affinity with Nardus soils and that in plot 12, Pteridium soils. Indeed the rate recorded by the boundary peg in plot 12 is low even for a Pteridium plot.

While such evidence is not conclusive it does allow

a tentative separation of vegetation and soil factors. This shows, as expected, that the complex of soil factors is predominant in affecting rates of creep. Since the soil profile characteristics of each community are distinctive, the existence of any overlap can be easily checked. In these cases excavations showed conclusively that the vegetation community and soil boundaries did not coincide in plots 9 (boundary 2), 11, 15 and 16. In plots 12 and 9 (boundary 1) evidence of overlap was less clear, while in plots 6 and 7 the edge of the vegetation community marked the position of a transitional soil profile. It should perhaps be stated that overlaps and coincident boundaries could have been similarly located by excavation before instrumentation. However, it was felt that having disturbed the site locally by digging an exploratory trench, the pegs would need to be located some distance away where conditions would still be largely unknown.

10.6. Open Tubes and Steel Rods

To provide a closer analogue with the laboratory soil block results and to indicate further evidence of their possible relevance, six Open Tubes were installed. Since in these the soil was unconfined, it was considered that they could provide a useful comparison with the laboratory soil troughs which were not completely filled to their lower ends. The Tubes were installed in transects, three on a 7° slope and three on a 22° slope with, in each case, one Tube in each main vegetation community. The bolts supporting the washers were inserted at a depth of 2.5cm below the root mat. Additionally in the case of Tubes in the Nardus communities a second bolt was positioned 5cm below the first. The Tube in the 7° Pteridium covered slope was damaged and no readings could be estimated with any precision.

Table 10.15. Annual Creep Rates: Open TubesSlope 7°

Vegetation type	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Annual movement (mm) (upper washer)	4.1	3.5	-
Annual movement (mm) (lower washer)		1.4	

Slope 22°

Vegetation type	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Annual movement (mm) (upper washer)	2.5	1.5	2.0
Annual movement (mm) (lower washer)		1.6	

The results indicate that slope angle appears to exercise little influence on creep rates. Of more importance is the fact that, on the 7° slope, movement recorded was approximately twice that which was expected. If the soil is unconfined, it would be expected that rates would be higher and this result was confirmed by measurements using the partially loaded laboratory soil troughs.

Further evidence was provided by three steel measuring rods which were installed near the basin outlet immediately above the Nardus and Juncus plots described in the pilot survey. They were inserted in positions where the vegetation mat of the main basin ended abruptly so that they could be used to record movement at different depths within the soil profile. For each rod the nails were inserted at three positions: (1) centrally in the root mat, (2) 2.5cm below the mat and (3) 7.5cm below the mat. One rod was damaged during the year and annual readings could only be taken from the other two, one immediately below the Juncus community (plot 17) and the other similarly below Nardus (plot 18).

Table 10.16. Annual Creep Rates: Steel Rods

Plot	<u>Juncus</u>	<u>Nardus</u>
Annual movement (mm):		
Nail 1	1.6	2.8
Nail 2	3.4	3.0
Nail 3	1.2	1.8

It can be seen that readings for nail 2 show in each case the largest rate of creep in the profile, a result similar to that monitored by the other devices. As the soil is unconfined the magnification might be expected, but it does provide a useful link between field measurements and laboratory work. Also indicated by the measuring rods is the retarding influence of the vegetation mat and the decline of rate with depth.

10.7. Control Pegs

As previously described, the control pegs were installed on flat facets at the summit of small mounds at the boundary of the basin. One was established above plot 1 near the highest point, one above basin 1 and near plot 20 on the approximate level of the centre contour and one at the basin outlet below plot 18. All were measured on 17 occasions during the year and all showed, as expected, a steady set of readings.

Table 10.17. Control Peg Readings: Main Experimental Area

Control peg position	Upper	Middle	Lower
Facet angle ($^{\circ}$)	0.0	0.5	0.0
Annual movement (mm)	+0.08	-0.13	-0.16

These rates are considerably lower than those measured

on even the most stable plot and they are similar to those obtained from the control pegs on basin 1. In contrast to the results from both sets of control pegs, it can be seen that the movement registered by the pegs in the plots is significantly larger and also comparatively uniform. The control pegs record haphazard rates.

10.8 The Settlement Time

As described in the section on instrumentation, an aluminium and a further red painted wooden peg were installed in each plot during the middle month of the measurement period to check on rates of settlement. By comparing plots of peg movement taken from these pegs with those from the original four (Fig. 13.18 A,B,C.), it was hoped that the time taken for the movement pattern when established, would be measured. Readings taken during this period were obtained at weekly intervals and it was found that after two weeks the majority of pegs conformed to the general pattern. After four weeks virtually all moved in unison, confirming that this period is the longest time delay required before accurate measurements can be taken. However, these results are discussed in more detail when plots of the movement recorded by all the measuring pegs are considered in a later section (Chapter 13).

10.9. Summary

The pilot study indicated that annual rates of creep range from approximately 0.3mm to 1.9mm, an order of values which accords well with that reported by other workers. Anderson's Tubes measured similar rates and provided supporting evidence that the techniques were valid. Furthermore, variability within the plots or transects was shown to be limited and the general uniformity of readings at a particular point was established. In contrast, the control pegs recorded little absolute movement and exhibited haphazard results.

Aspect was again shown to be important with annual creep rates on north-facing slopes averaging 1.5mm as

against 0.6mm on south-facing slopes. Results also demonstrate clearly that there is a definite relationship between the assemblage of variables distinguished by the major vegetation groups and soil creep. In each case movement was greatest under Juncus and least under Pteridium. Along the transect the following mean annual rates were recorded: Juncus 1.50mm, Nardus 1.27mm and Pteridium 0.78mm. The boundary pegs indicate a possible separation of soil factors and vegetation factors.

The responsive nature of bare slopes and immature soils is again illustrated. The plot with no vegetation recorded a mean annual movement of 2.9mm, while pegs on the north-facing slope of the spoil tip registered a rate of 4.0mm.

Slope angle and the position of a peg on a slope do not appear to be related to soil movement. Velocity profile measurements show that rates of creep decline with depth from a maximum recorded at approximately 2.5cm below the root mat.

CHAPTER ELEVEN

RATES OF SOIL CREEP

- 11.1. Introductory
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- 11.3. Results
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- 11.5. Maximum Depth of Movement
- 11.6. Volumetric Rates of Creep
- 11.7. Comparison with other Results
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11. RATES OF SOIL CREEP

11.1. Introductory

Measurements of soil creep rates were made at the Rookhope watershed for a period of two years and four months, from early November 1972 until the end of February 1975. As described in the section on design, the first year was occupied largely by the pilot study plots and a series of other subsidiary studies. Results obtained together with those from other plots and laboratory work, allowed the instrumentation of the main study area at Rookhope to take place in mid-October 1973.

Towards the end of the measurement period, the necessity to take final readings of certain site factors was clearly a source of possible plot disturbance. As a result, soil pits were never excavated directly upslope of the instruments and this part of the programme was mainly compressed into the period from December 1974 to April 1975. However while it is felt that any effect on the measuring devices or even on the creep rate itself was minimal, it was decided to calculate the annual creep rates over the twelve months from the beginning of November 1973. This particular period also allows closer comparisons to be made with the earlier pilot study results. Although the exact length of measurement time is not absolutely critical with the less accurate long term devices, they were read in the same order as they had been installed so that for the purpose of comparing results, each had been recording for one year. Therefore final readings were taken and where necessary checked, during November and early December 1974. Thus each category of instrument monitored creep rates over almost the same period, and bearing in mind the varying accuracies of the devices and also of the measurement methods, any slight discrepancy is unlikely to be significant in the calculation of annual rates. While for practical reasons the readings could not all be taken on the same day, there was a great

advantage in the approach adopted of obtaining results from one type of instrument throughout the basin at any one time. It was possible to read the Inclinator pegs, Anderson's Tubes and aluminium pillars before the dowelling pillars, Cassidy's Tubes, Young's Pits and sand pillars, all of which required excavation with possible attendant plot disturbance. However, as the first two devices require calculations or constructions to obtain the rates, the actual results were produced in a different order. Furthermore it was necessary to determine the velocity profiles which indicated that the depth of maximum creep was located at 2.5cm below the root mat. Only four individual profiles showed a different position, in each instance slightly lower, but in no case was this confirmed by other profiles from the same plot. Therefore to allow a comparison of instruments and to calculate the annual rate of soil creep as accurately as possible, 2.5cm was fixed as the depth for measurement.

As described earlier, only one instrument, the Anderson Inclinator, allowed truly short term readings to be obtained. Measurements could be taken regularly and any disturbance or damage through vandalism, checked. Furthermore, the importance of replication when dealing with soil and soil processes has been stressed repeatedly, and this particular device could be speedily used with a large number of pegs. Therefore, the creep rates calculated from the Inclinator readings are taken as the most accurate and are used as the standard against which other measurements are compared. This point is discussed in more detail when the complete data analysis procedure is described. As stated when the instrumentation programme was discussed, the other instruments provide data not obtainable from the Inclinator results and also act as a longer term check on rates of movement. The annual rates of soil creep as recorded by the different methods are listed and discussed for the twenty fully instrumented plots.

11.2. Measurement of Rates

The monitoring programme for each of the instruments on the twenty fully instrumented plots is discussed so that the annual rates of creep recorded can be judged in context. Problems of measurement peculiar to each of the devices are considered together with special precautions taken. Readings affected by plot disturbance are identified and the procedure for calculating linear rates from the field measurements is described.

11.2.1. Anderson's Inclinator

The four pegs originally installed on the grid to provide the basic measurements were read on a total of twenty-six occasions, nineteen of them within the year under consideration. Therefore the plots were visited for this purpose on an average, rather more than once every three weeks. It was felt that such a programme allowed the pegs to be accurately monitored, although for even more detailed measurements these results were supplemented by those from the plot at Brandon.

There were no problems in making the measurements as the Inclinator is not in place long enough to be affected by wind and fits easily over the pegs even when plant growth is at a maximum. However, care was always taken to ensure that no vegetation had become lodged in the peg housing. At each plot at least one peg was read twice as a check, while any measurement which appeared deviant in either running against the trend of a plot or displaying a violent change since the last visit was also re-read.

By careful monitoring, it was shown that only five pegs had been removed and five disturbed. Three pegs at plot 10 and one each at plots 14 and 17 were in the first category and one each at plots 1, 4, 12, 18 and 19 in the second. These last five were identified by gross changes in reading of an amplitude well beyond that encountered in regular monitoring. The peg on plot 19 was the only one in the entire basin to register a negative rate. The damage to plot 10 occurred early in the period and it was relatively simple to make adjustments. The dislodgement

of pegs at plots 14 and 17 and the disturbances elsewhere mean that a third of the plots were affected. but there is no reason to suppose that this would seriously alter the trend established by the remaining three pegs on any plot. Considering the use made of the basin for grazing, a loss of results from 7 pegs out of 80 is very satisfactory. Certainly it compares very favourably with the number of readings discarded by Kirkby (1963), who rejected 550 out of 1,100.

For each of the pegs on a particular plot, the angular change over the year was calculated directly from the Inclinator readings. This was then converted to a linear movement at 2.5cm below the root mat. As explained previously, the instrument was designed to facilitate rapid conversions in that the dial reading divided by 100 is the tangent of the angle. The sine of the angle can then be multiplied by the distance from the measuring depth to the pivot point expressed in mm. This gives the annual rate of creep at the required depth. The mean of the results from the three or four pegs on the particular plot was then taken as the annual rate of linear creep for that plot.

11.2.2. Anderson's Tube

This instrument is basically middle term in that, depending upon the accuracy of the callipers used, regular monitoring is possible. It can therefore give an idea of trends, but more important, it can indicate any disturbance. The Tubes were read on eight occasions, five of them within the measurement year specified. Considering the time involved, an average of just under once every two months seemed a reasonable frequency for checking movement and diagnosing problems.

The only real difficulty occurred on the wetter plots where water in the Tube prevented readings being taken at the 10cm level. In these cases the 6.3cm level, used as an occasional check on other plots, became the other main reading line. On each of the five visits to the basin, five Tubes were re-read as a check, and as with the pegs,

large alterations were carefully scrutinised.

By continuous monitoring, it was found that, during the course of the year, three Tubes were disturbed. In the case of plots 8 and 10, damage was minor and adjustments were made. Only in the case of plot 17 were the readings significantly affected. The Tube was clearly dislodged in July 1974 and the reading listed was based on movement up to that date and, from then on, the ordinal position of the plot using peg results.

To obtain the movement at a depth of 2.5cm the measurements for the required dates for the 10cm level were plotted and the downhill creep measured directly, using Vernier callipers.

11.2.3. Aluminium Pillars

Pillars are long term devices although when measurement over particularly short distances is involved, as in the present case, they could be read more regularly. However for this study they were only measured on two occasions, once at the beginning of the year and once at the end. It was considered that since they utilised the central rod of the Tubes as a fixed base and were therefore so near the Tubes on the grid, disturbance or dislodgement would be discerned through the more regular measurement of those instruments.

Since the greatest distance of any pillar from the fixed base was 25.42cm, all the readings were well within the range of a pair of large size Inside callipers. The only problem occurred where intervening plant growth obscured the pillar and had to be carefully cut back.

However, possibly because of their bright polished appearance and comparative ease of removal, these instruments were far more prone to disturbance than the previous two categories, which also protrude above the surface. In all, nine pillars were dislodged, one each from plots: 2, 5, 6, 7, 9, 11 and 17 together with both from plot 10. In the case of plot 10 the same procedure as used for the Tube on plot 17 was adopted in order to produce a complete set of readings.

As the dislodged pillars were predominantly those on the downslope side of the Tube and as this position also renders them more likely to be affected by the presence of the Tube, it was felt that where possible, readings from the upslope pillar should be taken. This obtained on all but plots 2 and 6 from which the upslope pillar had been removed. Where possible, the downslope reading was used as a check.

To find the rates of creep, the peg distance was measured as described earlier, by Inside callipers using the base of a notch cut in the pillar and the 1.3cm line on the central rod as reference points. Assuming that the pillar pivots at its base and that no bodily movement has occurred, the rate of movement at 2.5cm can then be calculated.

11.2.4. Young's Pits

The Young's Pit is a long term device in that it cannot be read over short time periods and it is comparatively insensitive to changes occurring over such periods. By careful excavation it is possible to obtain more than one set of readings. However, in the context of this study, it was considered more important to minimize any dislocation of the soil and therefore the pits were only measured once (Plate 11.1 A,B).

Problems of measurement were similar to those encountered with the previous devices and concerned precision, the use of the plumb line and the speed of the operation on wetter plots. These difficulties were largely overcome by using as described, a transparent plastic template on the plumb line. The new rod positions were marked on a strip of clear acetate fixed to the template and could be measured accurately later. To obtain the exact positions the template was suspended on the plumb bob and then fitted over the lowest rod (15cm) and held rigidly in place. It must be stressed however, that this, but more particularly the following two devices (dowelling pillars and Cassidy's Tubes) cannot be read with the same precision as the Tubes or pegs. However, by taking the precautions described



A



B

Plate 11.1

Young's Pits

A excavated and cleaned showing marker peg

B checked with plumb bob

in each case and by careful checks, it was felt that sufficient discrimination was possible to justify listing results to 0.1mm. This therefore allowed comparisons to be made with the readings obtained from the other instruments.

The position of each pit was marked by three red pegs, one at either end of the incision and one on the line of the rods. Location was therefore simple except in the case of plot 7 where the marker pegs had been removed, and despite the use of a probe, the pit could not be found. To complete the set of results, a value was estimated using readings from other instruments on plot 7 and the general deviations of Young's Pits from the Inclinator peg results.

To facilitate the determination of the creep rate, the acetate strip had been marked with circles fitting exactly over the six holes drilled in the template. The new rod positions were then recorded in red and it was possible to measure the horizontal and the vertical distance of the red marking from the circles, using Vernier callipers. In each case the rod at a depth of 2.5cm exhibited the greatest movement in a horizontal plane and this was the measurement taken.

11.1.5. Dowelling Pillars

Since, owing to the disturbances resulting from excavation, they can only be used to take one reading and since accurate measuring is difficult, dowelling pillars are long term devices. They were therefore only read on one occasion, at the end of the defined measurement year. Thus it was not possible to monitor changes although it was considered that, by duplication on each plot and by comparison with the other two similar instruments, any gross deviations could be recognised.

The major difficulty with this device concerns the accuracy of measurement. A plumb line even held in a soil pit, is highly sensitive to wind and the Rookhope basin is particularly exposed. Furthermore, even if the plumb line is stationary, it is extremely difficult to measure reliably the exact distance from it to the edge of the pillar.

When the many possible sources of error are considered, it can be appreciated that if the profile is recorded in the field and measured accurately later, at least some problems are overcome. Therefore for this study, the pillar was partially excavated until half of its circumference was visible over its entire length (Plate 11.2 A,B). A flexicurve was held against it and carefully bent to the same curve which could then be drawn in a field notebook. However the rapidly rising water on the wetter plots meant that even this shortened procedure had to be completed reasonably swiftly. Therefore, although the method is thought to be a distinct improvement upon that using a plumb bob, the results as discussed earlier, must still be considered as an approximate guide only. Furthermore, on six plots, including the four in which creep could be discerned throughout almost the entire profile, a check at the depth of measurement was made with the plumb bob and Vernier callipers.

Since they are subterranean devices, loss would not be expected, but in the case of plot 10, which was trampled, the pillars could not be located. A similar procedure to that already used for lost instruments was adopted to produce a complete table of readings. On excavation no pillar was found to be broken and so to minimize disturbance, only one device on each plot was read.

To obtain the creep rate, a vertical line was constructed upwards from the lowest undisturbed part of the profile and the horizontal distance from this to the curve at a depth of 2.5cm measured by Vernier callipers. However, while the callipers can be read easily to 0.1mm it is debatable whether such precision can be justified in view of the overall procedure. Nevertheless great care was taken so that a data set which could be compared with those from other devices was produced. This process was more difficult with the four profiles already mentioned, drawn from plots: 5, 16, 17 and 20, as the velocity curve extended beyond the penultimate length of dowelling. There was thus no completely undisturbed section to act as a guide and as described, in these cases the plumb line



A



B

Plate 11.2

Dowelling PillarsA Nardus plotB Juncus plot

check result was used. However, in all cases the determination of the creep rates was facilitated by the flexicurve method in that a smooth curve rather than a line consisting of short straight sections was produced. This smoothing effect allowed the depth of movement to be located more precisely.

11.2.6. Cassidy's Tubes

These instruments are similar in attributes and deficiencies to dowelling pillars. In the procedure devised by Cassidy, the tube was filled with quick setting cement at the end of the measurement period and could thus be removed. The profile could then be measured accurately, but if the curve extended to its base, a plumb line would still be required to establish the vertical in the field. Bearing in mind the problems, it was felt that the flexicurve technique was as satisfactory and less time consuming.

The difficulties of measurement were therefore almost the same as those experienced with the dowelling pillars. The smooth P.V.C. surface of the tubes made careful excavation and the location of the edge easier (Plate 11.3 A,B), but on the wetter plots, the time factor still remained. Checks were again made with a plumb line and Vernier callipers and this was once more particularly significant on the plots where there was little undisturbed profile, although with a tube the problem was not quite so acute.

All the tubes were located and when the profiles were compared with those obtained from the dowelling pillars, there was no sign of disturbance. To measure the rates of creep, exactly the same technique was employed as had been used to obtain readings from the pillars.

11.2.7. Sand Pillars

The sand pillars on plots: 3, 4 and 5 were located and carefully excavated with a knife. As each vertical strip of soil was cut away round the hole, it was inspected for evidence of sand penetration. In fact on none of the plots was there any sign of sand grain movement into the



A



B

Plate 11.3

Cassidy's Tubes

A Nardus plot

B Pteridium plot

soil, the interface between the two materials being clearly defined (Plate 11.4 A,B). This indicates that particulate creep does not occur, but it must be remembered that judging any movement, particularly lower down the pillar, is extremely difficult, that only particles of one size were used, and also that the insertion of the soil sampler undoubtedly causes compacting of the soil. Therefore definite conclusions cannot be drawn about creep as a diffusion process but the evidence available suggests that mass movement is more likely. Excavations on plots: 14, 15 and 16 provided support and as a result it was decided not to disturb the remaining plots.

11.3. Results

Since the Inclinator pegs were the only devices sufficiently replicated on the plots (Reynolds 1975A), it must be assumed, at least initially, that they provide the standard data set. Therefore these results are considered separately before readings from the other instruments are compared and discussed. As changes in the angle of a peg can be measured to an accuracy of less than 1 minute of arc, the linear movement is given to 0.01mm. It is however realised that creep of such an order is very small when considered in the context of soil heterogeneity. For the remaining instruments which are less sensitive, annual rates are given to 0.1mm.

11.3.1. Inclinator Peg Results

The rates listed are the means for the three or four pegs on the particular plot.

Table 11.1 Annual Creep Rates (Anderson's Inclinator):
Plot Measurements

Plot	1	2	3	4	5	6	7
Annual rate of creep (mm)	1.46	2.00	0.33	1.12	1.79	1.39	1.06
Standard deviation	0.26	0.10	0.06	0.19	0.12	0.13	0.10
Standard error	0.15	0.05	0.03	0.11	0.06	0.08	0.05



A



B

Plate 11.4

Sand PillarsA Nardus plotB Pteridium plot

Plot	8	9	10	11	12	13	14
Annual rate of creep (mm)	0.41	1.29	1.97	0.85	1.11	0.55	2.44
Standard deviation	0.08	0.12	0.22	0.11	0.13	0.13	0.13
Standard error	0.04	0.06	0.11	0.06	0.08	0.06	0.07

Plot	15	16	17	18	19	20	<u>Mean</u>
Annual rate of creep (mm)	1.04	1.47	2.32	0.95	0.86	1.67	1.30
Standard deviation	0.16	0.18	0.04	0.12	0.13	0.11	
Standard error	0.08	0.09	0.02	0.06	0.07	0.06	

The standard deviations indicate a comparatively low spread of results about the mean. When these are compared with standard deviations calculated for all six instruments on each plot (Table 11.6) it will be seen that on only three plots: 10, 15 and 19, is the deviation of peg results alone greater.

To compare within-plot and between-plot differences,* an analysis of variance was made. This showed that the difference between plot means is significant at the 99% level ($F = 69.42$, critical value for $n = 73$, $k = 20$ at $\alpha = 0.01$ is 2.20); 'n' refers to the number of instruments and 'k' to the number of plots.

Examination of the plot results reveals a broad grouping according to the three vegetation communities, although the boundaries between them are not clear cut. To compare within-plot and between-plot differences, an analysis of variance was completed for each plot group. This demonstrated that in each case the difference between the plot means is significant at the 99% level.

* within-plot: using all readings (in this case 4) from all twenty plots

between-plot: using plot means from all twenty plots

Table 11.2 Within-plot and Between-plot Comparison:
Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
F	8.60	25.72	29.14
Critical value ($\alpha = 0.01$)	3.67	3.63	4.04
n	25	26	22
k	7	7	6

To consider further the distinctiveness of annual creep rates within the vegetation communities, plot group data were analysed.

Table 11.3 Mean Annual Creep Rates (Inclinometer Pegs):
(mm) Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean	1.17	1.94	0.72
Standard deviation	0.22	0.33	0.30

It can be seen that the Juncus group is quite distinctive, but the boundary between the Nardus and the Pteridium groups appears somewhat blurred. To examine the differences between the groups, pair wise 't' tests were made. These showed that each is distinctive at the significance level stated.

Table 11.4 Distinctiveness of Annual Creep Rates
(Inclinometer Pegs): Plot Groups

	<u>Nardus/Pteridium</u>	<u>Juncus/Pteridium</u>	<u>Juncus/Nardus</u>
't' value	2.88	6.35	4.78
Significance level (%)	95	99	99

Using the standard error as a guide, the overlap in individual plot rates can be shown (Fig. 11.1). The rates are arranged in ascending order by plots. The Juncus plots display most distinctiveness and the Nardus plots most overlap.

11.3.2. Results for all Instruments

To facilitate comparison between the readings obtained by all six instruments, the results are tabulated together (Table 11.5).

<u>Plots</u>	<u>Instruments</u>						<u>Mean</u>
	<u>Inclin- ometer Pegs</u>	<u>Ander- son's Tube</u>	<u>Alumin- ium Pillars</u>	<u>Young's Pits</u>	<u>Dowel- ling Pillars</u>	<u>Cassidy's Tubes</u>	
1	1.46	1.4	1.3	1.8	1.7	1.1	1.46
2	2.00	2.2	2.6	2.0	2.1	1.9	2.13
3	0.33	0.3	0.3	0.5	0.3	0.4	0.36
4	1.12	1.2	1.2	1.0	1.5	1.1	1.19
5	1.79	1.6	1.9	1.9	1.3	2.2	1.78
6	1.39	1.4	1.3	1.5	1.4	2.1	1.52
7	1.06	1.1	1.1	(1.2)	1.3	1.0	1.13
8	0.41	0.7	0.4	0.7	0.6	0.5	0.55
9	1.29	1.2	0.7	1.3	1.1	1.6	1.20
10	1.97	1.9	2.0	1.8	(1.9)	2.0	1.93
11	0.85	0.9	0.8	1.2	0.9	1.5	1.03
12	1.11	1.1	0.9	1.2	1.0	1.2	1.09
13	0.55	0.6	0.6	0.8	0.5	0.6	0.61
14	2.44	2.3	2.0	2.2	2.0	2.2	2.19
15	1.04	1.1	1.1	1.3	1.0	1.2	1.12
16	1.47	1.6	1.4	1.6	1.2	1.7	1.50
17	2.32	(2.3)	2.4	2.6	2.1	2.3	2.34
18	0.95	1.1	0.9	1.2	1.0	1.8	1.16
19	0.86	0.9	0.8	1.0	0.8	1.0	0.89
20	1.67	1.5	1.6	1.7	1.7	1.9	1.68
Mean	1.30	1.32	1.27	1.43	1.27	1.47	1.34

Table 11.5 Summary of Annual Creep Rates: (All Instruments)

(mm)

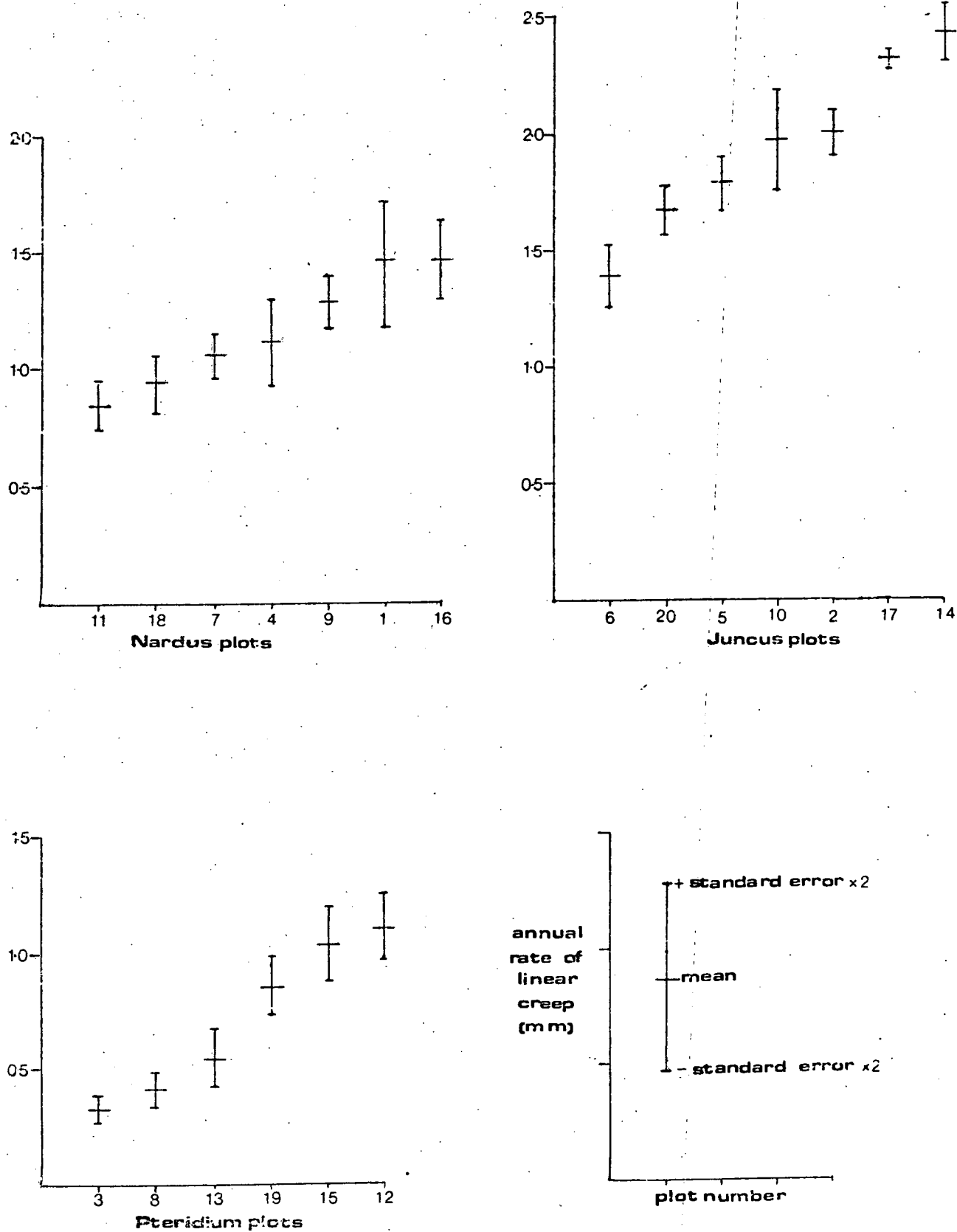


Fig. 11.1 Annual Linear Creep Rates (Inclinometer pegs):
Plot Variability

It can be seen that the Anderson's Tube results are similar to those obtained from the Inclinator pegs (Fig. 11.2). If discrepancies are examined, the rate for plot 8 is high, but as will be seen later, certain other devices show a similar tendency. The result for plot 20 is low; clearly the same pattern, which can be related to vegetation community, can be discerned. Since the pegs and Tubes are both angular measuring devices, such coincidence would be expected.

With regard to the aluminium pillars, bearing in mind the level of accuracy of the procedure and the simple nature of the device, exact accordance with the peg results would not be expected (Fig. 11.3). While the actual measurement is similar to that employed with the Tubes, the distance is substantially larger and this must affect the reliability of the conversion to depth of measurement.

Nevertheless, the grouping according to the three vegetation communities is clearly evident and the only major departure from the peg results occurs on plot 9. With the degree of disturbance already described in connection with the aluminium pillars, this particular device could well have been damaged. However, no obvious dislodgement was apparent and the reading has therefore been retained in the data set.

The Young's Pits, like the Cassidy's Tubes, show a tendency to read high although the deviation from the peg pattern is not so great (Fig. 11.4). The most marked differences occur on plots 8 and 11, but otherwise discrepancies are generally small. Therefore the familiar grouping emerges clearly.

The dowelling pillar results are somewhat less regular in following the peg readings than those previously discussed (Fig. 11.5). The rates for plots: 1, 4, 7 and 8 tend to be slightly enhanced whereas those for plots: 5, 9, 14, 16 and 17 are depressed. It is interesting to note that the first group is sited on drier areas while, apart from plot 9, the second occupies the wetter parts of the basin. This may indicate the lack of sensitivity of this technique, but it can more probably be attributed to the inherent problems of accurate

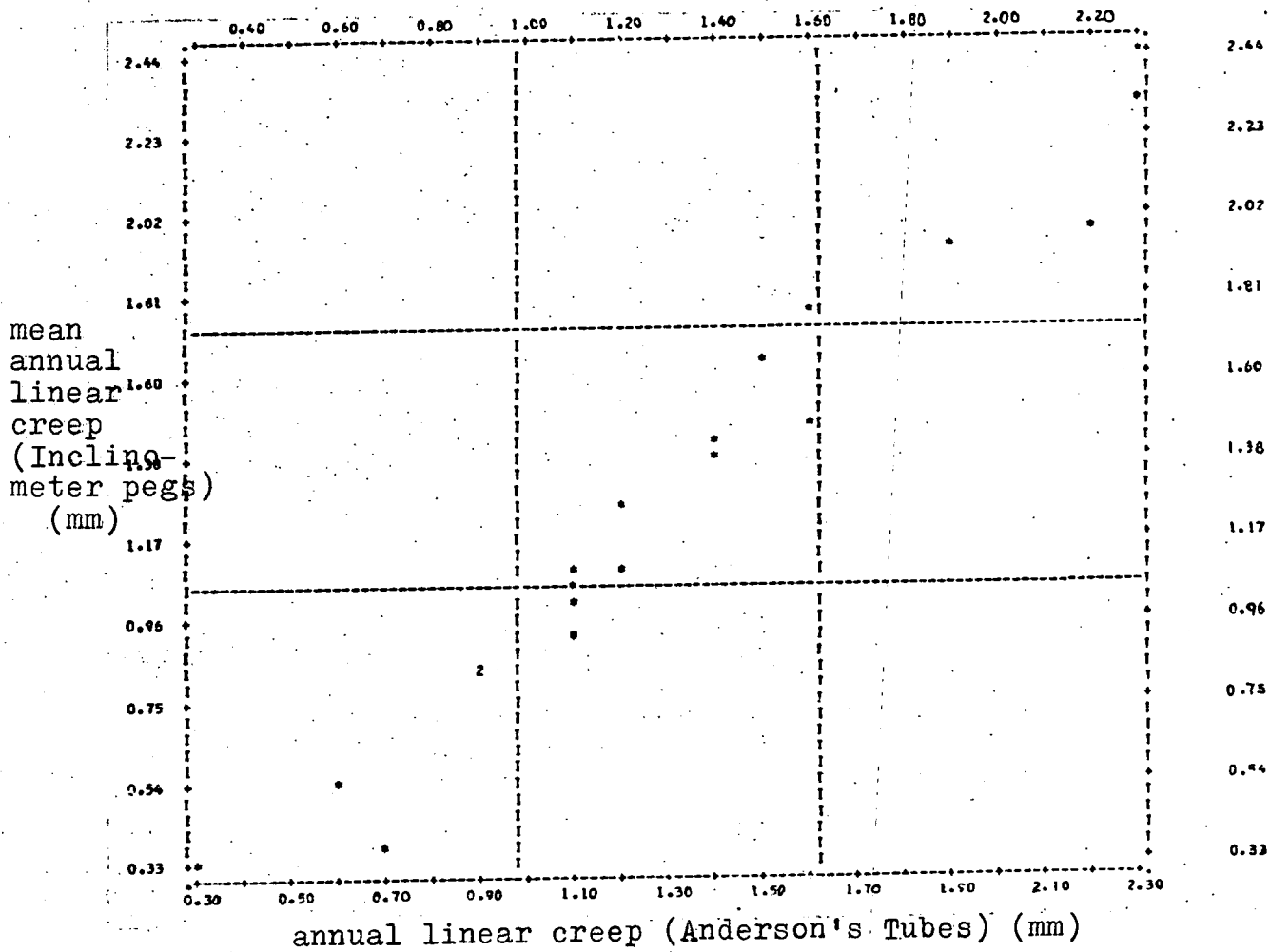


Fig 11.2 Scattergram: Mean Annual Linear Creep (Inclinometer pegs) and Annual Linear Creep (Anderson's Tubes)

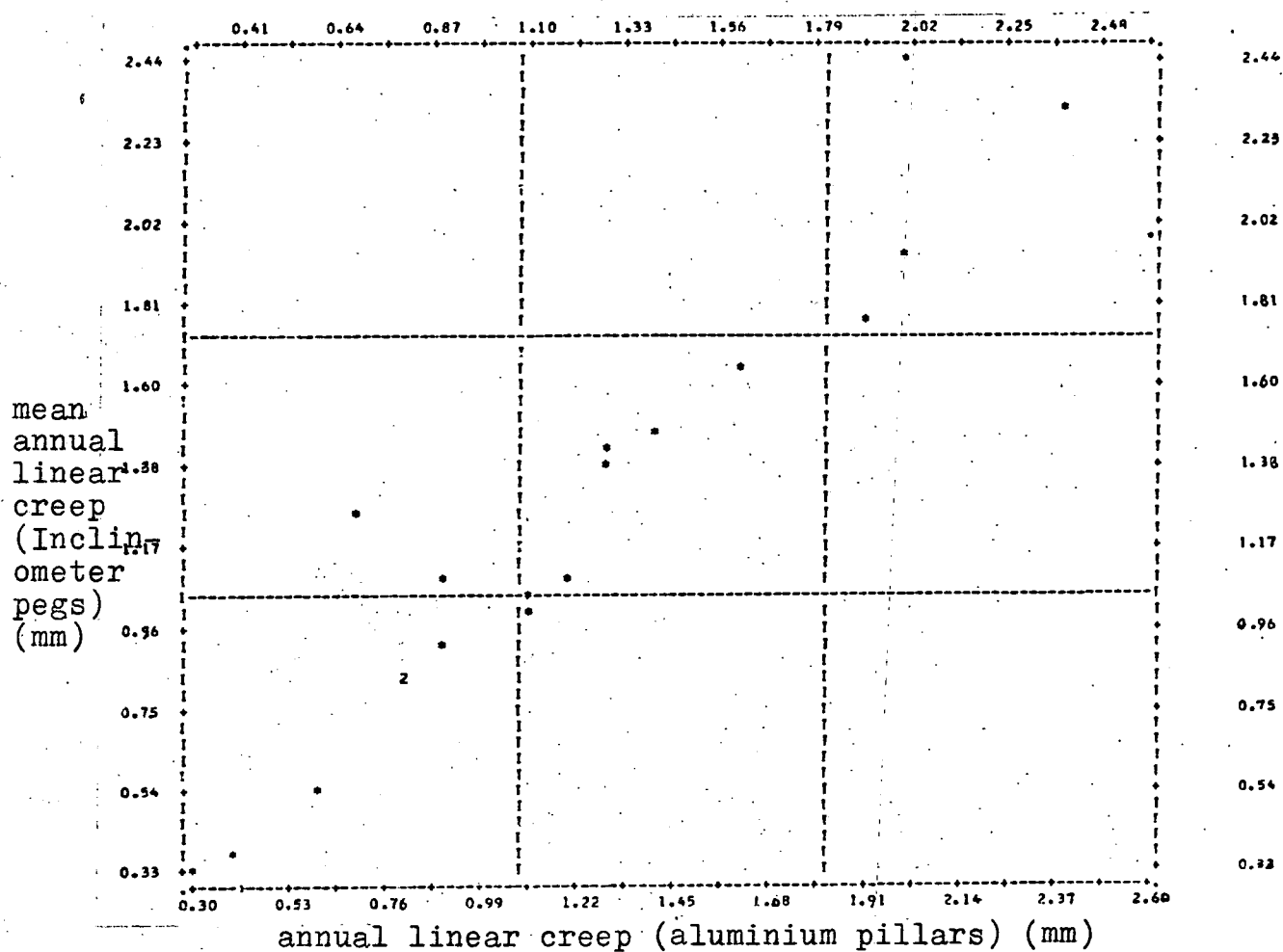


Fig. 11.3 Scattergram: Mean Annual Linear Creep (Inclinometer pegs) and Annual Linear Creep (Aluminium Pillars)

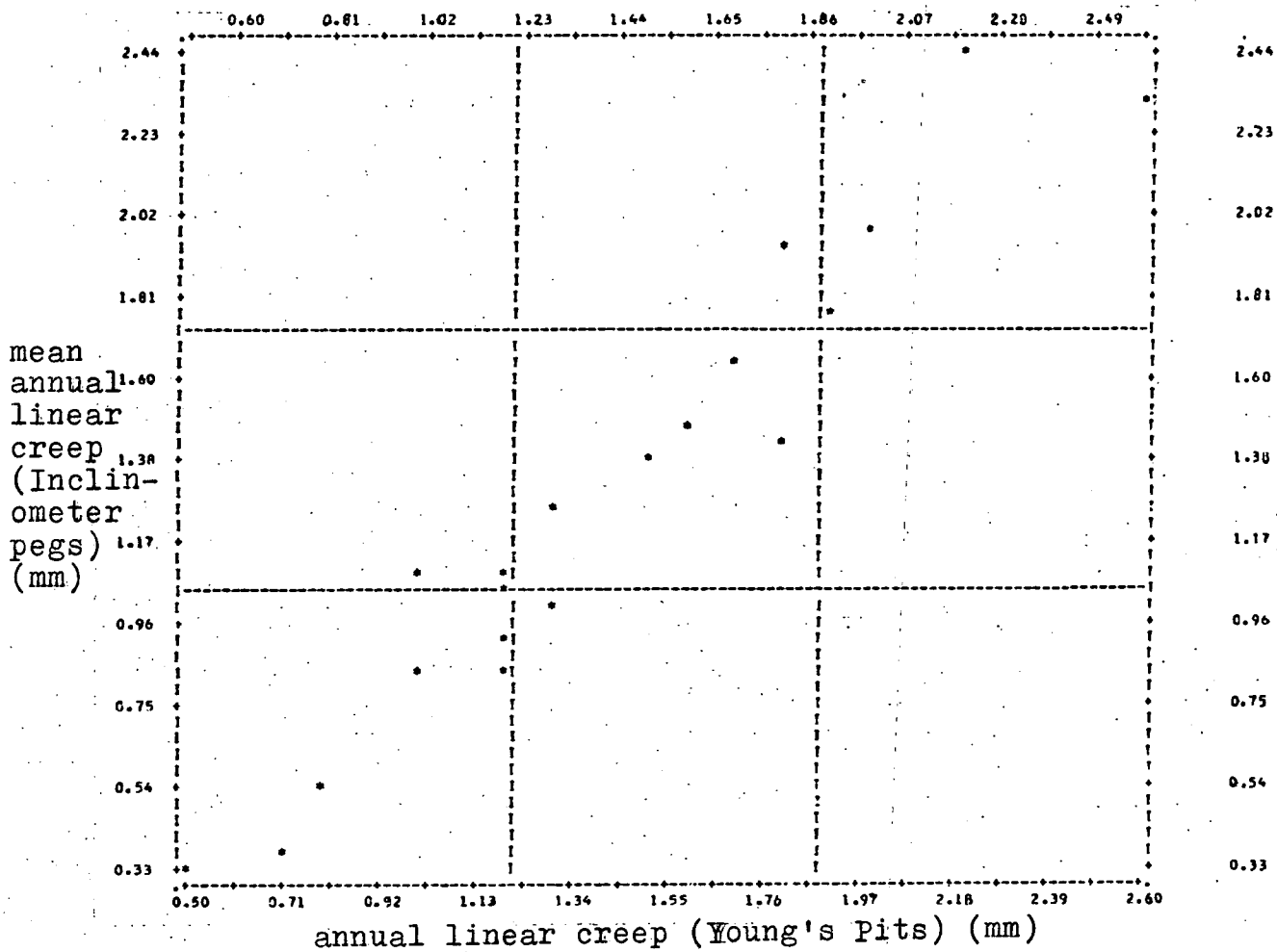


Fig. 11.4 Scattergram: Mean Annual Linear Creep (Inclinometer pegs) and Annual Linear Creep (Young's Pits)

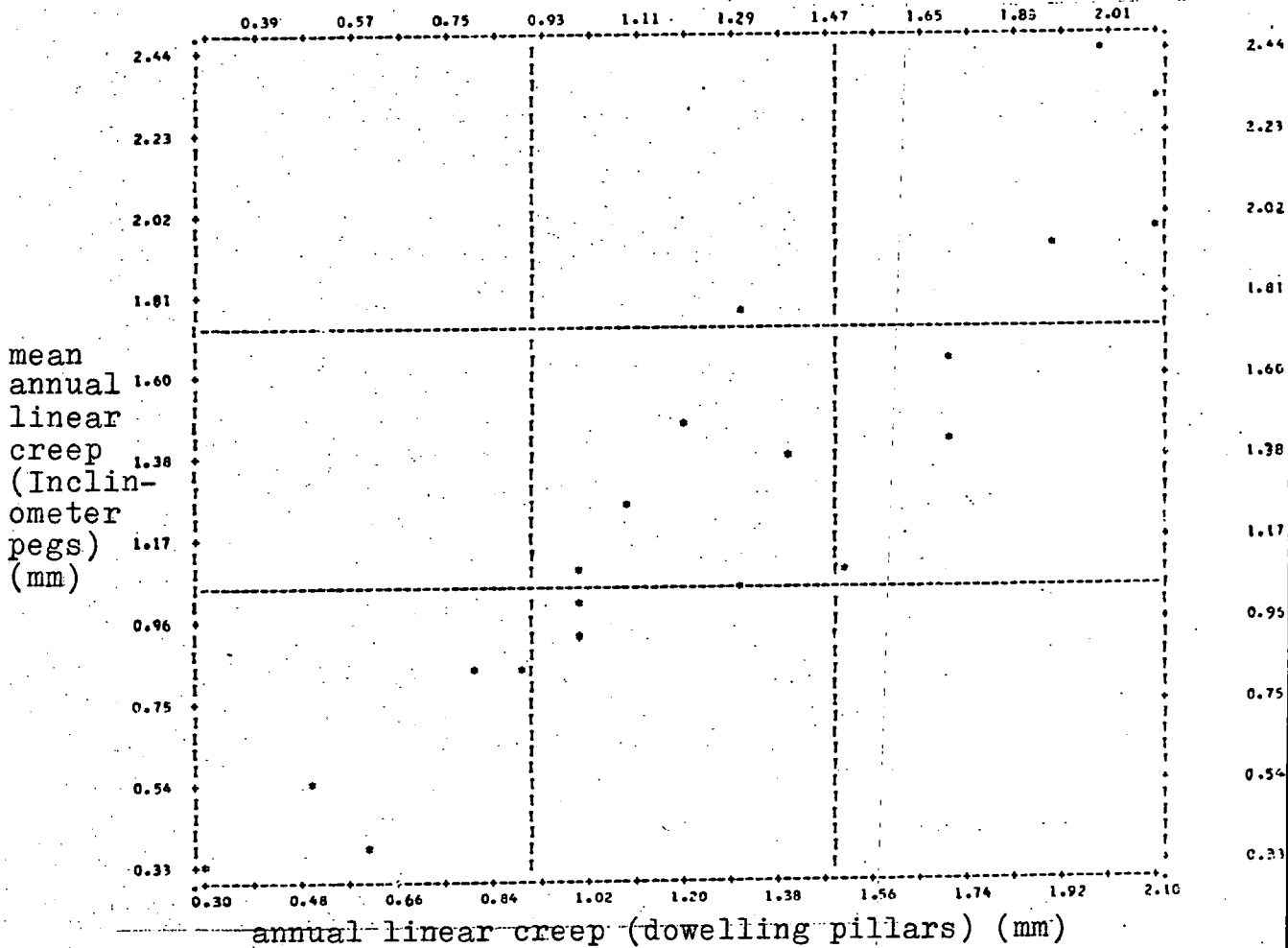


Fig. 11.5 Scattergram: Mean Annual Linear Creep (Inclinometer pegs) and Annual Linear Creep (Dowelling Pillars)

measurement.

In general, it is clear that the Cassidy's Tubes tend to read high, as rates from plots: 5, 6, 9, 11, 16, 18 and 20 are all obviously above those calculated from peg readings (Fig. 11.6). Only on plots 1 and 14 are the results lower. It seems possible therefore that the rather rigid nature of the tubing, selected to prevent any collapse inwards, militated against its recording the upslope effects of drying. Thus having attained a downslope curvature during the winter months the upslope forces resulting from soil contraction were insufficient to modify it.

11.3.3. Discussion

Major features of the experimental design were replication and the provision of a range of instruments so that differences could be determined between-plot, within-plot and within individual plots. The results for each plot were calculated from the means of the peg readings together with the results from the other instruments.

Table 11.6. Mean Annual Creep Rates (All Instruments):

	<u>All Plots (mm)</u>						
Plot	1	2	3	4	5	6	7
Mean	1.46	2.13	0.36	1.19	1.78	1.52	1.13
Standard deviation	0.26	0.25	1.08	0.17	0.31	0.29	0.11
Standard error	0.11	0.10	0.03	0.07	0.12	0.12	0.04
Plot	8	9	10	11	12	13	14
Mean	0.55	1.20	1.93	1.03	1.09	0.61	2.19
Standard deviation	0.14	0.30	0.08	0.27	0.12	0.10	0.17
Standard error	0.06	0.12	0.03	0.11	0.05	0.04	0.07

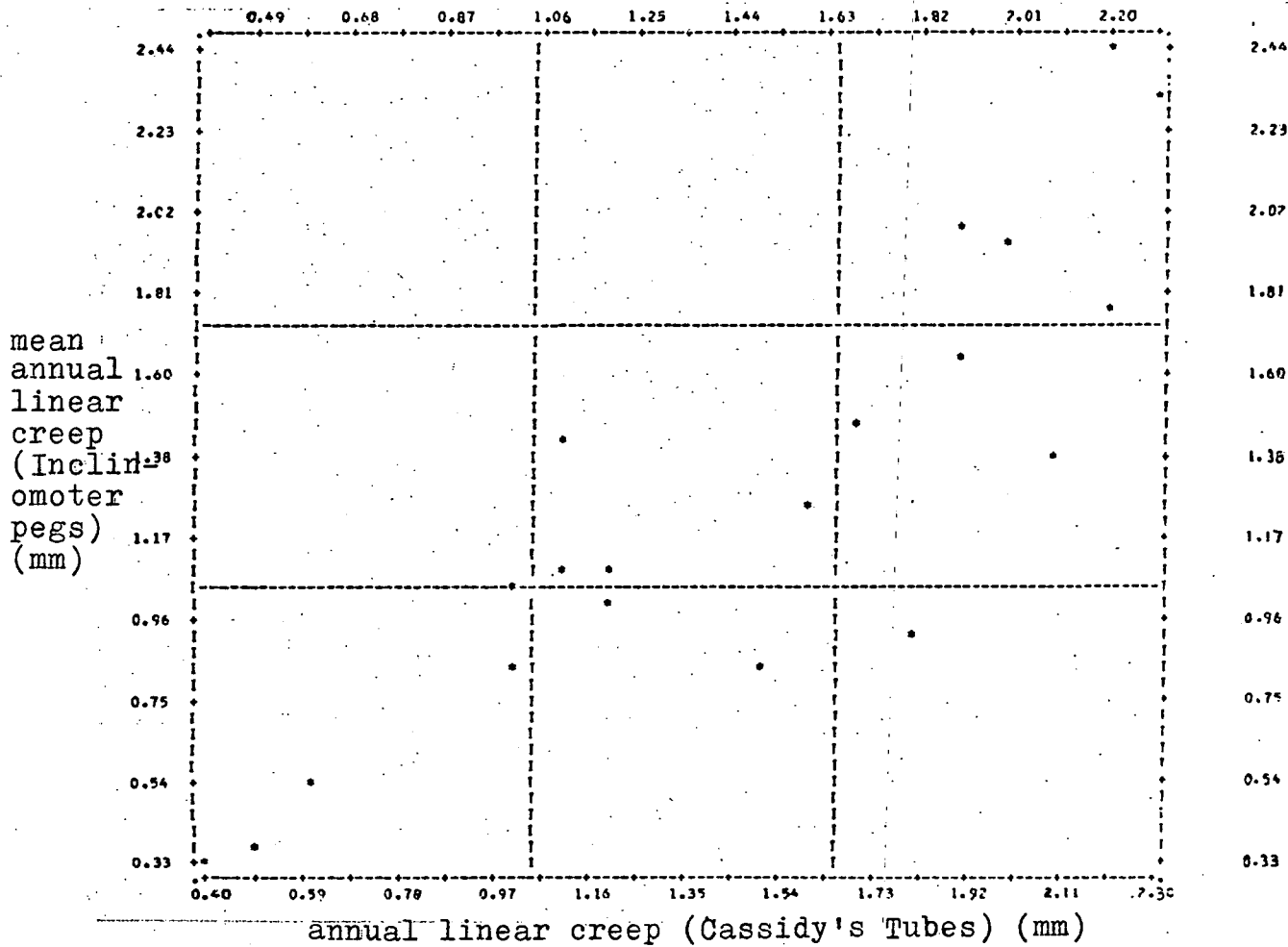


Fig. 11.6 Scattergram: Mean Annual Linear Creep (Inclinometer pegs) and Annual Linear Creep (Cassidy's Tubes)

Plot	15	16	17	18	19	20	<u>Mean</u>
Mean	1.12	1.50	2.34	1.16	0.89	1.68	1.40
Standard deviation	0.11	0.18	0.16	0.33	0.09	0.13	
Standard error	0.04	0.07	0.07	0.14	0.04	0.05	

To compare within-plot and between-plot differences, an analysis of variance was made. This demonstrated that the difference between plot means is significant at the 99% level ($F = 45.81$, critical value for $n = 120$, $k = 20$ at $\alpha = 0.01$ is 2.06).

The plot readings again indicate the grouping according to the three vegetation communities.

Table 11.7. Mean Annual Creep Rates (All Instruments):
(mm) Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean	1.24	1.94	0.77
Standard deviation	0.24	0.36	0.33

The Juncus group is clearly distinctive, but the boundary between the other groups is not so clear cut and to check on the differences, pair wise 't' tests were made. These showed that in each case the groups were distinctive at the significance level given.

Table 11.8. Distinctiveness of Annual Creep Rates (All Instruments): Plot Groups

	<u>Nardus/Pteridium</u>	<u>Juncus/Pteridium</u>	<u>Juncus/Nardus</u>
t value	2.69	6.1	4.61
Significance level (%)	95	99	99

When the standard deviation within individual plots is considered, it can be seen that plots: 1, 2, 5, 6, 9, 11 and 18 all record a relatively high value when compared with the standard deviations for the respective plot groups. In the case of plots: 1, 9, 11 and 18, the group deviation is exceeded. If the results for each instrument are examined, it will be seen that major departures from the trend, affecting the standard deviation, can be accounted for by one measurement on four of the seven plots and by two measurements on two of the remainder. Furthermore it must be remembered in this context that the Inclinator peg readings are themselves a mean derived from three or four devices. Therefore a trend is well established and apparent deviations from it can be investigated. As a result, it is found that in four cases out of the six, the Cassidy Tube accounts for at least part of the disparity. On plot 5 the dowelling pillar also appears anomalous while on plot 9 it is the aluminium pillar. On plots: 6, 11 and 18, the major discrepancy is shown by the Cassidy Tube alone and on plot 2 only the aluminium pillar departs markedly from the trend. The predominance of the Cassidy Tube indicates strongly that there may be a design weakness, particularly as in every case they produce a higher reading than the other devices. Certainly they are clearly the least consistent instrument when the general accordance of the others is considered. If the Cassidy Tube readings are discarded, the deviations in the relevant plots fit more closely into the pattern indicated in the remainder of the basin.

Table 11.9. Mean Annual Creep Rates (All Instruments except Cassidy's Tubes): Selected Plots
(mm)

Plot	5	6	9	11	18
Mean	1.70	1.40	1.12	0.93	1.03
Standard deviation	0.25	0.07	0.25	0.16	0.12
Standard error	0.11	0.03	0.11	0.07	0.05

The standard deviation of plots 5 and 9 are still large as these two plots contain, as explained earlier, a second deviant peg. Rather than delete other results from individual instruments, it is more appropriate to consider the problems of measurement already discussed. In this context it will be recalled that the dowelling pillars and Cassidy's Tubes were, for reasons of design and measurement technique, considered to be rather less accurate than the other instruments. The results for the other four devices only, should therefore be examined.

Table 11.10. Mean Annual Creep Rates (Anderson's Inclinator, Anderson's Tube, Aluminium Pillars, Young's Pits): All Plots (mm)

Plot	1	2	3	4	5	6	7
Mean	1.49	2.20	0.36	1.13	1.80	1.40	1.12
Standard deviation	0.22	0.28	0.10	0.09	0.14	0.08	0.06
Standard error	0.11	0.14	0.05	0.05	0.07	0.04	0.03

Plot	8	9	10	11	12	13	14
Mean	0.55	1.12	1.92	0.94	1.08	0.64	2.24
Standard deviation	0.17	0.29	0.09	0.18	0.13	0.11	0.19
Standard error	0.09	0.14	0.04	0.09	0.06	0.06	0.09

Plot	15	16	17	18	19	20	<u>Mean</u>
Mean	1.14	1.52	2.41	1.04	0.89	1.62	1.33
Standard deviation	0.11	0.10	0.14	0.14	0.08	0.09	
Standard error	0.06	0.05	0.07	0.07	0.04	0.04	

Using these readings, only three plots: 1, 2 and 9, exhibit deviation which is of comparable size to that of the respective plot group.

To compare within-plot and between-plot differences for this set of results, an analysis of variance was made. This showed that the difference between plot means is significant at the 99% level ($F = 53.92$, critical value for $n = 80$, $k = 20$ at $\alpha = 0.01$ is 2.17).

Using the standard error as a guide the overlap in individual plot rates can be displayed graphically (Fig.11.7). As would be expected, the rates are generally less distinctive than those recorded by the Inclinator pegs alone. However, in exactly the same way the Juncus plots show least and the Nardus plots most overlap.

11.4. Bodily Movement

Anderson's Tubes were specifically designed to provide additional data in that the pivot point can be plotted and thereby any bodily movement detected. The initial position of the upslope calibration line is plotted vertically and then, using the annual movement measurement at two levels, its new position relative to this can be constructed (Fig. 3.6 AB). There are three possible results from this procedure:

- (a) If the two lines cross at the Tube base, showing that the instrument has pivoted about this point, there is no bodily movement. The reading calculated from the tilt is therefore a true indication of creep rate.
- (b) If the new position line cuts the vertical above the base, the rate given is exaggerated since for the trigonometry used to convert the angular to a linear reading, a pivot point 12.5cm below the depth of measurement was assumed. With the new pivot position identified, the rate can be re-calculated.
- (c) If the two lines do not cross, bodily movement has occurred and this can be measured and added to the linear rate found from the angular readings.

Examples within each category occurred and these can be listed:

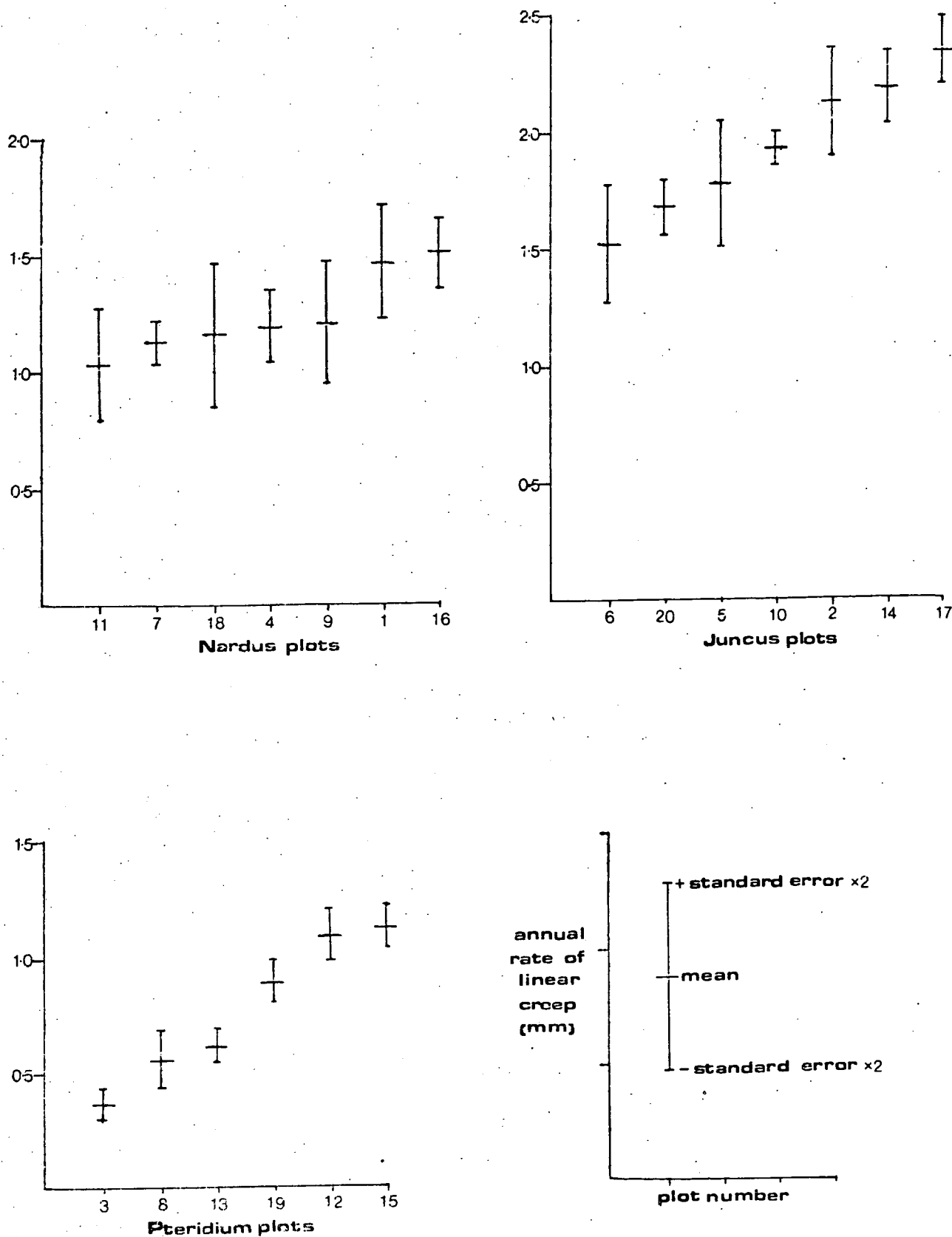


Fig. 11.7 Annual Linear Creep Rates (All Instruments):
Plot Variability

(a) plots: 7, 11, 12, 13, 19

(b) plots: 1, 3, 8, 9, 15, 16

(c) plots: 2, 4, 5, 6, 10, 14, 17, 18, 20 (Fig. 11.8
A,B,C,D)

It is noticeable that all the Juncus plots exhibit bodily movement, while for the Pteridium plots the pivot position was either at or above the base.

The Anderson Tube results already listed, which were calculated from tilt measurements only, can therefore be adjusted.

Table 11.11. Annual Creep Rates (Anderson's Tube): (mm)
Adjusted for Bodily Movement

Plot	1	2	3	4	5	6	7
before adjustment	1.4	2.2	0.3	1.2	1.6	1.4	1.1
adjusted	1.2	2.3	0.3	1.3	1.8	1.7	1.1
Plot	8	9	10	11	12	13	14
before adjustment	0.7	1.2	1.9	0.9	1.1	0.6	2.3
adjusted	0.5	1.1	2.4	0.9	1.1	0.6	3.1
Plot	15	16	17	18	19	20	<u>Mean</u>
before adjustment	1.1	1.6	(2.3)	1.1	0.9	1.5	1.32
adjusted	0.8	1.3	(2.8)	1.3	0.9	1.6	1.41

When compared with the rates before adjustment, these readings show a general slight decrease for Pteridium plots and an increase for Juncus plots. Thus the plot groupings appear slightly more distinctive. However it must be stressed that as they refer only to one instrument on each plot, they cannot replace the peg results as the standard set. Furthermore, since they were produced by a different device, their employment to adjust the peg readings could not be justified. They are seen therefore as providing an

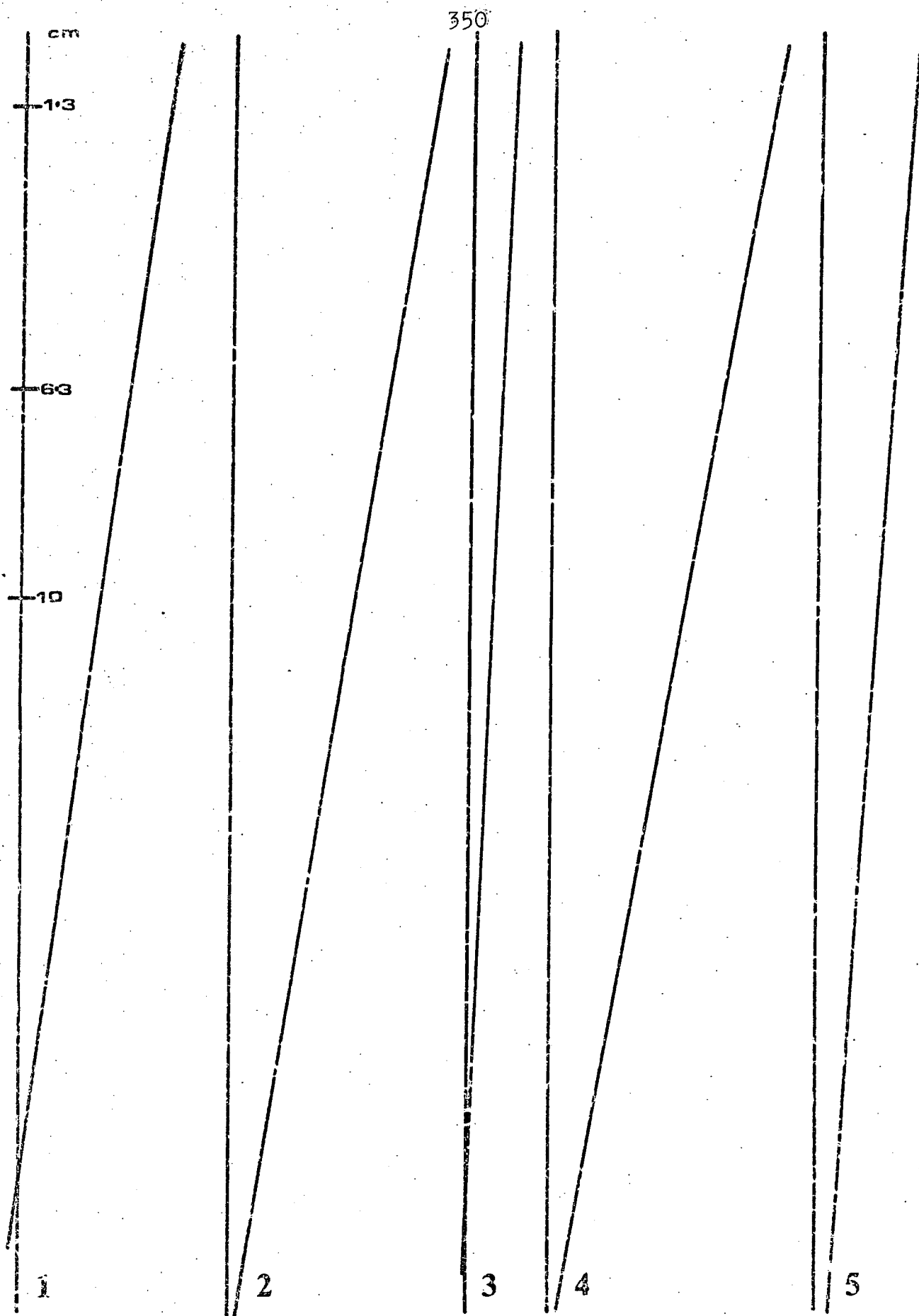


Fig. 11.8A

Anderson's Tubes: Bodily Movement
(plots 1-5)

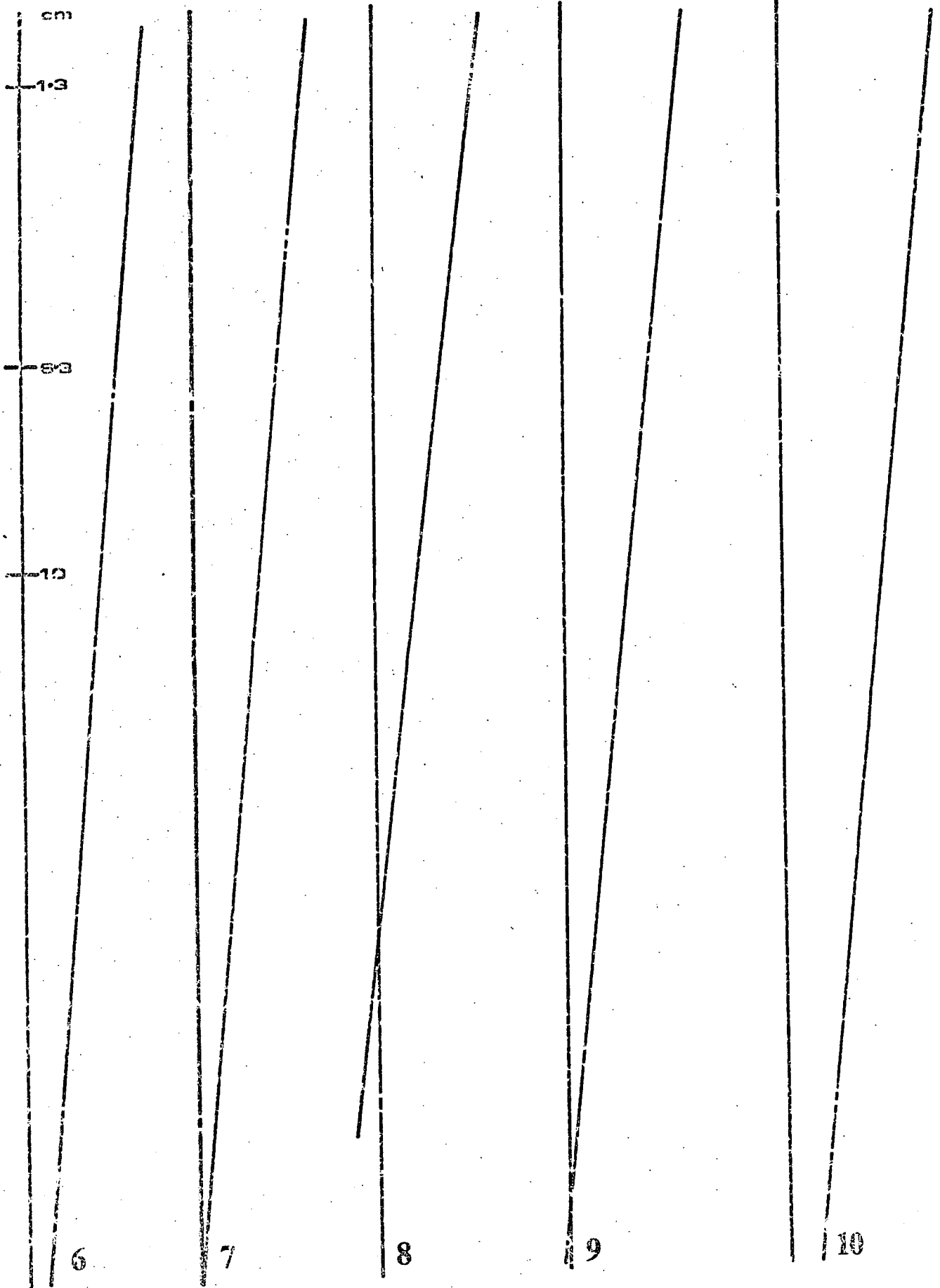


Fig. 11.8B. Anderson's Tubes: Bodily Movement
(plots 6-10)

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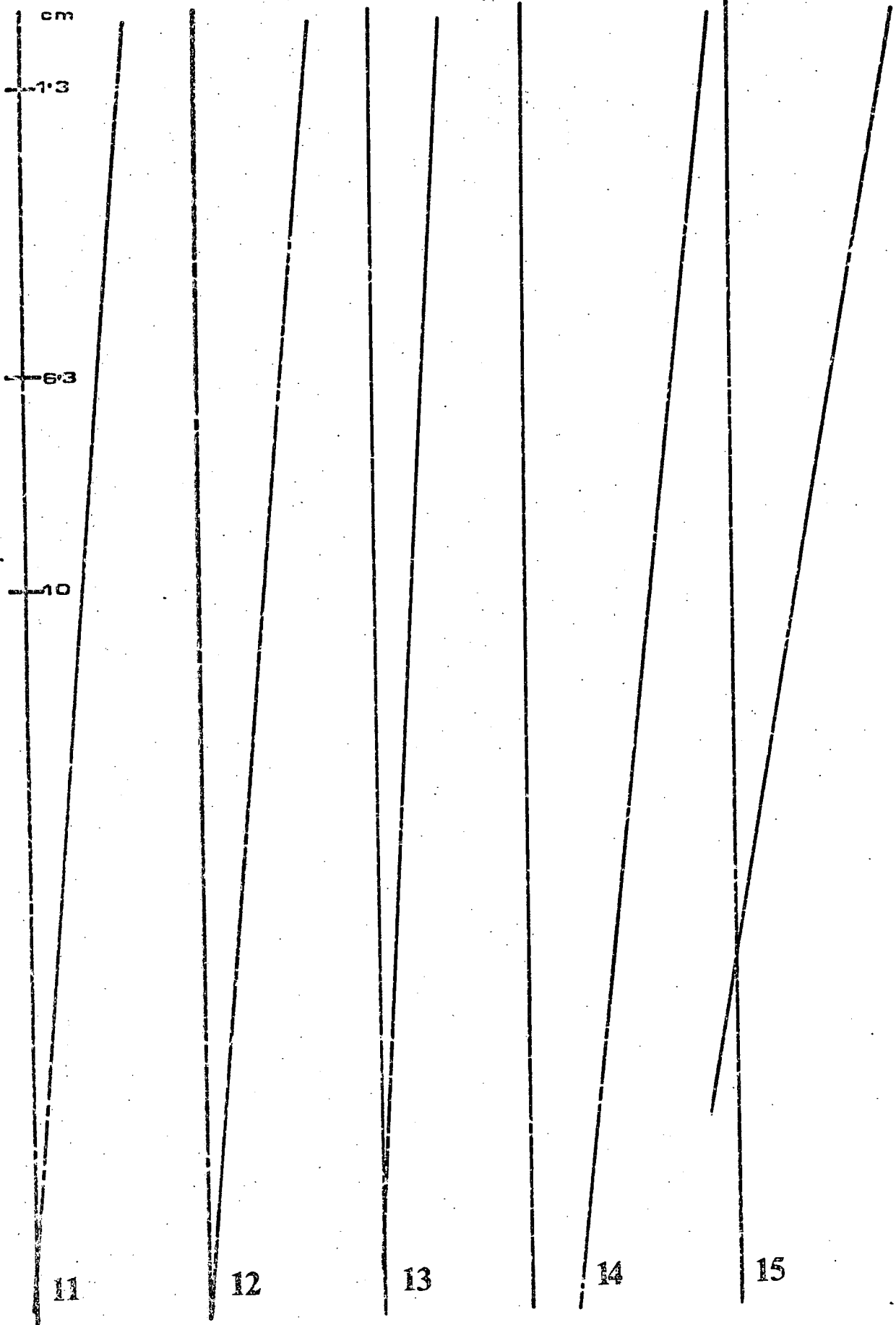


Fig. 11.8C Anderson's Tubes: Bodily Movement
(plots 11-15)

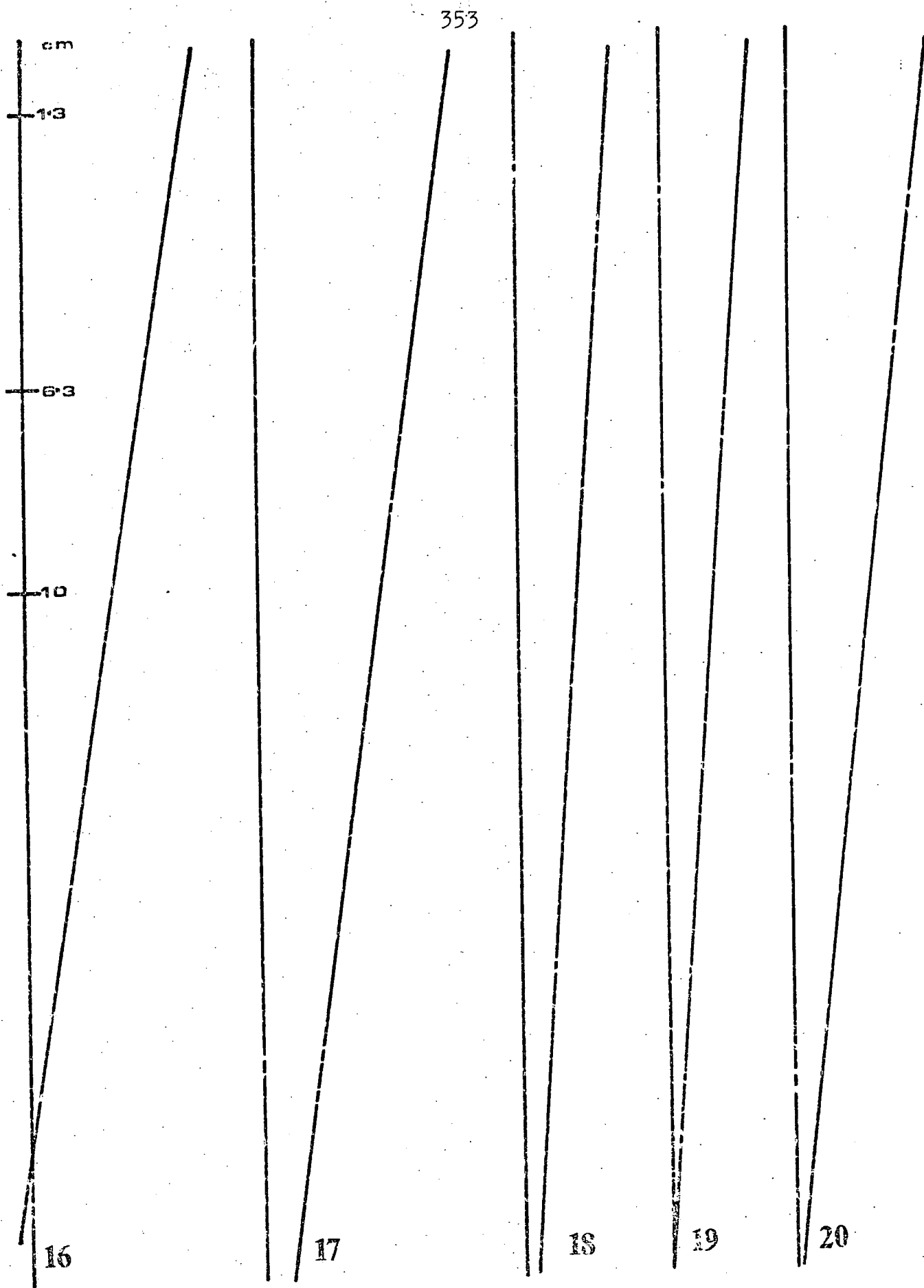


Fig. 11.8D Anderson's Tubes: Bodily Movement
(plots 16-20)

indicator which can be taken into account when the factors controlling creep rates are considered.

11.5. Maximum Depth of Movement

Three of the plot instruments provide a velocity profile so that the maximum depth of movement can be assessed. Dowelling pillars and Cassidy's Tubes are each inserted as a continuous column and the appropriate depth can be obtained by using Vernier callipers to measure the distance from the base of the root mat to the point where the curve in the profile ceases (Figs. 11.9 A,B,C and 11.10 A,B,C). Readings were taken to the nearest 0.5cm.

As the inserts for the Young's Pits did not constitute a continuous column, they were not used for the accurate measurement of the depth of movement. However, since the rod movement was recorded on the acetate strips, it was possible to note the depth to the nearest 2.5cm position.

Table 11.12 Maximum Depth of Movement: (cm)
 Plot Measurements

Plot	1	2	3	4	5	6	7
Dowelling Pillars	12.5	11.0	7.5	5.5	13.0	12.0	11.0
Cassidy's Tubes	10.5	11.0	8.0	9.0	15.0	12.5	11.0
Young's Pits	10.0	12.5	10.0	7.5	12.5	10.0	(10.0)
Plot	8	9	10	11	12	13	14
Dowelling Pillars	8.0	7.0	(11.0)	8.5	10.5	10.0	11.5
Cassidy's Tubes	9.0	11.0	11.0	12.0	10.5	8.5	8.5
Young's Pits	7.5	12.5	10.0	7.5	10.0	7.5	10.0
Plot	15	16	17	18	19	20	<u>Mean</u>
Dowelling Pillars	6.0	14.0	14.5	7.5	12.5	13.0	10.3
Cassidy's Tubes	9.0	13.5	14.0	12.0	10.5	13.0	11.5
Young's Pits	10.0	10.0	12.5	10.0	10.0	12.5	10.1

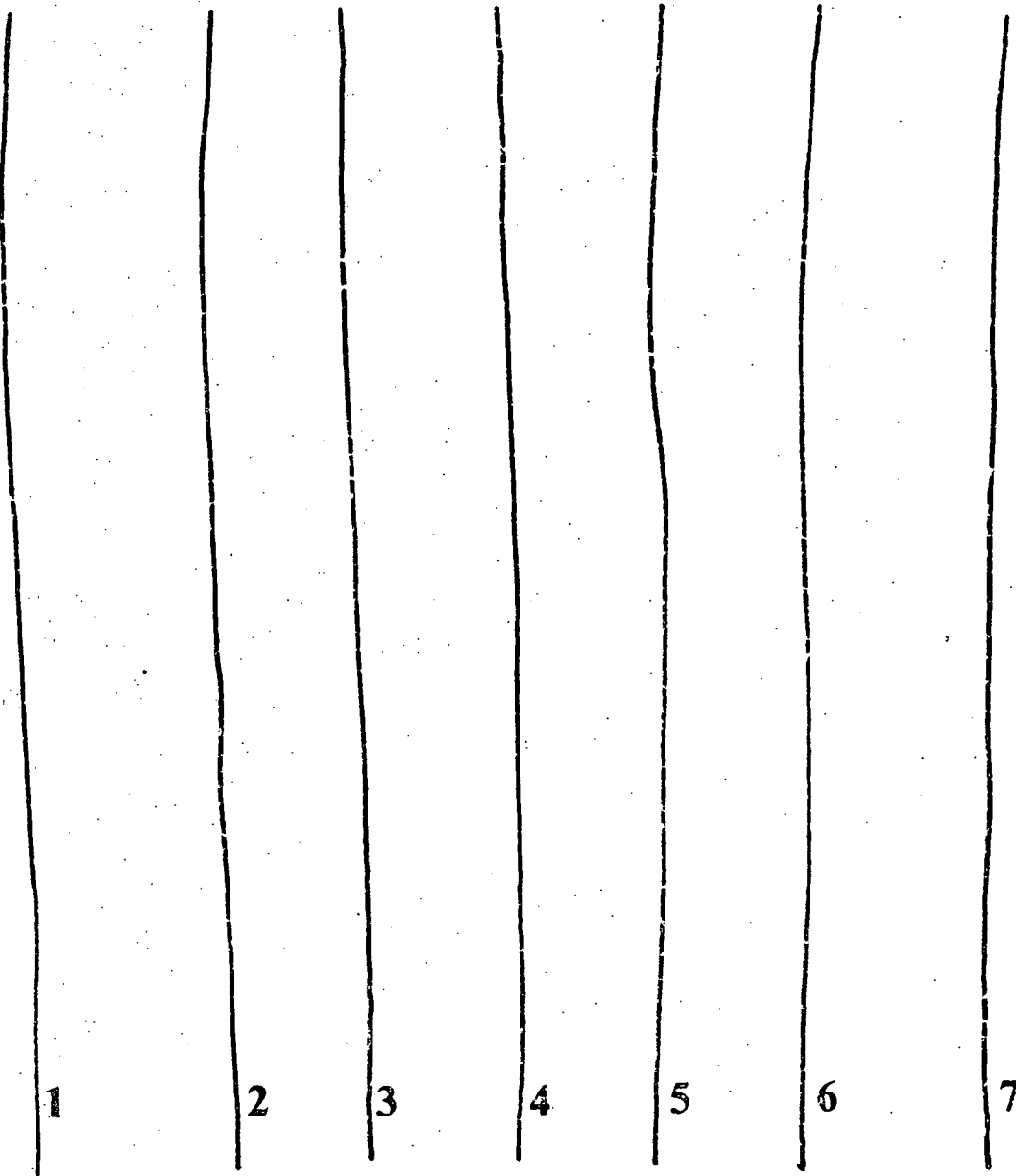


Fig. 11.9A

Dowelling Pillars: Depth Profiles
(plots 1-7)

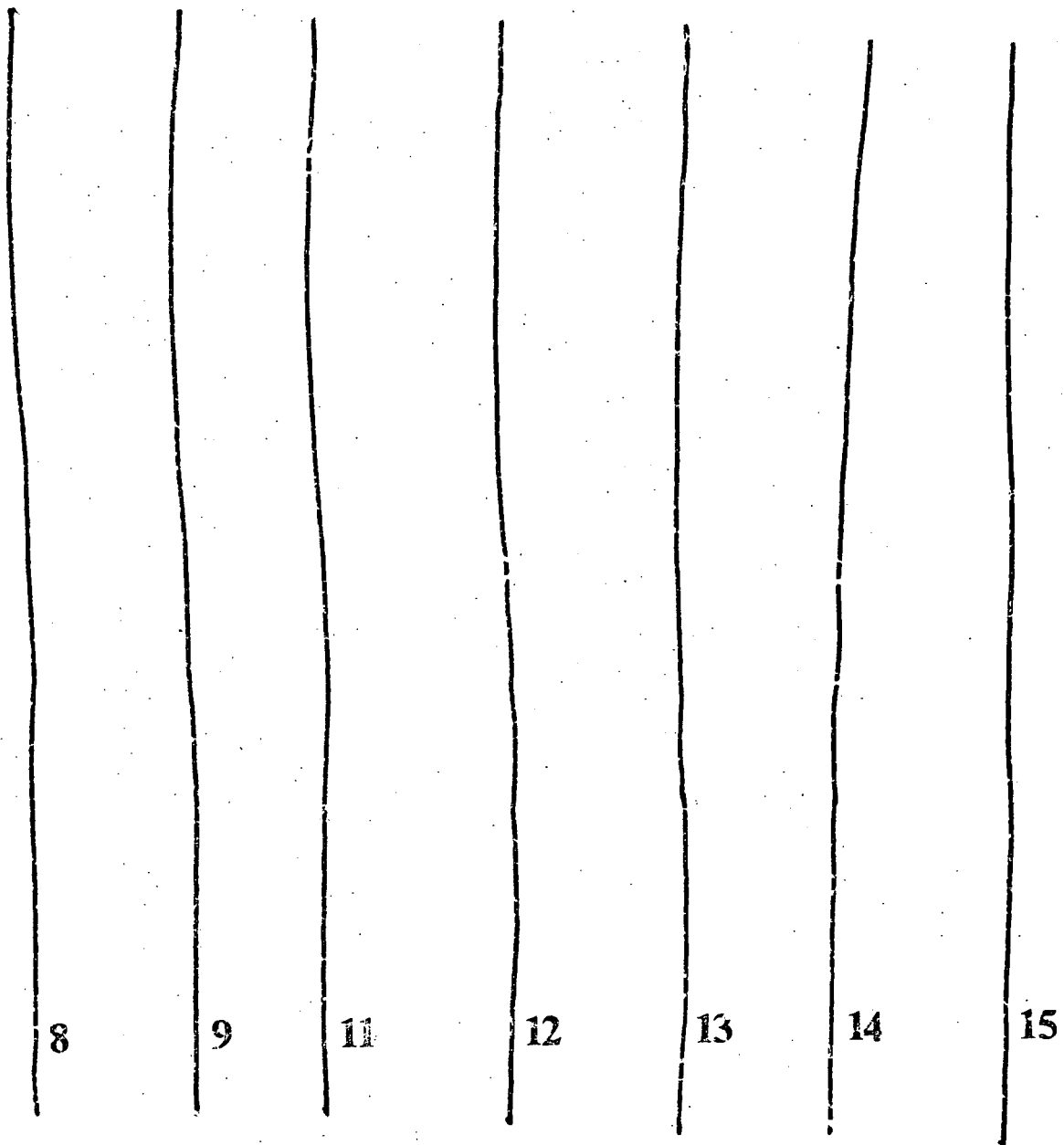


Fig. 11.9B

Dowelling Pillars: Depth Profiles
(plots 8-15)

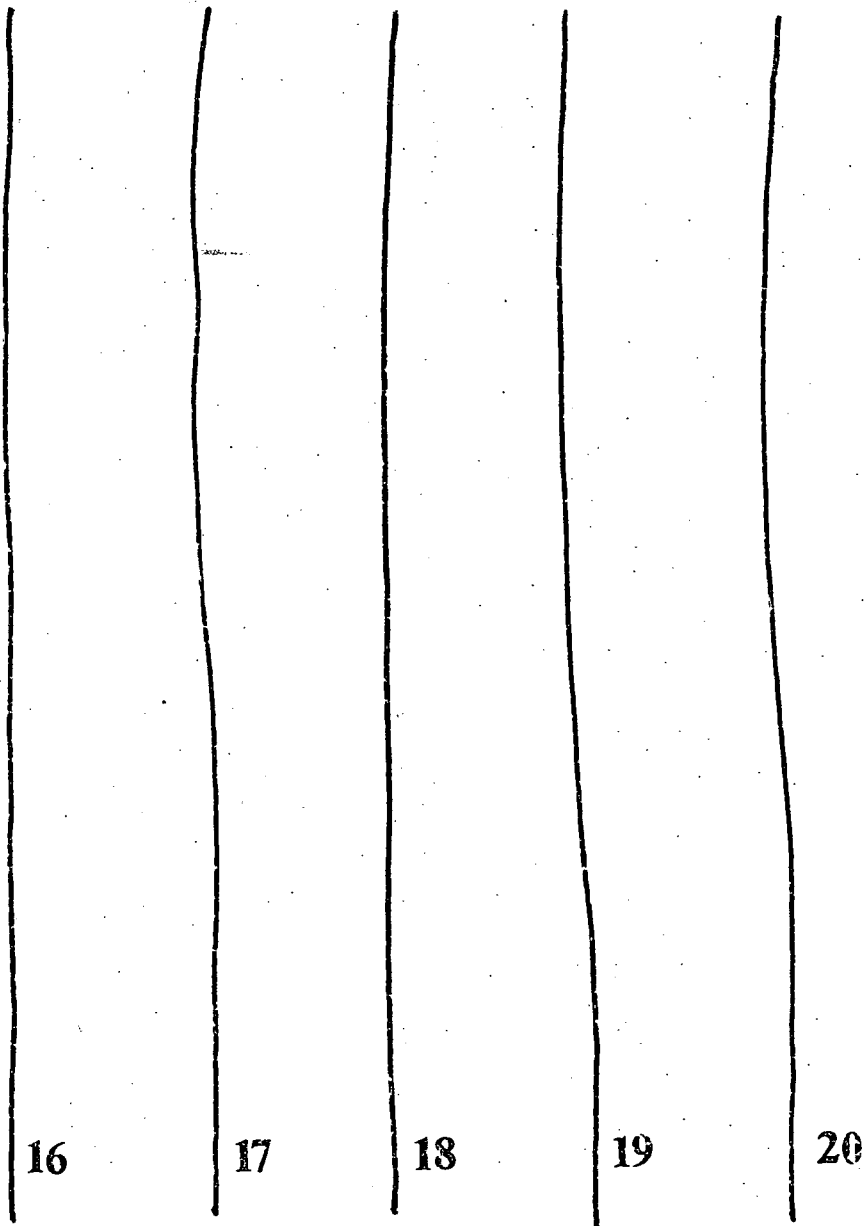


Fig. 11.9C Dowelling Pillars: Depth Profiles
 (plots 16-20)

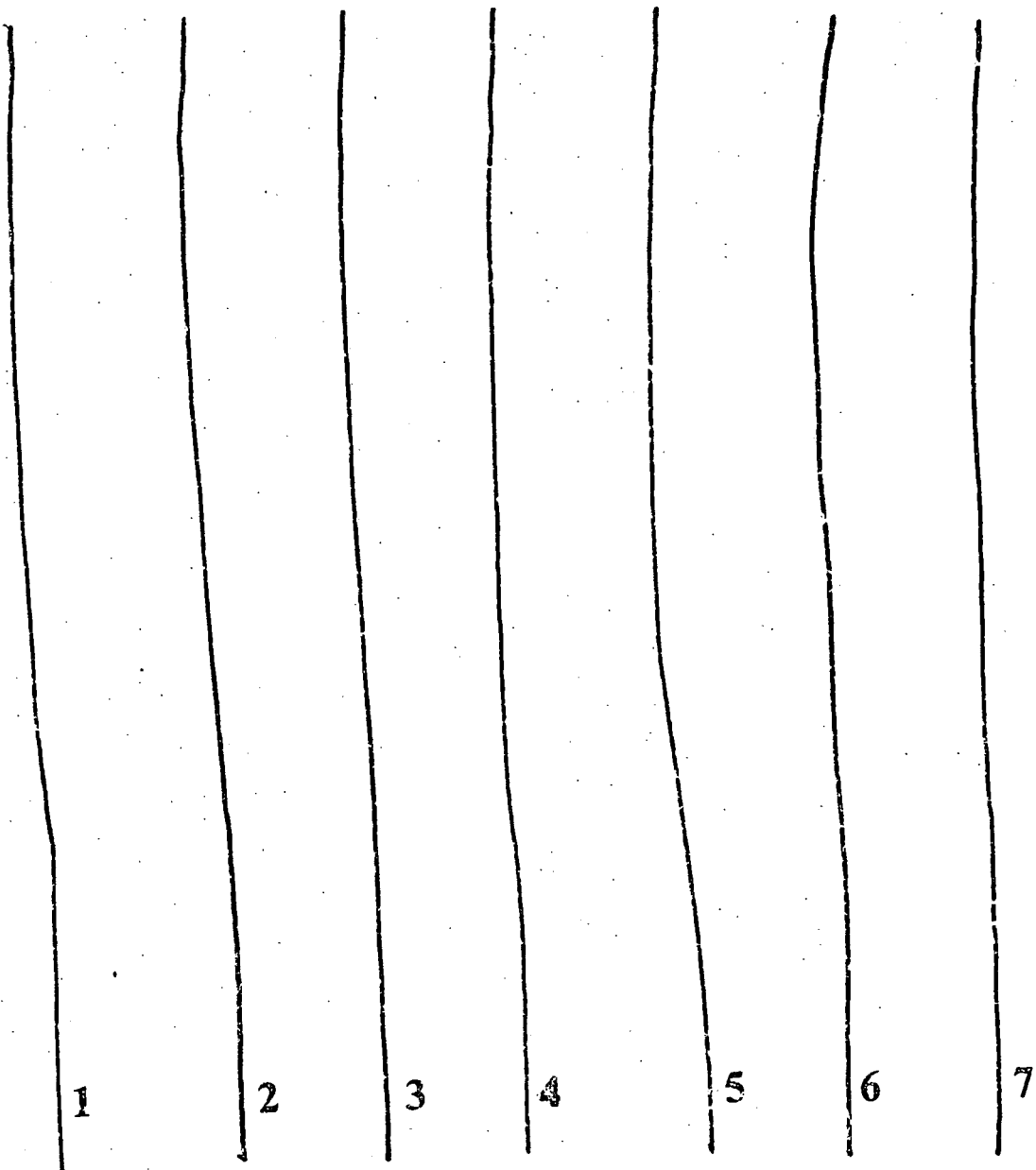


Fig. 11.10A Cassidy's Tubes: Depth Profiles
(plots 1-7)

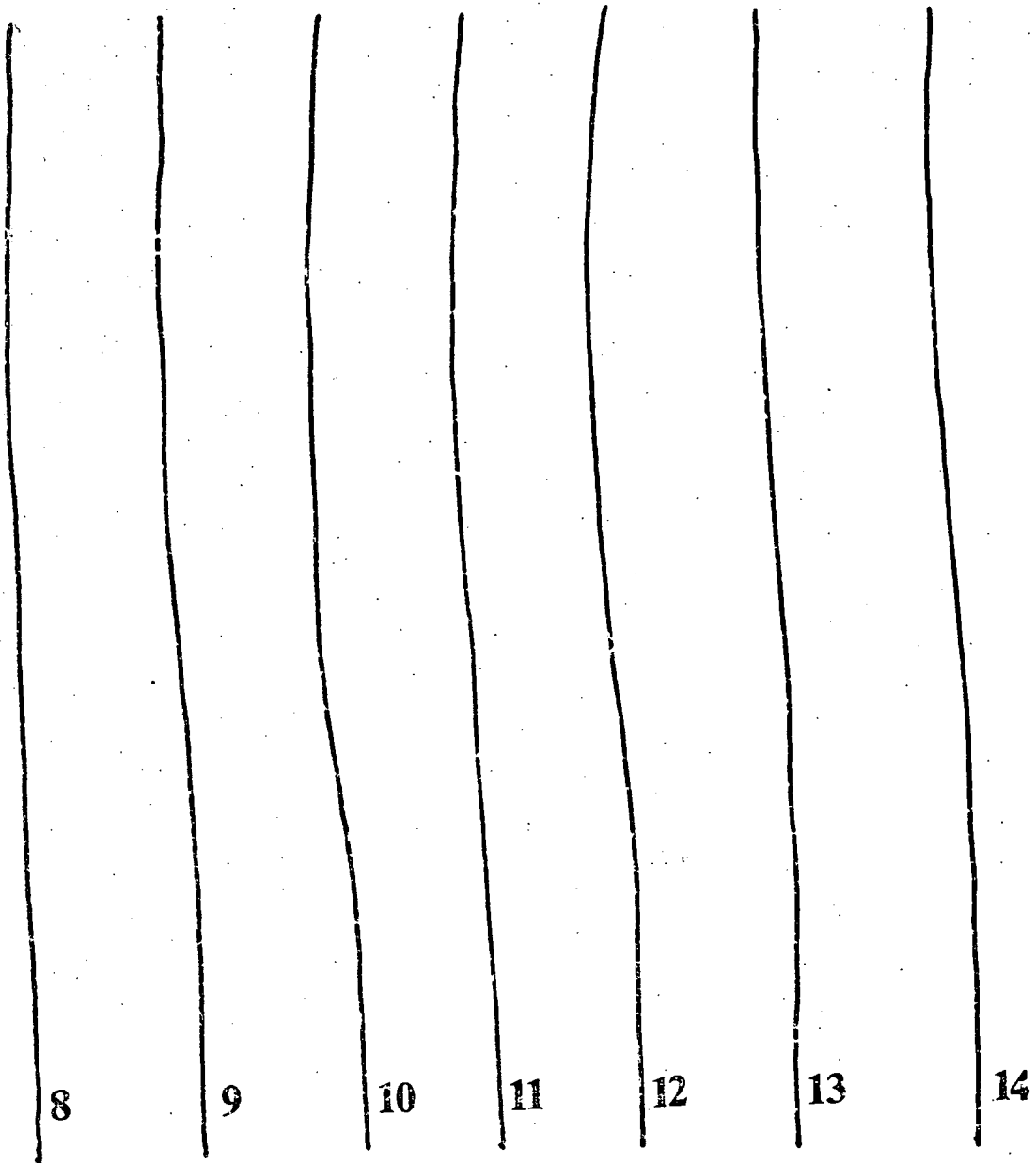


Fig. 11.10B Cassidy's Tubes: Depth Profiles
(plots 8-14)

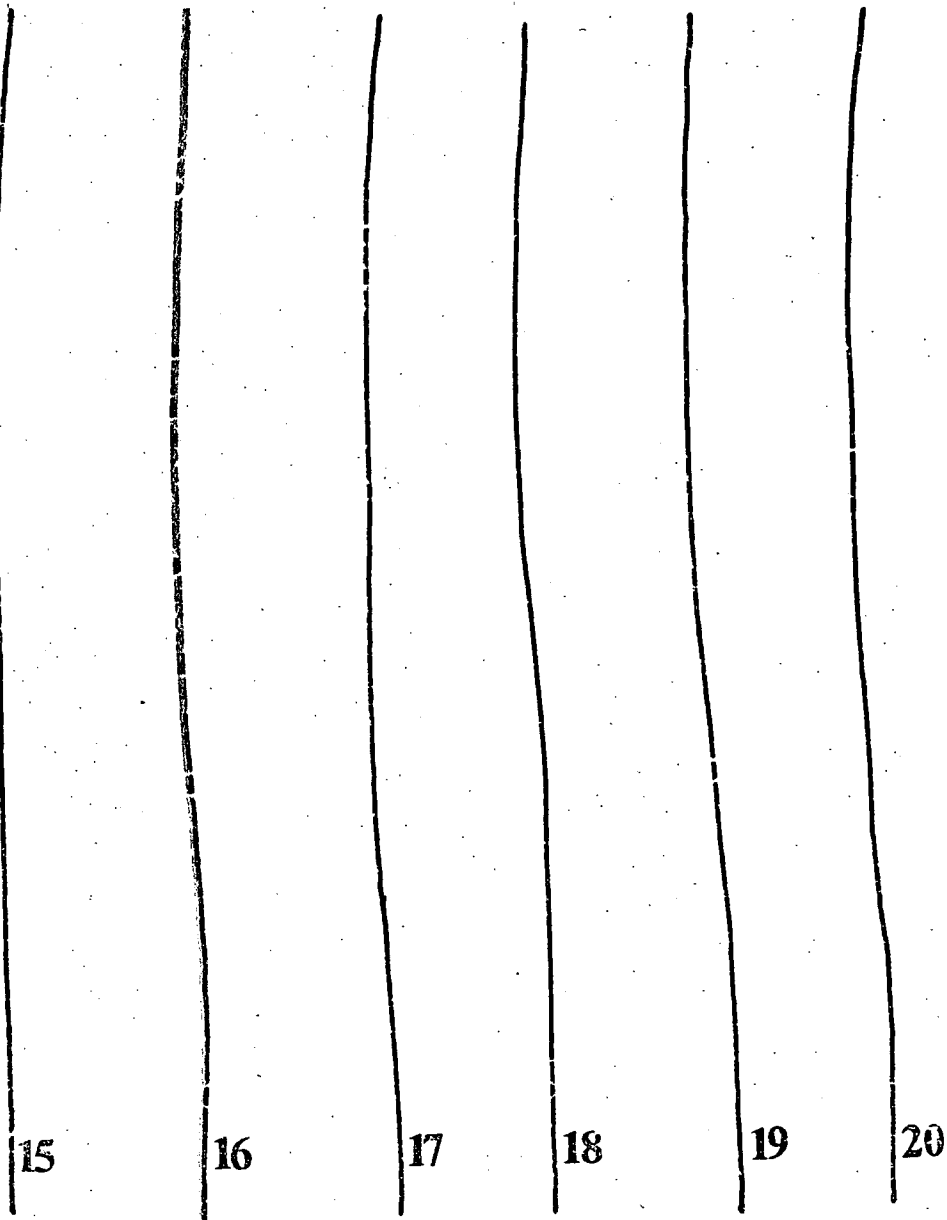


Fig. 11.10C Cassidy's Tubes: Depth Profiles
(plots 15-20).

While, for the reasons already discussed, the readings from dowelling pillars must be treated with caution, it is considered that the results for depth of movement provide a reliable guide. Since measurement was only required to 0.5cm it was not, in contrast to the determination of creep rates, approaching the limits of accuracy of the technique. The grouping according to the three vegetation communities again emerges with the deepest movement discernible on the Juncus plots and the shallowest on the Pteridium plots. The Nardus plots vary from a maximum of 14.0cm to a minimum of 7.0cm, thereby spanning almost the entire range. For this factor the boundaries between the three groups are therefore less clearly defined than for creep rates.

If the Cassidy's tube results are compared with those obtained from the dowelling pillars it will be seen that they follow the same general pattern. Marked discrepancies occur on six plots: 4, 9, 11, 14, 15 and 18, and in all but one of these cases the tube provided a higher value. Despite this, the groupings according to vegetation community are again in evidence. Since the curve was already smooth, rather than a jointed line, the device is considered in this respect more accurate than pillars. However, this must be counteracted by the inherent unreliability exhibited in monitoring the creep rates. Therefore, there is little to choose between the reliability of the two methods of measurement.

When the difficulties of recognising and recording the extremely small movement of the lower rods is taken into account, it can be seen that the Young's Pit results follow the trend set by the other two devices. Notable discrepancies occur only on plots: 3, 9 and 16. Therefore as there was general agreement, it was decided to use the mean of the dowelling pillar and Cassidy tube readings as the basis for further analysis.

Table 11.13. Mean Maximum Depth of Movement (Dowelling Pillars and Cassidy's Tubes): Plot Measurements

Plot	1	2	3	4	5	6	7
Mean max. depth of movement (cm)	11.5	11.0	7.7	7.2	14.0	12.2	11.0

Plot	8	9	10	11	12	13	14
Mean max. depth of movement (cm)	8.5	9.0	11.0	10.2	10.5	9.2	10.0

Plot	15	16	17	18	19	20	<u>Mean</u>
Mean Max. depth of movement (cm)	7.5	13.7	14.2	9.7	11.5	13.0	10.6

As previously discussed, these readings can be grouped according to the vegetation community, but there is considerably more overlap than when the plots were similarly grouped to analyse rates of creep. In fact the Pearson's product moment correlation coefficient for rate and maximum depth of movement is only 0.59, which is not significant.

To investigate further the distinctiveness of plot variations, the mean values for the maximum depth of movement were grouped according to the vegetation community.

Table 11.14. Mean Maximum Depth of Movement: Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean (cm)	10.2	12.1	9.1
Standard deviation	2.1	1.6	1.6
Standard error	0.8	0.6	0.7

While the expected variations in the mean occur, there is obviously a strong possibility that these results represent a small population which exhibits gradual changes.

To check on the differences between the plot groups, pair wise 't' tests were made. Only one boundary was found to be significant at or above the 95% level.

Table 11.15. Distinctiveness of Mean Maximum Depth of Movement: Plot Groups

	<u>Nardus/Pteridium</u>	<u>Juncus/Pteridium</u>	<u>Juncus/Nardus</u>
t value	1.04	3.26	1.9
Significance level (%)	-	99	-

It could be interpreted that small differences according to plot group occur but that there is little overall variation. While depth of movement depends on a number of factors, this general level of consistency would have been expected. Indeed it has already been discussed at some length in connection with peg design and the pivot point. Thus it can be concluded that unlike the creep rate, the downward limit of the velocity profile is not an important discriminatory factor. Furthermore, when it is recalled that the predominant vegetation community is utilised for grouping basically as a summary of a range of factors, including soil and moisture characteristics, it is unlikely that any other grouping will produce more clear cut boundaries. Therefore while it cannot be said to vary randomly, the zone within which seasonal creep occurs can be treated as a layer of variable depth not exceeding 15cm.

11.6. Volumetric Rates of Creep

Using the mean maximum depth of movement for each plot in conjunction with its linear creep rate, a volumetric measure can be calculated. This is defined as: 'the volume moved annually across a plane perpendicular to the ground surface and parallel with the contour of the slope, for unit horizontal distance along the plane' (Young, 1972).

Table 11.16. Volumetric Rates of Creep: Plot Measurements

Plot	1	2	3	4	5	6	7
Volumetric rate (cm ³ /cm/yr)	0.9	1.1	0.1	0.4	1.3	0.9	0.6

Plot	8	9	10	11	12	13	14
Volumetric rate (cm ³ /cm/yr)	0.2	0.6	1.1	0.5	0.6	0.3	1.2

Plot	15	16	17	18	19	20	<u>Mean</u>
Volumetric rate (cm ³ /cm/yr)	0.4	1.0	1.7	0.5	0.5	1.1	0.75

These volumetric measurements can be divided into three groups according to the vegetation community, with the Juncus plots displaying the greatest movement and the Pteridium plots the least. However, there is a certain blurring at the boundaries and this can best be shown using the grouped results.

Table 11.17. Volumetric Rates of Creep: Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean (cm ³ /cm/yr)	0.64	1.20	0.35
Standard deviation	0.22	0.25	0.19
Standard error	0.08	0.10	0.08

To examine the differences between the plot groups, pair wise 't' tests were made and these demonstrated that each is significant at the level stated.

Table 11.18 Distinctiveness of Volumetric Rates of Creep:
Plot Groups

	<u>Nardus/Pteridium</u>	<u>Juncus/Pteridium</u>	<u>Juncus/Nardus</u>
t value	2.64	6.75	4.44
Significance level (%)	95	99	99

These results are similar to those using linear creep rates but improved clarification would not be expected since readings for maximum depth of movement were not highly correlated with creep rates.

11.7. Comparison with other Results

The calculation of both linear and volumetric annual rates of creep allows comparisons to be made with the results published by other workers. As discussed initially in this study, there has been in recent years, a marked increase in the study of geomorphological processes. However this has not tended to focus on soil creep and consequently the number of readings available for comparison is limited. When the results from other climatic regions have been discarded, the choice is even more restricted. The following table summarizes observed rates of creep obtained in temperate latitudes (Anderson and Finlayson, 1975).

Table 11.19. Comparison with Other Published Creep Rates

<u>Source</u>	<u>Method</u>	<u>Movement of surface or upper 5cm mm/yr</u>	<u>Volumetric movement cm³/cm/yr</u>
Young 1960, 1963 ^b	Surface and buried pegs	1-2	0.5
Rapp 1960, 1967	Surface pegs	100	-
Everett 1963	Buried plates	1	6.0
Kirkby 1963, 1967	Surface and buried pegs	1-2	2.1
Kojan 1967	Buried tubes	10-50	650
Owens 1969	Buried tubes	11	3.2
Evans 1974	Surface pegs	0.6	-
Anderson 1977	Tubes and surface pegs	1.2	0.5-1.0

Since the readings were obtained from different locations, comparisons cannot be exact. Furthermore it would be expected that rates from a warm temperate area, such as those produced by Kojan in California, would be enhanced since the sparser vegetation cover exercises less control and also allows free access to meteorological elements. Similarly at the other extreme of temperate climates, Rapp, working in Northern Sweden, obtained high values since he was dealing basically with solifluction. Owens, in the Southern Alps, New Zealand, was also making measurements in an area liable to excessive freeze-thaw cycles.

The remaining results recorded by Young and Evans in the Upper Derwent valley, Central Pennines, Kirkby in the Water of Deugh Basin, Galloway, and Everett in Ohio, U.S.A. are all from climatically comparable locations. It will be seen that the readings obtained from the Rookhope basin

accord well with these and also with the general concurrence of results for humid temperate climates identified by Young (1974A). Therefore it is considered that for this reason together with other arguments advanced during discussions on instrument validation, experimental design and the analysis of readings, the results recorded in the Rookhope basin represent a valid measurement of the annual rates of creep.

11.8. Instrument Comparison

Since all the instruments were designed and employed to measure the same geomorphological process, it would be expected that the results would be highly correlated. Pearson's product moment correlation coefficients are tabulated (all significant at the 99% level).

Table 11.20. Correlation Matrix of Instrument Results

	<u>Inclin- ometer Pegs</u>	<u>Anderson's Tube</u>	<u>Alumin- ium Pillars</u>	<u>Young's Pits</u>	<u>Dowell- ing Pillars</u>	<u>Cassidy's Tubes</u>
Inclin- ometer Pegs	1.00	0.98	0.93	0.96	0.93	0.87
Ander- son's Tube		1.00	0.95	0.95	0.94	0.85
Aluminium Pillars			1.00	0.92	0.92	0.80
Young's Pits				1.00	0.90	0.86
Dowelling Pillars					1.00	0.76
Cassidy's Tubes						1.00

Within the generally high level of accordance the Cassidy's Tubes are quite distinctive in yielding with each instrument the lowest correlation. If on the other hand the highest correlation coefficient for each device is identified, it is found that the Inclinometer pegs are responsible in three instances and the Anderson's Tube in two. If the two highest coefficients are used, the aggregate

results can be listed.

Table 11.21. Correlation Matrix Analysis

	<u>Inclinometer Pegs</u>	<u>Anderson's Tubes</u>	<u>Young's Pits</u>	<u>Aluminium rods</u>
Number of high correlations	5	4	2.5	0.5

(0.5 indicates a tied score)

Bearing in mind the other evidence already discussed, the order revealed in this table is as expected.

The instruments may also be assessed simply by listing for each plot the device farthest from, and that nearest to, the mean. The number of occurrences is listed and it must be remembered that in some cases two instruments were equal.

Table 11.22. Relationship of Instrument Readings
to the Mean for each Plot

	<u>Nearest mean</u>	<u>Farthest from mean</u>
Inclinometer Pegs	10	1
Aluminium Pillars	4	5
Young's Pits	3	5
Cassidy's Tubes	4	6
Dowelling Pillars	3	5
Anderson's Tubes	10	1

This table indicates clearly the consistency of the Inclinometer pegs and Anderson's Tubes. There appears to be little to choose between the remainder but the range of discrepancy shown by the Cassidy's Tubes has already been discussed.

Since the peg results are means and form the basis

for the subsequent analysis, deviations from these rather than the overall means are also worthy of note.

Table 11.23. Relationship of Instrument Means to Anderson's Inclinator Means for each Plot

	<u>Nearest mean</u>	<u>Farthest from mean</u>
Aluminium Pillars	7	4
Young's Pits	4	7
Cassidy's Tubes	3	6
Dowelling Pillars	5	5
Anderson's Tubes	10	1

By this measure the aluminium pillars seem to produce a more consistent reading than all the other devices except the Anderson's Tubes. There appears to be little to choose between the remaining instruments.

Thus the analysis of creep rates as monitored by the different devices indicates strongly that for sensitivity, reliability and accuracy, the Inclinator peg results are to be preferred. Furthermore it is possible to rate the other instruments used on each plot according to the same instrument characteristics. The order from the most to the least sensitive would therefore be: Anderson's Tubes, Young's Pits, aluminium pillars, dowelling pillars, Cassidy's Tubes.

As a further check, each instrument was compared with a control comprising the mean reading of the other five devices. All the correlations are significant at the 99% level.

Table 11.24. Comparison of the Instrument Readings
with a Control

	<u>Inclinom-</u> <u>eter Pegs</u>	<u>Anderson's</u> <u>Tube</u>	<u>Aluminium</u> <u>Pillars</u>	<u>Young's</u> <u>Pits</u>	<u>Dowelling</u> <u>Pillars</u>	<u>Cassidy's</u> <u>Tubes</u>
Correl- ation with mean	0.98	0.98	0.94	0.96	0.92	0.85

This confirms the consistency of the four main instruments and reinforces the decision to use results from the Inclinator pegs for the detailed analysis of data.

CHAPTER TWELVE

BASIN FACTORS

- 12.1. Introductory
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12. BASIN FACTORS

12.1 Introductory

Justification has already been advanced for the selection of variables likely to influence rates of soil creep. To facilitate the initial analysis of results from the Rookhope basin, these factors can be divided broadly into three categories: external, surface and internal. For his consideration of slope models, Carson (1969) identified only two such groups: the bioclimatic setting and the characteristics of the rock mass. As illustrated, these constitute effectively external and internal, although biological elements could clearly be included in both. There is no obvious category for slope angle, a key component of the system and soil can only be viewed in this context as a derivative of rock. Caine (1971) listed under boundary conditions: geologic-pedologic controls, climatic controls and biologic controls. This recognises the importance of soil but, for the present study, gives undue emphasis to biological controls.

To overcome these problems and give greater clarification, the threefold division stated has been adopted although it is realised that the groups are closely inter-related. The external category comprises climatic influences, surface factors include slope angle and vegetation coverage, while the internal group consists chiefly of soil characteristics. Clearly such factors can vary not only in place but also in time, and therefore values measured must be analysed bearing in mind the areal scale of the basin and the time scale of the study. As a general guide it can be said that there will be little variation of external influences within the watershed and consequently in this case, time is the major element. Conversely, the surface and internal variables exhibit marked areal differences, but most can be taken as fixed over a three year period. The main factor which varies significantly in both dimensions is soil moisture.

The method of measurement for each possible control has already been described together with the validation of any non-standard instruments used. However, there are differences between the expected accuracies of techniques and these are considered particularly with regard to factor variability on the scale of the individual plot. This aspect of field measurement has been discussed by Carson (1967) and is of obvious importance when the validity of statistical data is being examined.

This problem results in particular from the heterogeneity of soil, and to achieve reliability, replication is essential. Therefore where practicable, more than one reading for a variable was taken on each plot and the mean recorded. As in several instances this was not possible, owing for example, to time constraints in the case of texture and to lack of instruments in the case of saturation level, no indication of plot variation is normally given. Indeed for few factors could more than two readings be taken and therefore the sample would be considered too small for the standard deviation to be quoted. Thus when comparing differences between plots, the internal-plot variability is regarded as being indicated by the results from sampling near plots 2, 3 and 4. These plots were selected as they represent the three main vegetation communities and display the associated soil development. They are also all on the same slope facet (Leopold, Wolman and Miller, 1964, Savigear, 1956), and are consequently all of approximately the same slope angle. For each factor, samples were taken from these three plots before the main measurement programme began. The inherent range was therefore known before the twenty plot readings were taken. Results from this pilot study thus provided firstly a guide for the investigation of the control factors and secondly a standard against which between-plot variations could be compared.

However, despite these precautions which allow a more informed judgment to be made of variations throughout the basin, certain limitations are recognised. Internal-plot differences: readings result not only from the variability of the factor being monitored, but also from measurement errors connected either with the measuring technique or

its application. On the other hand it is felt that as the method used was standard throughout the basin and as there was only one operator, the differences indicated by the three sets of samples can be accepted for the purposes of the analysis. With this range of readings it is possible to identify, examine and compare three sources of variability: internal-plot (within one plot), between-plot (between the means of the twenty plots), and between plot group (grouped according to vegetation in three groups). To make within-plot comparisons requires results to show internal plot differences for all twenty plots. This is therefore only possible with the Inclinator peg readings (Chapter 11)

With the mean values tabulated, there can then be a more detailed discussion on possible groupings and the occurrence of results outside the general trend. These two elements, isolates or residuals and groups, can be identified by scattergrams which therefore form the basis for a consideration of correlations. Such visual presentations are seen as essential in interpreting correlations, since a purely mathematical computation may bear little resemblance to reality. For example, one isolate in the data may be responsible for a statistically high correlation coefficient. Using the Pearson's product moment correlation coefficients, a correlation structure illustrating the inter-correlations between the basin factors can be constructed.

The values to be tabulated and discussed were all taken from the twenty fully instrumented plots within the Rookhope basin during and immediately following the main measurement period.

12.2. External Factors

As discussed above, for the purposes of this study, the external or climatic factors are considered to vary primarily with time. They were measured principally to establish wetting-drying and freeze-thaw cycles, together with the general moisture state of the basin and, except where specifically mentioned, they are taken to apply to the entire experimental area at Rookhope. Consequently, meteorological data obtained from the Weardale Lead Company provided the basis for this part of the work and readings were not taken on individual plots. The Weardale Lead

Company maintain station number 42/02 1617 (G.R. NY 938426) which is situated at an altitude of 330m O.D. adjacent to the confluence of Bolts Burn and Rookhope Burn. It is only 0.8km from the study area and is therefore considered to provide an accurate record of meteorological conditions obtaining within the basin. It must also be remembered in this context that the altitudinal range of the basin is only 120m, and that one factor in the selection of the actual experimental area was the constancy of aspect.

12.2.1. Wetting and Drying

While the rainfall figures are complete for the year of measurement in the basin, as there was only one operator at the station it was not always possible to take them on a daily basis. Certain short periods, of usually four or five days, are recorded as an aggregate. As the peg readings were taken on average once every seventeen or eighteen days, these variations in the rainfall record are unimportant. However, if any clarification had been required, daily values measured* at the recording station in the grounds of the Castle School, Stanhope (G.R. NY 996392) could have been used. The station is at an altitude of 161m O.D. in the Wear Valley itself, 6.0km from the Rookhope drainage basin. Since Upper Weardale and Upper Rookhopedale are parallel and in many other ways similar, the results recorded at Stanhope would have allowed an approximate qualitative comparison with those at Rookhope (G.R. NY 945437). The Stanhope records were obtained but were not required for this study.

The rainfall figures are required to indicate:

- (a) the normality or otherwise of certain periods during the year of measurement (1973-74)
- (b) the general moisture state of the basin at different times
- (c) the stage of a wetting-drying cycle at the time of a reading

So that the creep rates monitored could be viewed in a more long term perspective, it was considered important to discover how the rainfall values recorded compared with those for previous years. An indication of this can be obtained from the monthly totals, and these were collected for the period 1961-1974 inclusive.

*(Meteorological Office Mark II rain gauge)

Table 12.1Monthly Rainfall Totals (mm) 1961-74 (Weardale Lead Company)

(1973-74 refers to the year of measurement)

Month	January	February	March	April	May	June
Mean	104.8	85.4	85.8	81.7	75.3	63.0
Standard Deviation	52.1	38.1	40.1	28.8	33.8	26.5
Total 1973-74	171.1	84.2	55.6	34.4	48.8	45.4

Month	July	August	September	October	November	December
Mean	76.7	97.8	82.5	81.6	131.2	101.3
Standard Deviation	30.3	36.3	40.6	49.8	69.7	47.1
Total 1973-74	88.0	88.2	96.2	106.5	42.7	65.1

Totals above the mean for the period were recorded for four months with the January reading being particularly excessive. Seven monthly totals were below their respective means and those for April and November were markedly low. Only February approached closely to the mean figure. However all the standard deviations are also high indicating considerable variability in these totals from year to year. None the less, the year of measurement, November 1973 to October 1974 inclusive was a particularly dry period.

From the means for the period 1961-73, it was possible to infer the most probable driest and wettest months.

Table 12.2 Mean Monthly Rainfall 1961-73

Month	May	June	July
Mean rainfall 1961-73 (mm)	77.3	64.4	75.8

Month	January	August	November	December
Mean rainfall 1961-73 (mm)	99.7	98.5	130.3	96.1

Measurements to determine the soil moisture content in summer and winter, both of which values are described in detail later, were accordingly made in June and November 1974 when the totals were respectively 45.4mm and 142.9mm.

When the total rainfall for the measurement period, 926.2mm, is compared with the totals for the same months (November to October inclusive) it can be seen that only two periods, 1963-64 and 1971-72 were drier, 1970-71 and 1972-73 received a similar total.

Table 12.3 Annual Rainfall Totals (November to October incl.)

Year	1961 to 1962	1962 to 1963	1963 to 1964	1964 to 1965	1965 to 1966	1966 to 1967	1967 to 1968
Annual total (mm)	1037	1003	892	1322	1229	1363	1338

Year	1968 to 1969	1969 to 1970	1970 to 1971	1971 to 1972	1972 to 1973	1973 to 1974
Annual total (mm)	1106	1116	938	692	936	926

An approximate guide to the general moisture state of the basin is provided by the mean daily rainfall over the time since the last measurement was taken. However this value can only be interpreted bearing in mind the season when it was recorded.

Table 12.4 Mean Daily Rainfall between Measurement Dates

Measurement Dates	25.10.73 to 10.11.73	10.11.73 to 16.11.73	16.11.73 to 21.11.73	21.11.73 to 11.12.73	11.12.73 to 22.1.74
Mean daily rainfall (mm)	1.4	2.7	1.1	1.3	3.3

Measurement Dates	22.1.74 to 21.2.74	21.2.74 to 14.3.74	14.3.74 to 28.4.74	28.4.74 to 12.5.74	12.5.74 to 16.6.74
Mean daily rainfall (mm)	5.2	1.4	1.2	1.6	1.7

Measurement Dates	16.6.74 to 21.6.74	21.6.74 to 25.7.74	25.7.74 to 12.9.74	12.9.74 to 5.10.74	5.10.74 to 9.11.74
Mean daily rainfall (mm)	1.4	2.7	3.0	3.5	2.4

The stage of a particular wetting-drying cycle at the time the peg reading was obtained is clearly significant as evidence from the plot at Brandon shows (Chapter 6). Results from there indicate strongly that the response time is very short, being of the order of one day. Therefore the rainfall total for the 24 hours prior to each peg measurement date is listed.

Table 12.5 Rainfall Total for 24 hours prior to Measurement Date

Measurement Date	25.10.73	10.11.73	16.11.73	21.11.73	11.12.73
24 hr. total (mm)	0.8	5.2	2.3	0.2	3.8

Measurement Date	22.1.74	21.2.74	14.3.74	28.4.74	12.5.74

24 hr. total (mm)	0.6	0.6	4.8	0	0

Measurement Date	16.6.74	21.6.74	25.7.74	12.9.74	5.10.74	9.11.74

24 hr. total (mm)	1.0	0	1.8	0.4	3.0	7.1

Monitoring at Brandon reveals clearly that as stated, the lag is short but also that longer term variations are also discernible. It is considered therefore that these two sets of data cover both eventualities and allow an analysis which is sufficiently detailed, considering the frequency of peg readings.

12.2.2. Freeze-thaw

Temperature readings are used to give a guide to the occurrence and duration of freeze-thaw cycles. The records from the Weardale Lead Company station therefore indicate:

- (a) whether the year of measurement was typical with regard to the number of freeze-thaw cycles
- (b) the number of freeze-thaw cycles occurring between one peg reading and the next
- (c) when appropriate, the stage of a freeze-thaw cycle at the time of a reading

A minimum temperature of below 0°C is taken to indicate the onset of a cycle while thaw is judged from the maximum temperature and the description of weather recorded. This is clearly somewhat subjective but for the general level of interpretation required seems realistic. The written description provided with the readings is almost complete and is particularly valuable for days when no temperatures are given.

To establish how typical the year of measurement was, the mean number of cycles was calculated for each relevant month using the 1961-1974 records.

Table 12.6 Mean Monthly Totals of Freeze-thaw Cycles
1961-74

Month	January	February	March	April	May	Oct.	Nov.	Dec.
Mean number of cycles	11.9	12.3	8.9	5.0	1.5	1.8	9.3	9.3
Standard Deviation	5.1	5.8	6.2	2.0	1.6	1.7	4.0	5.9
Number of cycles 1973-74	5	9	4	5	1	4	12	5

While again standard deviations are large, it can be clearly seen that the year of measurement was, for most months, considerably milder than average. If the totals for the same months as the measurement period (November to October inclusive) are examined, on only two is a lower number of freeze-thaw cycles recorded.

Table 12.7 Annual Freeze-thaw Totals (November to October incl.)

Year	1961 to 1962	1962 to 1963	1963 to 1964	1964 to 1965	1965 to 1966	1966 to 1967
Total of cycles	67	82	61	72	60	60

Year	1967 to 1968	1968 to 1969	1969 to 1970	1970 to 1971	1971 to 1972	1972 to 1973	1973 to 1974
Total of cycles	75	75	67	45	39	44	45

However, as these results could not be checked locally, they must be considered to provide less definite evidence than the rainfall figures.

Since it has been demonstrated through the laboratory

programme (Chapter 5) and other evidence that freeze-thaw cycles affect soil creep, the number of cycles which occurred between readings is clearly important.

Table 12.8 Total Number of Freeze-thaw Cycles between Measurement Dates

Measurement Date	25.10.73 to 10.11.73	10.11.73 to 16.11.73	16.11.73 to 21.11.73	21.11.73 to 11.12.73	11.12.73 to 22.1.74
Number of cycles	4	1	3	6	9

Measurement Date	22.1.74 to 21.2.74	21.2.74 to 14.3.74	14.3.74 to 23.4.74	23.4.74 to 12.5.74	12.5.74 to 16.6.74
Number of cycles	10	5	9	2	2

Measurement Date	16.6.74 to 21.6.74	21.6.74 to 25.7.74	25.7.74 to 12.9.74	12.9.74 to 5.10.74	5.10.74 to 9.11.74
Number of cycles	0	0	0	3	10

Obviously the number of cycles must be viewed in the context of the length of time over which it was recorded. Since it is the actual number which is important, the tabulation of the mean number of cycles per day or per month seems inappropriate.

When a set of peg measurements was taken during a freeze-thaw cycle, the probable effects must be considered during analysis. To provide an approximate guide to this, it is taken that the freeze stage (-) is indicated if a temperature below freezing is recorded for the day of measurement. The thaw stage (+) is listed if the pegs were monitored within one day following the occurrence of a temperature below freezing.

Table 12.9 Stage of Freeze-thaw Cycle on Measuring
Dates

Measurement Date	25.10.73	10.11.73	16.11.73	21.11.73	11.12.73

Cycle state				+	-

Measurement Date	22.1.74	21.2.74	14.3.74	23.4.74	12.5.74

Cycle state	-	+	+		

Measurement Date	16.6.74	21.6.74	25.7.74	12.9.74	5.10.74	9.11.74

Cycle state						

It can be seen that only five sets of readings were obtained actually during freeze-thaw cycles. Furthermore these and the preceding data derived from temperature records are taken to provide accurate information as to conditions within the study basin. The Weardale Lead Company station is at a lower altitude down the valley and therefore liable to more severe temperature inversions, but this is thought to be compensated by the presence of heating appliances in the plant and also in the village.

It is realised that any analysis relating creep rates to the meteorological data from Rookhope can only provide an approximate guide. The pegs could only be read intermittently and any effects of meteorological change, other than the most immediate, are very difficult to judge. However, when the results from the plot study at Brandon and the laboratory programme are also considered, it is possible to obtain a clearer assessment.

Finally, in interpreting the meteorological effects at Rookhope, it must be remembered that the period of measurement was drier and recorded less freeze-thaw cycles

than comparable periods in most of the preceding years since 1961.

12.3 Surface Factors

This group comprises those factors which are not climatic and are not directly concerned with the soil or its constituents. Over the time scale of this study they can be considered static, although clearly there may be a great difference in the time element involved between changes in the angle of a slope and alterations in the boundary position of a vegetation community.

12.3.1. Slope Angle

Since the plots are of very limited area and the facets on which they are sited were selected for their constant slope, little variation in this factor would be expected. The Abney level used can be accurately read to 5 minutes of arc, but bearing in mind micro-features on the soil surface and particularly the effects of vegetation, such refinement is not realistic.

To examine variability, readings were taken to the nearest 30 minutes for four parallel positions across the centre of plots 2, 3 and 4. The positions selected were as far as possible equidistant, but the 1m long metal rod could not be placed as accurately when large tufts of vegetation obtruded.

Table 12.10 Slope Angle: Within-plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean ($^{\circ}$)	6.4	7.5	6.4
Standard Deviation	0.4	0.8	0.6

As expected, the internal-plot variation is small and the order of regularity indicated seems to hold throughout the basin.

The reading for each plot was taken with the 1m metal rod laid down the slope as centrally as possible and the Abney was again read to the nearest 30 minutes (Fig. 12.1).

Table 12.11 Slope Angle: Plot Measurements

Plot	1	2	3	4	5
Slope angle ($^{\circ}$)	11.5	6.5	8	6	11.5
Sine of slope angle	0.199	0.113	0.139	0.105	0.199
Plot	6	7	8	9	10
Slope angle ($^{\circ}$)	22	20.5	23	12.5	2.5
Sine of slope angle	0.375	0.350	0.391	0.216	0.044
Plot	11	12	13	14	15
Slope angle ($^{\circ}$)	10	12.5	23.5	9	11
Sine of slope angle	0.174	0.216	0.399	0.156	0.191
Plot	16	17	18	19	20
Slope angle ($^{\circ}$)	9	6.5	6.5	6.5	7.5
Sine of slope angle	0.156	0.113	0.113	0.113	0.131

The grouping of plots according to slope angle has already been described in relation to the original experimental design. Clearly the total variation is relatively small with a lowest angle of 2.5° , a highest of 23.5° and therefore a range of 21° . Within this are



Fig 12.1

Rookhope Plots: Slope Angle(°)

three tight clusters: 6° to 8° , 11° to 12.5° and 20.5° to 23.5° . This leaves plot 10 with 2.5° , the lowest angle, and plots 11, 14 and 16 all with angles at the boundaries of groups. There are no plots with slope angle between 2.5° and 6° or between 12.5° and 20.5° and the steady rise from 6° to 12.5° shows that the group boundary established there is one of convenience rather than real significance. When the results are further analysed into three groups, a clearer impression of the clustering emerges.

Table 12.12 Plot Slope Angles (grouped)

<u>Group</u>	<u>Mean</u>	<u>Standard Deviation</u>
$2.5^{\circ} - 8^{\circ}$	6.25	1.54
$9^{\circ} - 12.5^{\circ}$	10.90	1.32
$20.5^{\circ} - 23.5^{\circ}$	22.25	1.15

When the standard deviations revealed by the measurements on plots 2, 3 and 4 are applied, the regularity of the facets can be appreciated. It is illustrated by the following groups of neighbouring plots, the slope angles of which could be drawn from the same population: 2, 3, 4: 6, 7, 8: 14, 15, 16: 17, 18, 19. Therefore in these cases there is obviously no important between-plot variation.

For analysis therefore, the basin can be seen as displaying basically three recurrent slope angles and so it is possible to use slope as a control when the other factors are being investigated. However, it is realised that with a mean of 11.3° and a standard deviation of 6° , the range of angles represented by the plots is small and this may preclude some of the contrasts expected when the correlation structure is produced.

As discussed earlier, the critical value would seem, from a theoretical appraisal, to be the sine of the angle (e.g. Kirkby, 1967, Young, 1972) and the limited variance at Rookhope can be again illustrated by the following

summary statistics.

Table 12.13 Slope Angle (sine): Basin Summary

Mean	0.195	Standard Error	0.023	Standard Deviation	0.104
Minimum	0.044	Maximum	0.399	Range	0.355

Since the downslope length of the plots is small and therefore the angles were measured using a metal rod only 1m long, it was considered important to make checks to ascertain how representative they were of the actual basin factor. A 5m base line was measured down the centre of each plot extending 2.5m above the centre point and 2.5m below. It therefore continued the same line as the original reading and was comparable with it. Using a sighting rod, the Abney was read and the values recorded to the nearest 30 minutes. The same procedure was then repeated but with a 10m base line, extending an equal distance above and below the centre point of each plot.

Table 12.14 Slope Angle: Plot Measurements with Varying Facet Length

Plot	1	2	3	4	5	6	7
Slope angle (^o) (1m)	11.5	6.5	8	6	11.5	22	20.5
Slope angle (^o) (5m)	10	7	8.5	7.5	8.5	13	14
Slope angle (^o) (10m)	10	7	8	8	8.5	13	12

Plot	8	9	10	11	12	13	14
Slope angle ($^{\circ}$) (1m)	23	12.5	2.5	10	12.5	23.5	9
Slope angle ($^{\circ}$) (5m)	17.5	9	2.5	7.5	10.5	15	10
Slope angle ($^{\circ}$) (10m)	15	10	4	8	11.5	14.5	10

Plot	15	16	17	18	19	20
Slope angle ($^{\circ}$) (1m)	11	9	6.5	6.5	6.5	7.5
Slope angle ($^{\circ}$) (5m)	11	10.5	5.5	5.5	7.5	9.5
Slope angle ($^{\circ}$) (10m)	11	11.5	5.5	6	7	10

Whichever of the two base lines is used, the angular reading differs little and, when the standard deviation for this factor is taken into account, the differences listed are not important. If these results are compared with those from the 1m base line it can be seen that the range is smaller and variability is less apparent. Obviously this general evening would be expected as the base line of measurement is lengthened.

12.3.2. Distance from the watershed

In several slope models involving soil creep (Ahnert, 1971, Young, 1963A) the distance of a particular point from the watershed or conversely the local base level is considered critical. At Rookhope the experimental design allowed for this by the selection of more than one line of plots down the basin. As discussed earlier, while the main watershed is the obvious hydrological divide, the area was selected to be self-contained with regard to soil creep rather than water. Therefore the mine railway embankment provides a limiting line for creep rate measurement. The base level is less easy to define since the experimental area is sited on a flattish interfluvium and drainage is

predominantly directly downslope towards the confluence. Thus, rather than attempting any exact measurement of distance it seems more appropriate for the analysis to rank the plots in order from the creep divide. This would give four base sets:

- (a) 1: 2: 5: 6: 10: 11: 13: 14: or 15: 17:
- (b) 4: 7: 11: 16: 18:
- (c) 3 or 4: 8 or 7: 20: 19:
- (d) 12: 15: 18:

Plots listed as alternatives are contiguous on the same facet. A further advantage for this procedure is that the plots are also arranged in reverse order of their distance from the local base levels defined by structure. For example, the order above the first scarp from the basin outlet is 13, 11, 10, while that from the scarp above is 6, 5, 2.

12.3.3. Vegetation

A significant point mentioned in the basic selection procedure was the occurrence at Rookhope of a limited range of well defined vegetation groups. The number of species represented is small and only some twelve occurred in sufficient abundance to be measured on the plots. Basically there were three main associations dominated respectively by Heath Rush (Juncus squarrosus), Mat Grass (Nardus stricta) and Bracken (Pteridium aquilinum). Apart from these, the other species commonly found there, in order of coverage were varieties of sedge, notably Oral Sedge (Carex oralis) and Star Sedge (Carex echinata), Sphagnum Moss (Sphagnum palistre), Common Hair Moss (Polytrichum commune), Ling (Calluna vulgaris), Bilberry (Vaccinium myrtillus), Common Tormentil (Potentilla erecta), Cranberry (Empetrum nigrum), Wavy Hair Grass (Deschampsia flexuosa) and Velvet Bent (Agrostis canina).

Measurement of this particular variable was different from that of all the other plot factors in that no selection of points or transects was involved. It was the only truly areal measure and it covered the entire area of the grid. The coverage of species was recorded to the nearest

5% and thus the variability within each plot can be seen in the table. Variations of the major component within any one main association were indicated by random quadrats and averaged between 20% and 25%. It is difficult to comment on relative homogeneity of the associations as conditions in different parts of the basin affected the composition of the vegetation. For example, the Nardus areas appeared to exhibit the least variety but on damper slopes Carex species and on drier ones Calluna vulgaris provided sizeable coverage.

A particular problem of areal assessment arose from the nature of the predominant species. At one extreme Pteridium aquilinum grows in dominant stands which tend to preclude effective competition in the lower vegetation layers but individual plants can be comparatively widely dispersed. The notion of coverage is therefore difficult to interpret. In contrast, Nardus stricta forms a close mat which therefore restricts competition by a different means. As Juncus squarrosus plants grow less densely than Nardus but do not exercise the shading effect of Pteridium they are less dominant than either. However it is easier to quantify the areal coverage than is the case with Pteridium. The importance of root competition below ground should also be remembered, but this will be considered in a later section. Vegetation cover is tabulated using only the generic name except where a number of related species occurred, none sufficiently evident for individual recording.

Table 12.15 Vegetation Coverage: Plot Measurements

Plot	1	2	3	4
Vegetation cover (%)	<u>Nardus</u> 60	<u>Juncus</u> 60	<u>Pterid-ium</u> 50	<u>Nardus</u> 85
	<u>Carex</u> 35	<u>Sphag-num</u> 20	<u>Carex</u> 10	<u>Carex</u> 5
	<u>Potentilla</u> 5		Mosses 10	<u>Empet-rum</u> 5
			Litter 30	

Plot	5		6		7		8	
Vegetation cover (%)	<u>Juncus</u>	50	<u>Juncus</u>	50	<u>Nardus</u>	50	<u>Pteridium</u>	60
	<u>Sphag-num</u>	30	<u>Carex</u>	30	<u>Carex</u>	40	<u>Vaccinium</u>	30
	<u>Carex</u>	10	<u>Sphag-num</u>	20	Grasses	10	<u>Calluna</u>	5
	<u>Empet-rum</u>	10					Litter	5

Plot	9		10		11		12	
Vegetation cover (%)	<u>Nardus</u>	50	<u>Juncus</u>	60	<u>Nardus</u>	50	<u>Pteridium</u>	50
	<u>Carex</u>	40	<u>Sphag-num</u>	20	<u>Carex</u>	30	Litter	35
	<u>Call-una</u>	10	<u>Carex</u>	5	Grasses	10	Grasses	10
			<u>Polytr-ichum</u>	5	<u>Polytr-ichum</u>	5	Mosses	5
			Others	10	Others	5		

Plot	13		14		15		16	
Vegetation cover (%)	<u>Pteridium</u>	65	<u>Juncus</u>	60	<u>Pteri-dium</u>	60	<u>Nardus</u>	85
	Grasses	25	<u>Sphag-num</u>	30	Litter	35	<u>Polytri-chum</u>	10
	Litter	10			Others	5	Others	5

Plot	17		18		19		20	
Vegetation cover (%)	<u>Juncus</u>	50	<u>Nardus</u>	60	<u>Pteri-dium</u>	50	<u>Juncus</u>	60
	<u>Polytr-ichum</u>	35	<u>Polytr-ichum</u>	35	Grasses	35	<u>Carex</u>	30
	<u>Sphag-num</u>	10	Others	5	Litter	10	<u>Polytri-chum</u>	5
	Others	5			<u>Polytr-ichum</u>	5	<u>Sphagnum</u>	5

It can be seen that on no plot does the predominant genus cover less than 50% of the area while the maximum

coverage measured was the Nardus on plots 4 and 16.

Table 12.16 Mean Percentage Cover of Predominant Genus

Genus	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean percentage cover	56	63	59

If the number of genera and species groups (as defined for Table 12.15), per plot is averaged, the more homogeneous nature of the Nardus associations again emerges.

Table 12.17 Mean Number of Genera and Species per Plot
Type

Plot type	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean number of genera and species	3.4	2.9	3.5

The only 'sub-dominant' recorded on every plot within its association was Sphagnum, although on four of the five Nardus plots on which Carex occurred, it closely rivalled the predominant species. As a result of the growth form already described, litter was in evidence on every Pteridium plot and was effectively the sub-dominant cover.

Table 12.18 Mean Percentage of the Main 'Sub-dominants'

'Sub-dominant'	<u>Sphagnum</u>	<u>Carex</u>	<u>Litter</u>
Mean percentage cover	19	21	21

It can be concluded that although over the twenty plots the predominant cover is clearly established with none of the three key genera being recorded substantially within the

other associations, the remaining vegetation exhibited a degree of variation.

When correlations with the other factors within the basin are considered, the importance of vegetation can be seen. The cover provides a guide to root density, probable infiltration rates (Ward, 1967) and also the protection of the soil cover from the meteorological elements. Furthermore it is a clear indicator allowing grouping of most of the major factors including soil depth and the variables linked with moisture or humus. This grouping can in fact be traced through most of the statistical analysis within the study (Imeson, 1974).

12.4. Internal Factors

Within this category a range of variables is examined, from the fixed constituents through to the most significant mobile element, soil water. For discussion purposes a natural progression can therefore be discerned from what might be classified as the physical dimensions such as soil depth, through the organic factors to the physical properties and eventually moisture. Apart from the last mentioned and any factor where moisture is concerned, all would be judged static on the time scale of this study. Therefore, in contrast to the climatic factors, it is the spatial variation which is chiefly important.

While the procedures used were largely standard, as already described, it was considered particularly important that they should be related as far as possible to likely conditions within the basin rather than to the more rigid principles of soil mechanics. That is not to say that testing was any less rigorous than would be demanded in engineering, but that the different objectives of geomorphology were recognised and account taken of them. Thus while an approved technique for measuring dry bulk density was adopted it was also thought important to obtain readings for the same factor with saturated samples so that the possible range of effects could be examined. More directly related to the specific conditions in the drainage basin was the investigation of factors included under the broad heading of shear strength. In this case

it was felt strongly that the moisture factor should not be a standard such as saturation point or field capacity but should be at a value which actually occurred. For example, while in the winter, field capacity was closely approached throughout the basin, it was only exceeded on seven plots. Therefore since the correlation of these shear strength parameters with the rates of soil creep was to be examined, it was considered vital that measurements should be made at the maximum moisture conditions actually obtaining on a particular plot.

Resulting from this approach, the shear strength factors would be classed as at least marginally, time-dependent. This therefore dictated the procedure in that it was necessary to monitor the moisture condition of the basin throughout the winter of 1973-74 in order to establish a likely period for readings in 1974-75. Using this evidence together with rainfall statistics and field observations, a three week period in November 1974, when moisture conditions were at an expected maximum, was used to measure shear strength factors and to obtain a value for winter moisture.

Most of the variables discussed result from point samples obtained from the soil pits. These were themselves located with regard to the grid, using random number tables. However in many cases no check could be made on a particular reading since the actual sample had been destroyed in testing. Therefore the importance of variation even on the local scale of one pit must be stressed. To establish a measure of variability so that the values tabulated for any factor can be seen in perspective, a series of tests was made on the three contrasting plots already described.

To obtain a single value for a plot, even when measurements were made for each horizon, a number of factors had to be considered with regard to the possible effect on the rate of creep. Since the Inclinator pegs, the major measuring device, can be seen as merely replacing a column of soil which can therefore be identified, where appropriate, a linear mean for this column was calculated. Thus the value of a particular reading was weighted according to the proportion of the column it would have occupied. Equally

this can be seen as a weighting according to the surface of contact with the peg. With certain other factors it seemed more appropriate to take the maximum value since if creep was to occur, this was the resistance or impeding element which had to be overcome. Particular cases are discussed as each individual factor is described.

12.4.1. 'Force' Variables

From the introductory discussion on controlling variables, a key factor to emerge was soil moisture both because of its effect on the soil state and also because of its influence on meteorological cycles. It was decided therefore that some indication of annual variation should be obtained. Readings were taken in percentage wet weight and also percentage dry weight so that comparisons could be more easily made with other variables, some normally recorded in one unit, some in the other. However this result must be seen in the context of the soil's capacity to hold water and therefore field capacity was measured. Since continuous monitoring could not be undertaken, the saturation level was recorded as a guide to short term conditions of excess soil moisture. Clearly in any consideration of water in the soil, organic matter is relevant and two organic characteristics were recorded, percentage by weight and depth beneath the root mat. The latter was less accurate but allowed some comparison with another 'force' variable, the soil depth. It was also considered vital that results should be obtained of changes in the soil resulting from wetting and drying and therefore measures of plasticity and linear shrinkage were made. Finally, apparent cohesion is also a moisture factor but appears more obviously as a 'resistance' variable.

12.4.2. Soil Moisture

While most of the other variables discussed could be evaluated from either standard or closely related measurements, moisture presented rather different problems. It was considered essential to collect readings for the actual moisture state of the basin at any one time so that the relative wetness of individual plots could be assessed.

The more closely these results could be related to the maximum and minimum moisture content for a sustained period during the year, the more valuable they would be. Using evidence from the years 1961-73 as described earlier, together with local meteorological observations, two periods were selected as being at least equal to the wettest and driest. These were in June and November 1974 and it proved possible to obtain two complete sets of readings during each period. Later spot checks revealed that at no subsequent time was the basin nearer maximum or minimum moisture conditions respectively.

These measurements illustrate very clearly the advantage in being able to take rapid on-site readings of moisture content. It was possible to sample all the relevant horizons during a period of five hours. However it is realised that even during this time, changes could occur, and to allow for this, one set of readings in each case was taken from the top to the bottom of the basin and one set in the reverse direction.

Internal-plot variation of moisture was sampled as nearly as possible under winter conditions using specimens from the organic or upper horizons.

Table 12.19 Soil Moisture: Plot Variability

Plot group	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean moisture (winter) (% wet weight)	92.0	50.9	69.9
Standard deviation	2.9	5.5	3.2

It should be mentioned that while it is hoped that the two states measured approach closely to maximum and minimum soil moisture content, this cannot be guaranteed as it was not possible to monitor the basin with continuous measuring apparatus. Therefore the terms 'winter' and 'summer' moisture are preferred respectively, to maximum and minimum. It must also be stated that the values listed refer only to the year of measurement, 1973-74 and extreme moisture

conditions in other years may well be different.

Bearing in mind the variability already shown, it was felt that the best assessment of a required moisture content could be obtained by averaging the two relevant data sets. The resulting means were then weighed according to horizon width to calculate a single value for each plot. Moisture content is normally expressed in a standard form as percentage of the dry soil weight, but as comparisons with field capacity are relevant in this study, the percentage of the wet soil weight is also given (Fig. 12.2).

Table 12.20 Soil Moisture (winter): Plot Measurements

Plot	1	2	3	4	5	6	7
% Dry weight	108	720	47	108	810	300	56
% Wet weight	52	88	33	52	89	75	36
Plot	8	9	10	11	12	13	14
% Dry weight	70	50	720	108	66	43	900
% Wet weight	41	32	88	52	40	30	90
Plot	15	16	17	18	19	20	
% Dry weight	38	140	900	100	56	440	
% Wet weight	27	58	90	50	36	82	

The three groups are again well defined except for Nardus plots 7 and 9 which exhibit a similar winter moisture condition to the Pteridium plots. However when considering the distinctiveness of individual plots the relatively large internal-plot standard deviation for Pteridium plots must be noted. Generally however the differences between the plot groups are clear and this can be illustrated using percentage of wet weight as the unit. For this section and throughout the analysis where appropriate, plot groups are labelled

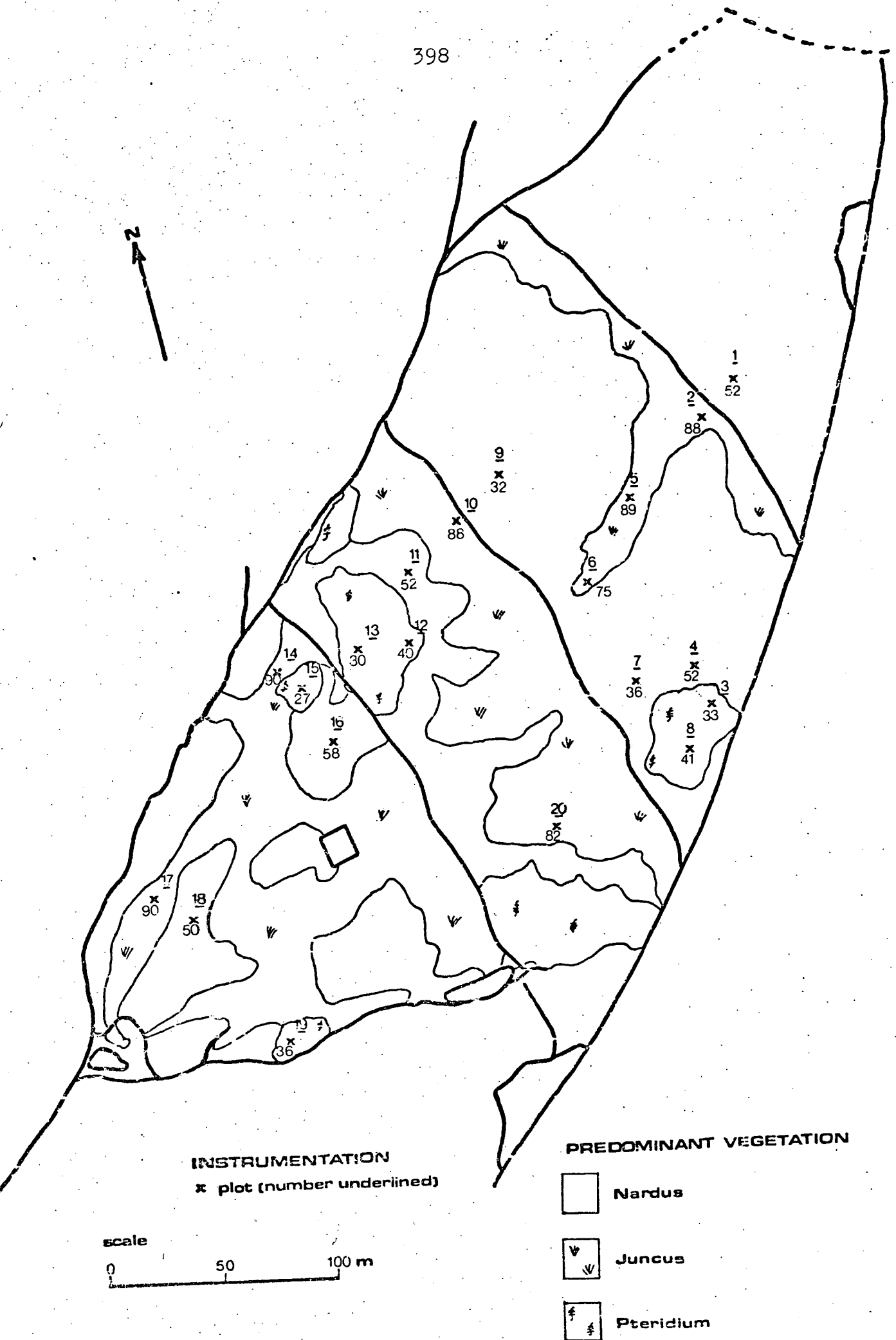


Fig. 12.2

Rookhope Plots: Winter Moisture
(% wet weight)

by the predominant vegetation which distinguishes them.

Table 12.21 Soil Moisture (winter): Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (% wet weight)	86.0	47.4	34.5
Standard deviation	5.5	9.6	5.5

To show the overall range and variability a summary for the basin is also given using the same units.

Table 12.22 Soil Moisture (winter) (% wet weight):
Basin Summary

Mean	Standard error	Standard deviation
57	5.2	23.4
Minimum	Maximum	Range
27	90	63

Since creep rates vary seasonally, summer moisture conditions are also highly relevant. These results were prepared in the same way as those already listed for winter moisture content (Fig. 12.3).

Table 12.23 Soil Moisture (summer): Plot Measurements

Plot	1	2	3	4	5	6	7
% Dry weight	82	540	43	75	440	200	48
% Wet weight	45	85	31	43	82	67	31
Plot	8	9	10	11	12	13	14
% Dry weight	48	43	670	106	56	38	614
% Wet weight	31	30	87	51	36	27	86



Fig. 12.3 Rookhope Plots: Summer Moisture
 (% wet weight)

Plot	15	16	17	18	19	20
% Dry weight	33	117	440	92	51	400
% Wet weight	25	54	82	48	34	80

The groupings appear very much as would be predicted from the winter readings with Nardus plots 7 and 9 again displaying somewhat deviant results. Once more the differences are clarified when the plot group results, in percentage wet weight, are examined.

Table 12.24 Soil Moisture (summer): Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (% wet weight)	81.3	43.1	30.7
Standard deviation	6.8	9.4	4.1

The basin summary, in the same units, makes an interesting comparison with that for winter conditions, as the variation is very similar.

Table 12.25 Soil Moisture (summer) (% wet weight):

Basin Summary

Mean	Standard error	Standard deviation
52.8	5.2	23.1
Minimum	Maximum	Range
25	87	62

When the winter and summer moisture results are compared, every plot shows a lower reading for summer conditions and, on a percentage wet weight scale, the mean lowering is very regular although loss is clearly greatest on Juncus plots and least on Pteridium plots. The difference between the winter and summer wet weight is given.

Table 12.26 Difference between Soil Moisture (winter)
and Soil Moisture (summer) (% wet weight)
Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean (% wet weight)	4.3	4.7	3.8
Standard deviation	2.7	2.7	2.8

If these results are converted into percentage dry weight the contrast between the plots is more obvious, with marked drying in evidence on the Juncus plots. However, it must be remembered that the readings on this scale are less sensitive as the percentage increases.

Table 12.27 Difference between Soil Moisture (winter)
and Soil Moisture (summer) (% dry weight)
Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
Mean (% dry weight)	15.3	212.3	8.5
Standard deviation	10.9	151.8	5.9

Whichever unit is used, the variation, indicated by the standard deviation is high, but when differences in such factors as exposure, vegetation cover and soil characteristics are considered, this is to be expected. The plots with the highest winter moisture content dry out most and those with the lowest, show least change. Thus the Pteridium plots are not particularly wet in winter and therefore have a reduced potential for drying.

When the data are expressed in percentage wet weight this also allows a direct comparison with field capacity. The table lists the percentages wet weight above or below field capacity.

Table 12.28. Differences between Field Capacity and
(a) Soil Moisture (winter, (b) Soil Moisture (summer)
(% wet weight): Plot Groups

Plot group	<u>Nardus</u>	<u>Juncus</u>	<u>Pteridium</u>
(a) Winter moisture: mean difference	-6.0	+1.3	-13.2
standard deviation	2.1	0.7	4.0
(b) Summer moisture: mean difference	-10.3	-3.4	-17.0
standard deviation	4.4	2.6	6.3

This shows that, over a sustained period, only the Juncus plot group exceeds field capacity under winter conditions. As would be expected from the previous discussion, the Pteridium group is considerably farther below field capacity than the Nardus group. The standard deviations for these two plot groups are of a similar order but those for the Juncus group indicate greater variation.

12.4.3. Field Capacity

Although this value is less favoured scientifically than the states of saturation or dryness, partly because of the judgment required in its measurement, it is none the less significant in the context of the drainage basin. Field capacity can be defined as the maximum amount of water which a soil can hold when it is drained as freely as its texture will allow. It is therefore the water remaining when the only hindrance to free drainage is the soil itself (Townsend, 1973). The value obviously varies with time and, in this study, samples drained for 30 minutes. Within the basin then, it is the maximum moisture content which can occur other than momentarily, throughout, as steeper slopes can only remain saturated for very limited periods. Therefore it is a particularly useful standard.

To test internal-plot variability, readings were obtained for the organic or upper horizon from the three sample pits. Readings were taken from the centre of each

relevant horizon and these can be used to illustrate the variability of this factor.

Table 12.29 Field Capacity: Plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean (% wet weight)	89.0	60.0	74.7
Standard deviation	1.4	1.4	2.0

A certain range would be expected, as has been mentioned above, but the standard deviations are particularly small and this indicates that accurate measurements can be made.

Having obtained the mean of each horizon, the mean for the plot was calculated using the weighting based on horizon depth. Results are given to the nearest 1% and applying the standard unit, these are percentages of wet weight (Fig. 12.4).

Table 12.30 Field Capacity: Plot Measurements

Plot	1	2	3	4	5	6	7
Mean field capacity (% wet weight)	61	87	44	60	89	74	41

Plot	8	9	10	11	12	13	14
Mean field capacity (% wet weight)	61	36	88	55	49	44	87

Plot	15	16	17	18	19	20
Mean field capacity (% wet weight)	43	63	88	58	45	80

These values show a clear division into the three categories although plots 7 and 9 appear more closely related to the Pteridium plot conditions. Of the Juncus plots, only plot 6 is in any way an isolate and this can be attributed statistically to its mineral horizon. When the small internal-plot variations are taken into account it can be seen that between-plot variations are mostly clearly distinctive. The between-plot group differences help confirm this conclusion although the possible overlap between Pteridium plot and Nardus plot results is evident.

Table 12.31 Field Capacity: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (% wet weight)	84.7	53.4	47.7
Standard deviation	5.6	10.6	6.9

A summary for the basin illustrates the overall range and variability.

Table 12.32 Field Capacity (% wet weight): Basin Summary

Mean	Standard error	Standard deviation
62	4.2	18.7
Minimum	Maximum	Range
36	89	53

12.4.4. Linear Shrinkage

As described earlier, the test was non-standard as the objective was not to provide a check on the plasticity index results but to obtain a measure of potential seasonal shrinkage. As will be shown later, the devices monitoring creep rates indicate that summer upslope movement occurs and therefore this must be considered when controlling variables are correlated with the annual creep rate.

Therefore cores 5cm long and 2.5cm in diameter, similar to those used for shear testing were extracted under winter moisture conditions. Later remeasurement after drying to constant dimensions yielded the maximum potential linear shrinkage. The variability was found to be small and can be illustrated by readings from upper horizons in the sampling pits.

Table 12.33 Mean Linear Shrinkage: Plot Variability

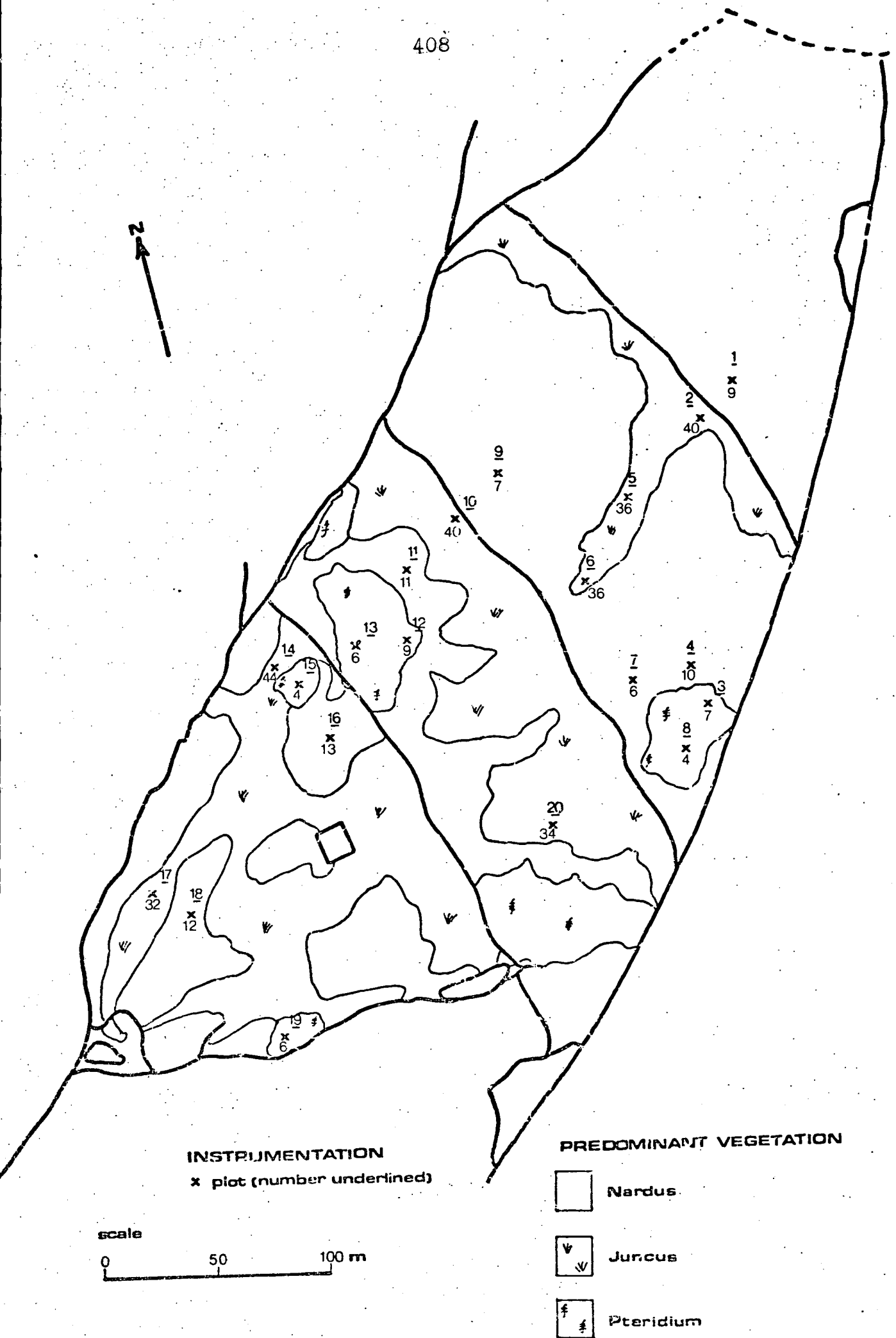
Plot group	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean linear shrinkage (%)	32.5	22.0	23.0
Standard deviation	2.3	1.6	1.6

The mean for the Juncus sampling pit is quite distinctive but those for the other two pits show obvious overlap. However the Pteridium result is equal to the highest recorded on any plot within that vegetation category. The mean figure for each plot (Fig. 12.5) is calculated with a weighting for the horizon depth, but as most shrinkage occurred within the organic horizon, values for this are also listed. It is possible therefore to compare similar values for the organic horizon throughout the basin.

Table 12.34 Linear Shrinkage: Plot Measurements

Plot	1	2	3	4	5	6	7
Linear shrinkage (%)							
(a) mean	9	40	7	10	36	36	6
(b) organic	22	40	16	15	36	36	15

Plot	8	9	10	11	12	13	14
Linear shrinkage (%)							
(a) mean	4	7	40	11	9	6	44
(b) organic	10	14	40	24	22	17	44



Plot	15	16	17	18	19	20
Linear shrinkage (%)						
(a) mean	4	13	32	12	6	34
(b) organic	14	14	32	28	8	34

The important and expected fact to emerge is that the organic horizons shrank by a far greater percentage than the mineral and therefore the Juncus plots with soils which are totally organic are clearly defined. However, with regard to movement, this point has to be weighed against the factor of summer moisture, as the Juncus plots are still wet even in summer. The tendency for Pteridium plot soils to shrink less than those from the Nardus plots is also marked, although again there is a certain overlap. When the limited internal-plot difference is taken into account, it can be seen that between-plot variations of mean percentage linear shrinkage are mostly distinctive.

These points are clarified if the values for the mean percentage linear shrinkage are summarized by groups and for the basin.

Table 12.35 Linear Shrinkage: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (%)	37.4	9.7	6.0
Standard deviation	4.1	2.6	1.9

Table 12.36 Linear Shrinkage (%): Basin Summary

Mean	Standard error	Standard deviation
18.3	3.3	14.8
Minimum	Maximum	Range
4.0	44.0	40.0

12.4.5. Plasticity Index

The calculation of this factor of course involves the measurement of the liquid limit and the plastic limit since, as stated earlier:

$$\text{Plasticity Index} = \text{Liquid Limit} - \text{Plastic Limit}$$

The plasticity index therefore indicates the range of water content over which a particular soil behaves as a plastic. This also shows the range within which soil creep is most likely to occur, although expansion and contraction below the plastic limit and particularly above the liquid limit are likely to have some effect. It follows that the actual value of the plastic limit is of great importance and especially the frequency with which this is exceeded on an individual plot. These three related values are all recorded to percentage dry weight.

After initial trials with the standard method, the liquid limit was measured using the shortened procedure described in the British Standard (B.S. 1377: 1967). Furthermore the soil was in its natural condition rather than air dried, although roots and larger sand particles were removed by sieving and tweezers. Since this is the more difficult limit to measure accurately, the range of local variation within the three pits is illustrated by these liquid limit results.

Table 12.37. Plasticity Index: Within-plot Variability

Plot	2 <u>Juncus</u>	3 <u>Pteridium</u>	4 <u>Nardus</u>
Liquid limit mean (% dry weight)	1960.3	322.8	324.2
Standard deviation	15.5	4.4	5.4

The plastic limit was also obtained using soil in its natural condition, but with roots and larger sand particles carefully removed. In the case of the lower horizons from plots 12, 13, 15 and 19, all with a high

sand percentage, definitive readings could not be taken as the soil threads tended to collapse at about the test diameter. Therefore, to calculate the mean index for these plots it was necessary to use an estimate based on the moisture content at disintegration and the plastic limit measured for similar horizons.

Since plasticity index results were obtained for each relevant horizon, the mean value for each plot was calculated using the weighting resulting from horizon width as discussed previously (Fig. 12.6).

Table 12.38 Plasticity Index: Plot Measurements

Plot	1	2	3	4	5	6	7
Plasticity index (% dry weight)	45	316	37	88	406	239	56
Plot	8	9	10	11	12	13	14
Plasticity index (% dry weight)	42	27	337	47	53	53	380
Plot	15	16	17	18	19	20	
Plasticity index (% dry weight)	32	80	395	91	59	206	

Again the consistently high value for the Juncus plots may be contrasted with the much lower readings for the other two categories. However, the indices for plots 6 and 20 should be noted as being considerably lower than those from the other Juncus plots. There is an overlap between the Nardus and Pteridium results although the latter tend to be lower. The mean for the Nardus plots is 62 while that for the Pteridium is 46, but the lowest value of all occurs on plot 9, a Nardus plot. When the internal-plot difference indicated earlier is considered, it is clear that between-plot variation is mostly distinctive. However the results for



Fig. 12.6

Rookhope Plots: Plasticity Index
 (% dry weight)

one group of neighbouring plots: 11, 12 and 13 could be drawn from the same population.

When the plots are grouped according to the vegetation community, the variation is well in excess of that within plots.

Table 12.39

Plasticity Index: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (% dry weight)	379.8	62.0	46.0
Standard deviation	132.2	24.5	10.6

The variations among and between the three major groupings can also be viewed in the context of the summary statistics for the whole basin.

Table 12.40 Plasticity Index (% dry weight): Basin Summary

Mean	Standard error	Standard deviation
149.5	31.4	140.5
Minimum	Maximum	Range
27	406	379

As stated earlier, a further factor which must be considered is whether the plastic limit is exceeded. As will be explained, the readings given for winter moisture necessarily result from somewhat subjective judgment although it is believed that they are the most accurate which could be obtained in the circumstances. If these are compared with the plastic limit values, they will at least provide a general guide to potential plasticity. However, it must be appreciated that after any moderate fall of rain and certainly after snow melt, the soil anywhere in the basin may behave at least temporarily, as a plastic. Since only the organic layer is common to all plots, means

are calculated for this.

Table 12.41. Comparison of Mean Plastic Limit and Mean Soil Moisture (winter): Organic Horizon

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean plastic limit (% dry weight)	536	250	208
Mean soil moisture (winter) (% dry weight)	833	303	173

Thus, as a group the Pteridium plots fail to achieve plasticity over a sustained period, although it is only on plots 3, 12 and 13 that the discrepancy is comparatively large. Nardus plots 4, 7 and 9 also fall marginally below the critical moisture content as does Juncus plot 20. This is important and must be borne in mind when the basin factors are discussed in the later analysis.

With regard to the mineral horizons, the plastic limit was exceeded on the Nardus plots but not on the Pteridium. However it must be remembered that the mean plastic limit for the latter plots is in some cases of limited value for the reason given earlier.

Table 12.42. Comparison of Mean Plastic Limit and Mean Soil Moisture (winter): Mineral Horizons

Plot group	<u>Nardus</u>	<u>Pteridium</u>
Mean plastic limit (% dry weight)	32	30
Mean soil moisture (winter) (% dry weight)	41	21

Clearly the importance of the plasticity index for any plot is only apparent when viewed in the context of the

respective plastic limit. Once the soil is behaving as a plastic, creep will predominate, but once it becomes liquid this cannot by definition be classified as soil creep. In fact the liquid limit is only likely to be exceeded at the surface and the resulting movement would then be categorised as surface wash. Therefore the plasticity index indicates effectively when, during the annual fluctuations of soil moisture, conditions are most conducive to creep.

12.4.6. Percentage of Organic Matter

A core of soil was extracted from the centre of the relevant horizon, tested and the percentage of organic matter calculated to the nearest 1%. To facilitate the removal of roots, the specimens were first oven dried and then reduced by pestle and mortar. The roots could then be separated by sieving and using tweezers.

Variability was again measured with samples from the same pits using, to illustrate the range of values, the cores from the upper horizon on the Juncus plot, the organic horizon on the Nardus plot and the mineral horizon on the Pteridium plot. Calculations were made to the nearest 0.1%.

Table 12.43 Percentage of Organic Matter: Within-plot
Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean (%)	85.0	3.1	64.5
Standard deviation	3.8	0.6	0.6

The internal-plot variability is therefore comparatively limited, particularly in the case of the Nardus plot. Since, in the case of the Pteridium plot, the sample was taken from the mineral horizon, a somewhat greater variation would have been expected.

To obtain a value for each plot, the mean was calculated as discussed, with the individual horizon readings being weighted according to the depth of horizon (Fig. 12.7).



Fig. 12.7

Rookhope Plots: Percentage Organic Matter

Table 12.44 Percentage of Organic Matter: Plot Measurements

Plot	1	2	3	4	5	6	7
Mean organic content (%)	42	86	30	34	82	48	25

Plot	8	9	10	11	12	13	14
Mean organic content (%)	27	18	89	42	37	33	80

Plot	15	16	17	18	19	20
Mean organic content (%)	29	35	79	27	26	85

The Juncus plots are distinctive with a very high mean organic content, but the results for plots in the other two categories are not clearly differentiated. There is a general tendency for the Nardus plots to have a higher organic percentage than neighbouring Pteridium plots, although plot 9 displays the lowest value recorded. When the standard deviations are considered, it is clear that between-plot variability is distinctive although, for example plots 18 and 19 might be drawn from the same population. The distinctiveness is further emphasised when the variation within plot groups is considered.

Table 12.45 Percentage of Organic Matter: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (%)	78.4	31.9	30.3
Standard deviation	13.9	9.0	4.1

This table indicates the high level of consistency of the Pteridium plots in contrast to the considerably

larger range of readings from Nardus plots. The standard deviation for the Juncus plots is clearly influenced by the result from plot 6 where there is a mineral horizon.

The range of values within the basin as a whole can be shown by a summary.

Table 12.46 Percentage of Organic Matter: Basin Summary

Mean	Standard error	Standard deviation
46.0	5.2	23.2
Minimum	Maximum	Range
18.0	88.0	70.0

12.4.7. Soil Depth

The procedures for measuring soil depth have already been described and a distinction needs to be made between depth sampling by soil sampler and the more accurate process possible in a soil pit. However, both were necessary as clearly the degree of plot destruction resulting from pit excavation is not acceptable in such a confined area where sensitive monitoring is taking place.

The only real problem occurred in sampling, as readings were susceptible to distortion by the presence of rock fragments in the soil mantle. The technique can therefore be seen as a measure not only of depth, but also of auger penetration. While this was a limitation, there was the great advantage that this method could be used with precautions, on the actual plot. To avoid any undue weighting to the final mean figure, readings giving a value of under 50% of the maximum depth measured were discarded. The mean from this method was then compared with the reading from the soil pit, which was, as already described, sited just off the main grid and a value for the plot itself calculated.

To produce comparable results for each factor throughout the study, it was decided that within-plot variability should not be recorded for each plot but should

be restricted to results from the pits near plots 2, 3 and 4. The pits were excavated to provide a floor of approximately 300cm² and readings were taken at the centre and down the middle of each wall.

Table 12.47 Soil Depth: Within-plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean (cm)	63.7	22.5	26.5
Standard deviation	0.5	0.4	0.4

Internal-plot difference appears small but it must be remembered that the area of sampling was very restricted and therefore possibility of chance variations in the bedrock was minimized.

Readings for each plot were taken to the nearest 0.5cm as the greatest justifiable accuracy, particularly bearing in mind the foregoing discussion. Effectively each value tabulated results from nine readings arranged in two stages (Fig.12.8).

Table 12.48 Soil Depth: Plot Measurements

Plot	1	2	3	4	5	6	7
Mean depth (cm)	27	70.5	15	27	53.5	75	26
Plot	8	9	10	11	12	13	14
Mean depth (cm)	18.5	15	77.5	26	19	16.5	54
Plot	15	16	17	18	19	20	
Mean depth (cm)	18	27.5	59.5	38.5	23.5	71	



Fig 12.8

Rookhope Plots: Soil Depth (cm)

It can be seen that with few exceptions these results fall into the three well defined categories indicated by vegetation. The Pteridium plots: 3, 8, 12, 13, 15 and 19 are all characterised by thin soils although plot 19 is somewhat deeper. Plot 9 occurs as an isolate being a Nardus plot, but the others within the same group, apart from plot 18, display a marked consistency with a maximum value of 27.5cm and a minimum of 26cm. Possibly plots 18 and 19 illustrate the thickening of a soil mantle which might be expected on the lower parts of slopes. The Juncus plots display deep profiles with the lowest value almost exactly twice the mean for the Nardus plots. Apart from the three plots specifically mentioned, the trends are very clear. When these results and the low standard deviations are viewed together, it can be appreciated that the variation between plots is distinctive for the Pteridium and Juncus plots but less so for the Nardus plots which display a marked regularity. If the plots are grouped as already discussed, the high degree of consistency within the three groups can be seen.

Table 12.49 Soil Depth: Plot Groups

Plot group	<u>Juncus</u>	<u>Pteridium</u>	<u>Nardus</u>
Mean depth (cm)	65.9	18.4	26.7
Standard deviation	10.0	2.9	6.8

However, within the basin as a whole the variation is considerable and this can be shown by a summary.

Table 12.50 Soil Depth (cm): Basin Summary

Mean	Standard error	Standard deviation
37.9	5.0	22.4
Minimum	Maximum	Range
15.0	77.5	62.5

12.4.8. Organic Depth

To preserve as far as possible drainage conditions and the natural soil packing on the measurement grid, the depth of the organic layer was only measured in the soil pits. The mean and variability were calculated in the manner already described. During the excavation of the long term devices, it was possible to check the values on the plots themselves, and no significant differences were found. A similar procedure was adopted to establish where present, the boundaries of lower horizons, since these depths were required for later calculations. It should also be remembered that except in the cases of plots 6 and 14, readings for organic depth on Juncus plots were the same as those for total soil depth.

The only problem occurred in judging the actual extent of the organic horizon. The upper level was comparatively clearly defined by the root density, but on the Nardus plots the lower limit tended to grade into the mineral horizon. However, by a close examination of the texture, it was felt that this difficulty was overcome. In the case of the Pteridium plots and also plots 6 and 14, the boundary was extremely clear-cut, coinciding with, among other factors, a marked colour change.

Table 12.51 Organic Depth: Within-plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	3 (<u>Nardus</u>)
Mean (cm)	-	3.8	6.6
Standard deviation		0.4	0.2

It can be seen that the expected variation in organic depth is of a similar order to that in soil depth. Again, measurements were made to the nearest 0.5cm, the greatest precision which can be justified bearing in mind the boundary problems outlined. The value was then measured for each plot and checked later (Fig. 12.9).

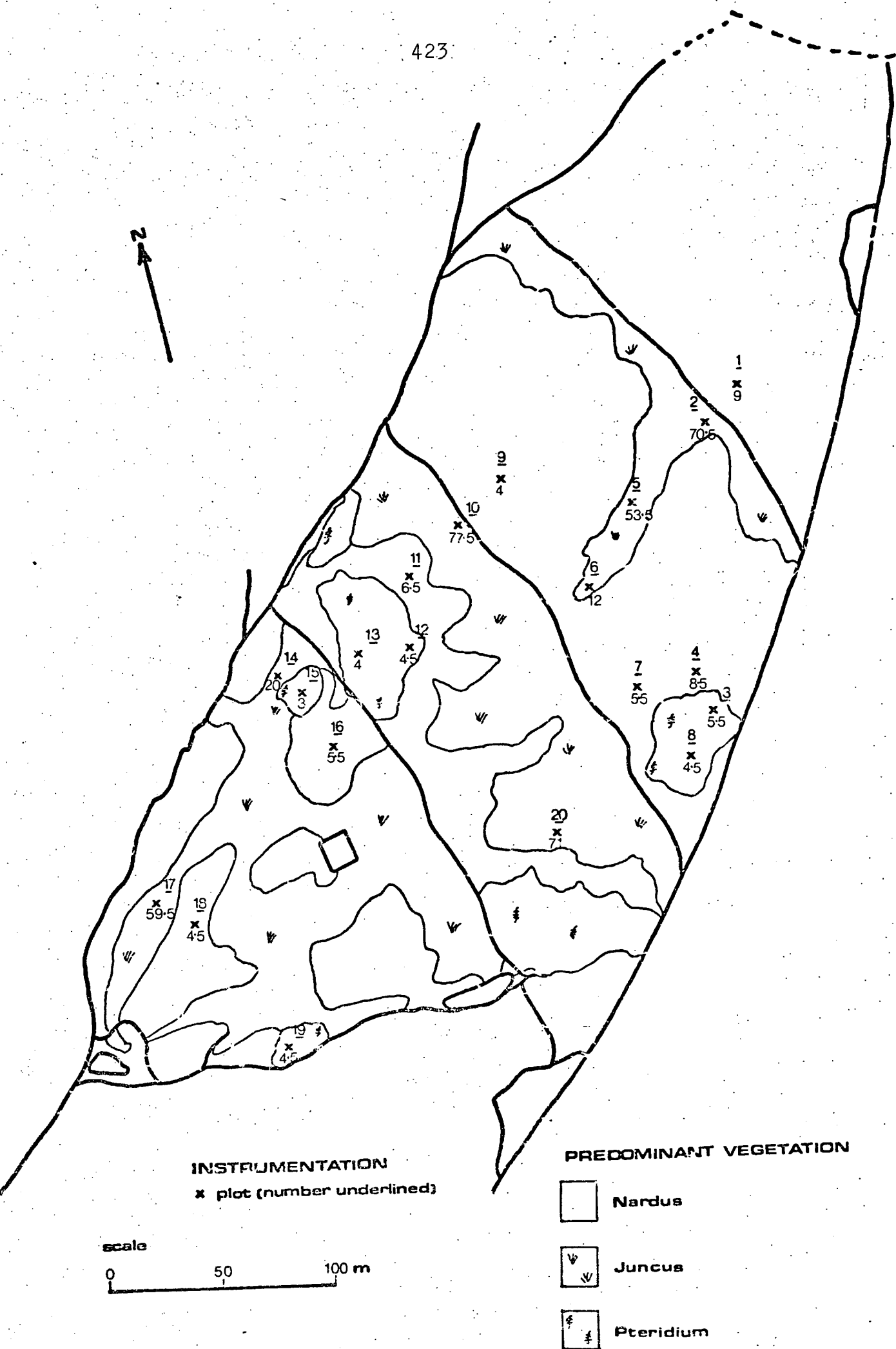


Fig. 12.9

Rookhope Plots: Organic Depth (cm)

Table 12.52 Organic Depth: Plot Measurements

Plot	1	2	3	4	5	6	7
Organic depth (cm)	9	70.5	5.5	8.5	53.5	12	5.5
Plot	8	9	10	11	12	13	14
Organic depth (cm)	4.5	4	77.5	6.5	4.5	4	20
Plot	15	16	17	18	19	20	
Organic depth (cm)	3	5.5	59.5	4.5	4.5	71	

If the values are grouped according to the vegetation indicated, the Juncus plots are clearly distinguishable, although plots 6 and 14 are somewhat different in exhibiting a mineral horizon. Results for the other two categories display no clear dividing line and any possible boundary is even more blurred when the standard deviations are also considered. If the plot readings are grouped, the degree of consistency can be seen.

Table 12.53 Organic Depth: Plot Groups

Plot group	<u>Juncus</u>	<u>Pteridium</u>	<u>Nardus</u>
Mean organic depth (cm)	52.0	4.3	6.2
Standard deviation	25.9	0.8	1.9

Clearly there is a marked regularity in the case of the Pteridium and Nardus plots but the Juncus plots display a particularly large variation. This is accounted for mainly by plots 6 and 14 which, as noted earlier, have mineral horizons. A summary of the total population again as expected, reveals a large standard deviation.

Table 12.54 Organic Depth (cm): Basin Summary

Mean	Standard error	Standard deviation
21.7	6.1	27.1
Minimum	Maximum	Range
3.0	77.5	74.5

12.4.9. Saturation Level

From a consideration of its soil moisture and field capacity values the possibility of a particular plot reaching or even exceeding its field capacity in winter can be approximately assessed. However the effect of short term increases such as those produced by heavy rainfall, have been neglected. Furthermore, the level of saturation, rather than reaching the surface may only rise part of the way up a lower horizon. The saturated part of a horizon is clearly highly important when creep rates are being examined, but its level and even the fact that it occurs, tends to be masked by the procedure of averaging moisture content for a horizon and then for a plot profile.

To overcome these problems, the Tube, already discussed, was used so that the highest level of saturation could be measured. Readings were taken from a datum selected 15cm below the surface to coincide with the probable pivot point of the Inclinator pegs.

As not more than one Tube could be accommodated on a grid, and as by definition, only one result a year could be obtained, internal-plot variability could not be assessed. However, the Juncus transect, plots 2, 5 and 6, shows a range of only 3mm. Similarly plots 10, 14 and 17 have a range of 5mm. It can therefore be normally assumed that local variation is small.

Measurements for each plot were made to the nearest 1mm (Fig. 12.10).



Table 12.55 Saturation Level: Plot Measurements

Plot	1	2	3	4	5	6	7
Saturation level (cm)	6.5	14.8	11.2	11.3	14.5	14.5	5.7

Plot	8	9	10	11	12	13	14
Saturation level (cm)	6.5	11.5	16.7	13.2	8.3	11.5	16.4

Plot	15	16	17	18	19	20
Saturation level (cm)	11.0	12.2	16.9	13.9	7.7	16.9

It can be seen that during this year all the Juncus plots were virtually saturated for a period. In the case of plots 10, 14, 17 and 20, the level rose above the surface. The Nardus plots display the greatest variation with plots 11 and 18 being almost saturated, while plots 1 and 7 were comparatively dry. As a group, the Pteridium plots were the least saturated although the level on plots 3, 13 and 15 was comparatively high.

Table 12.56 Saturation Level: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (cm)	15.8	10.6	9.4
Standard deviation	1.1	3.2	2.1

Bearing in mind the previous discussion on moisture, this table shows the expected order of plot groups. Of particular note is the small standard deviation illustrating the constancy of the Juncus group. These results can be compared with the summary for the whole basin, which indicates the large range of readings overall.

Table 12.57 Saturation Level (cm): Basin Summary

Mean	Standard error	Standard deviation
12.1	0.8	3.6
Minimum	Maximum	Range
5.7	16.9	11.2

12.4.10 'Resistance' Variables

The major variables in this category would seem to be connected with yield strength (Kirkby, 1967) and therefore a range of related characteristics was measured. Since the detailed mechanism of creep and particularly the scale of yielding is largely conjectural it was considered especially important to obtain results from a number of different factors. Kirkby (1967) describes the actual movement as the making and breaking of contacts among individual soil aggregates and, although it is likely to be on a larger scale, the measurement of shear strength appeared to provide the nearest approximation. However, through differential rates, compression must also occur and if unconfined compression is investigated, direct readings of stress and strain can be obtained. The fourth related variable was penetration which was included partly because it is a factor which has been reported previously (Chorley, 1959, 1964), but also because it provides a direct reading of resistance and is less affected by roots than the other two measurements. However, it is realised that while shear testing and unconfined compression testing reproduce tolerably situations which occur in the field, penetration is in that respect unnatural. A further variable which must resist creep at least in the initial stages is bulk density. Furthermore it can be related to compaction in the lower layers of the soil, precluding the absorption of water, and also to the organic percentage. The other factor concerned with resistance as mentioned earlier, is apparent cohesion.

12.4.11. Bulk Density

The specific gravity of soil particles is a particularly difficult measurement to make accurately and it is accepted that a figure of 2.65 will suffice as a basis (Reid, 1973 and oral communication). Therefore if it is required to discriminate among factors affecting rates of soil creep, bulk density is a far more suitable measure. However the Chepil method for the determination of dry bulk density, described earlier, is somewhat approximate, especially in the case of organic soils. While mineral soil samples can be ground to their textural constituents allowing a reasonably accurate reproduction of the natural packing, organic specimens when dried, are comparatively resistant to breakdown. Consequently the aggregated particles tend to occupy a greater volume than the original soil.

To overcome this problem but still retain a relationship with the standard measure, it was decided to obtain readings for bulk density with dried soil and also with soil at field capacity. This second value accords more with the natural basin conditions but, more important, shows the possible contrast in mass per unit volume.

To indicate internal-plot variability, cores were extracted and weighed at field capacity. From the results, the mean for each profile was calculated.

Table 12.58 Bulk Density: Within-plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean (g/cm ³)	1.56	2.44	2.04
Standard deviation	0.03	0.08	0.04

The internal-plot variation is of much the same order as that obtaining for texture and is comparatively small.

Both bulk density values, dry (Fig. 12.11) and at field capacity are listed for each plot for comparative purposes, having been averaged down the profile by the method already discussed.

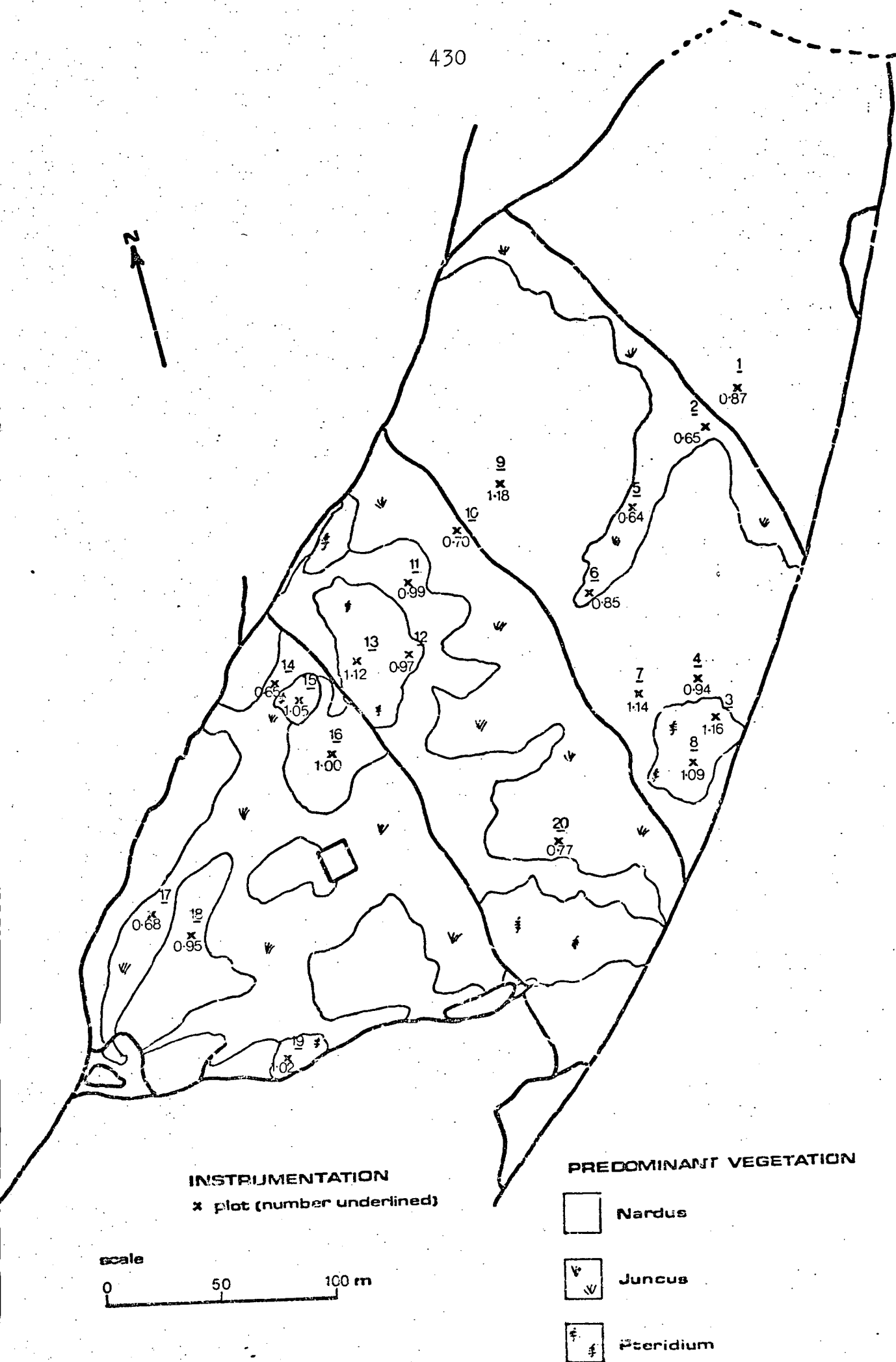


Fig. 12.11 Rookhope Plots: Dry Bulk Density
 (g/cm³)

Table 12.59 Bulk Density: Plot Measurements

Plot	1	2	3	4	5	6	7
Bulk density (g/cm ³)							
(a) dry	0.87	0.65	1.16	0.94	0.64	0.85	1.14
(b) field capacity	1.62	1.53	2.39	1.91	1.38	1.88	2.30

Plot	8	9	10	11	12	13	14
Bulk density (g/cm ³)							
(a) dry	1.09	1.18	0.70	0.99	0.97	1.12	0.65
(b) field capacity	2.52	2.54	1.26	2.20	2.12	1.96	1.25

Plot	15	16	17	18	19	20
Bulk density (g/cm ³)						
(a) dry	1.05	1.00	0.68	0.95	1.02	0.77
(b) field capacity	2.12	2.20	1.23	1.97	1.92	1.76

The three groups are clearly discernible with, as would be expected, increasing values from Juncus to Nardus and then Pteridium. Again the Juncus group is particularly distinctive but the boundary between the other two categories is somewhat blurred. Broadly the bulk density of a sample at field capacity is twice the dry value, although bearing in mind the sources of variation already discussed, this is not consistent. Bulk density at winter moisture percentage further clarifies the groups, and of course provides a more accurate measure of actual conditions within the basin.

Table 12.60 Bulk Density (Winter Moisture): Plot Measurements

Plot	1	2	3	4	5	6	7
Bulk density (g/cm ³) (winter moisture)	1.50	1.53	2.08	1.75	1.38	1.88	2.07

Plot	8	9	10	11	12	13	14
Bulk density (g/cm ³) (winter moisture)	2.36	2.39	1.27	2.14	1.97	1.69	1.27

Plot	15	16	17	18	19	20
Bulk density (g/cm ³) (winter moisture)	1.70	2.05	1.75	1.82	1.75	1.27

It can be seen that owing to their generally lower winter moisture content, values for Pteridium plots tend to be lower than those for Nardus. Since soils on these two categories of plot are similar and markedly different from those on the Juncus plots, it might be expected that the difference in bulk density would be reflected in varying rates of creep. When the small standard deviations are considered, it is clear that the between-plot variations are distinctive. This variability is again well seen when the standard deviations for plot groups are calculated.

Table 12.61 Bulk Density: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (dry) (g/cm ³)	0.71	1.01	1.07
Standard deviation (dry)	0.08	0.11	0.07
Mean field capacity (g/cm ³)	1.47	2.11	2.17
Standard deviation (field capacity)	0.26	0.30	0.24

The internal-plot group standard deviations are markedly greater than those recorded within the individual plots. They also provide a comparison between the two values measured, illustrating the expected greater variability when the bulk density is calculated with the soil at field capacity. In this case the variations inherent in the dry soil are enhanced by local differences in porosity and other factors which affect soil absorption.

The range of dry bulk density within the whole basin can be summarized.

Table 12.62 Bulk Density (g/cm^3): Basin Summary

Mean	Standard error	Standard deviation
0.92	0.04	0.18
Minimum	Maximum	Range
0.64	1.18	0.54

12.4.12. Shear Strength

Measurements of shear strength provide two basic factors significant in the study of soil creep: angle of internal friction and apparent cohesion. The tangent to the angle of internal friction is defined as the ratio:

$$\frac{\text{resistance to sliding on an internal plane}}{\text{the pressure normal to the plane}}$$

Cohesion is the resistance a soil exhibits to external forces which are tending to pull the particles apart. In terms of the above definition, it can be seen as the shear resistance at zero normal pressure. However since the resistance results not only from the pore water pressure but also from the packing of the soil particles and the presence of rootlets, the factor measured in the field is taken to be apparent cohesion (Capper and Cassie, 1969).

As for any sample, the pressure normal to the plane is provided by the overlying soil layers and therefore varies throughout the basin, field conditions could not be reproduced in testing. The major concession to field

conditions was the use of specimens at winter moisture percentage which was in fact, for many plots similar to field capacity. In soil mechanics the sample should be saturated for testing, but for geomorphology, the highest moisture content attained seems more realistic.

It is clear from the definitions that the two factors can be measured at the same time with the cohesion value as the first reading in a series of four which define the angle of internal friction. Samples were extracted horizontally from the centre of each horizon but discarded if they contained drift particles or large roots. A similar inspection was made after testing, but smaller roots cannot be so easily detected and their presence must to an extent, be reflected in the results which are likely therefore to be enhanced. However it is felt that as with winter moisture content, this factor provides a closer approximation to reality within the basin.

Internal plot variability can be illustrated from the apparent cohesion readings, using samples from the organic horizons of the three soil pits already described.

Table 12.63 Apparent Cohesion: Within-plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean (kg/cm ²)	0.80	0.50	0.55
Standard deviation	0.14	0.14	0.06

To obtain a single reading for each plot, the maximum value was taken as it was considered that this would be the most crucial in a correlation with creep rates. For soil creep to occur, cohesion must be overcome. Furthermore, as this particular value resulted as might be expected, exclusively from measurements of the organic horizon, it was possible to give a comparison for the entire basin (Fig. 12.12)

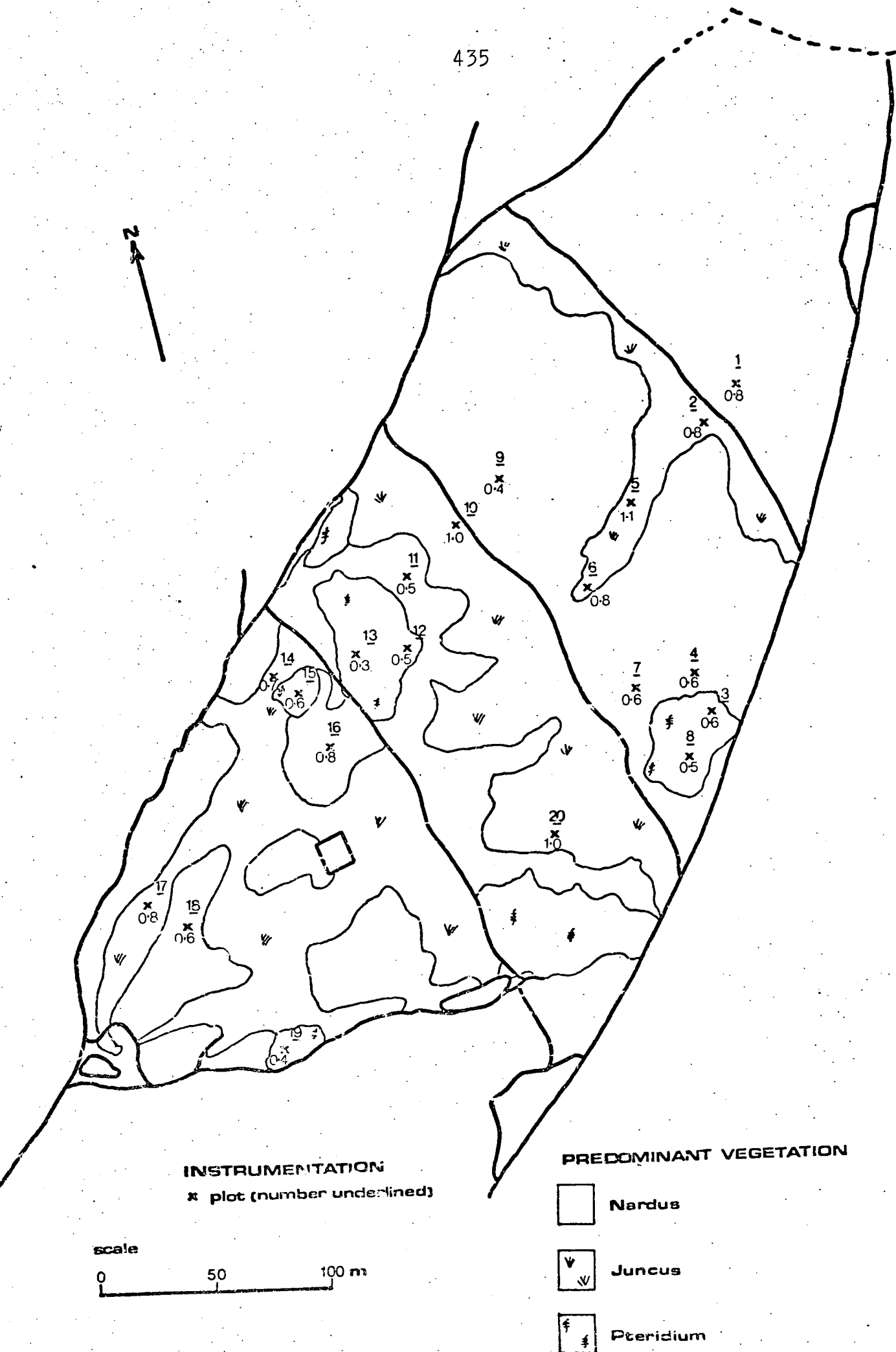


Fig. 12.12 Rookhope Plots: Maximum Apparent Cohesion
 (kg/cm²)

Table 12.64 Maximum Apparent Cohesion: Plot Measurements

Plot	1	2	3	4	5	6	7
Maximum apparent cohesion (kg/cm ²)	0.8	0.8	0.6	0.6	1.1	0.8	0.6

Plot	8	9	10	11	12	13	14
Maximum apparent cohesion (kg/cm ²)	0.5	0.4	1.0	0.5	0.5	0.3	0.7

Plot	15	16	17	18	19	20
Maximum apparent cohesion (kg/cm ²)	0.6	0.8	0.8	0.6	0.4	1.0

While the grouping according to vegetation association again appears, the range of values is comparatively small and this variable is not particularly useful for purposes of discrimination. However, when the standard deviations established at the sampling pits are taken into account, there is still some clear between-plot variation. On the other hand this is closely related to vegetation community as the plot group standard deviations indicate.

Table 12.65 Maximum Apparent Cohesion: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (kg/cm ²)	0.89	0.63	0.48
Standard deviation	0.15	0.14	0.12

The variation within any group is only marginally in excess of that between internal-plot samples. This therefore reinforces the original contention that the apparent cohesion value for individual plots is not sufficiently distinctive for it to be a key indicator of creep controls. However

it should be stressed that field conditions are likely to cause distortions in the results and furthermore that this variable is, as discussed earlier, in effect both a 'force' and a 'resistance' factor. A summary of the statistics for the whole basin provides a further guide to the modest range of variation.

Table 12.66 Maximum Apparent Cohesion (kg/cm^2): Basin Summary

Mean	Standard error	Standard deviation
0.67	0.05	0.22
Minimum	Maximum	Range
0.30	1.10	0.80

A more clearly defined resistance factor having an obvious relationship to the mechanics of creep is the maximum angle of internal friction. As defined earlier, this represents resistance to sliding on an internal plane, and is therefore a factor which must be overcome if creep is to take place. However, as the maximum value is provided where this is possible, by the mineral horizons (Fig. 12.13), to allow a more direct comparison, the readings for the organic horizon are also listed. To obtain the angle, the normal force comprised additional increments of 0.92kg until four readings had been taken.

Table 12.67 Maximum Angle of Internal Friction:
Plot Measurements

Plot	1	2	3	4	5	6	7
Maximum angle of internal friction ($^{\circ}$)	40	28	38	40	26	34	45
Angle of internal friction (organic) ($^{\circ}$)	22	25	34	28	18	29	30

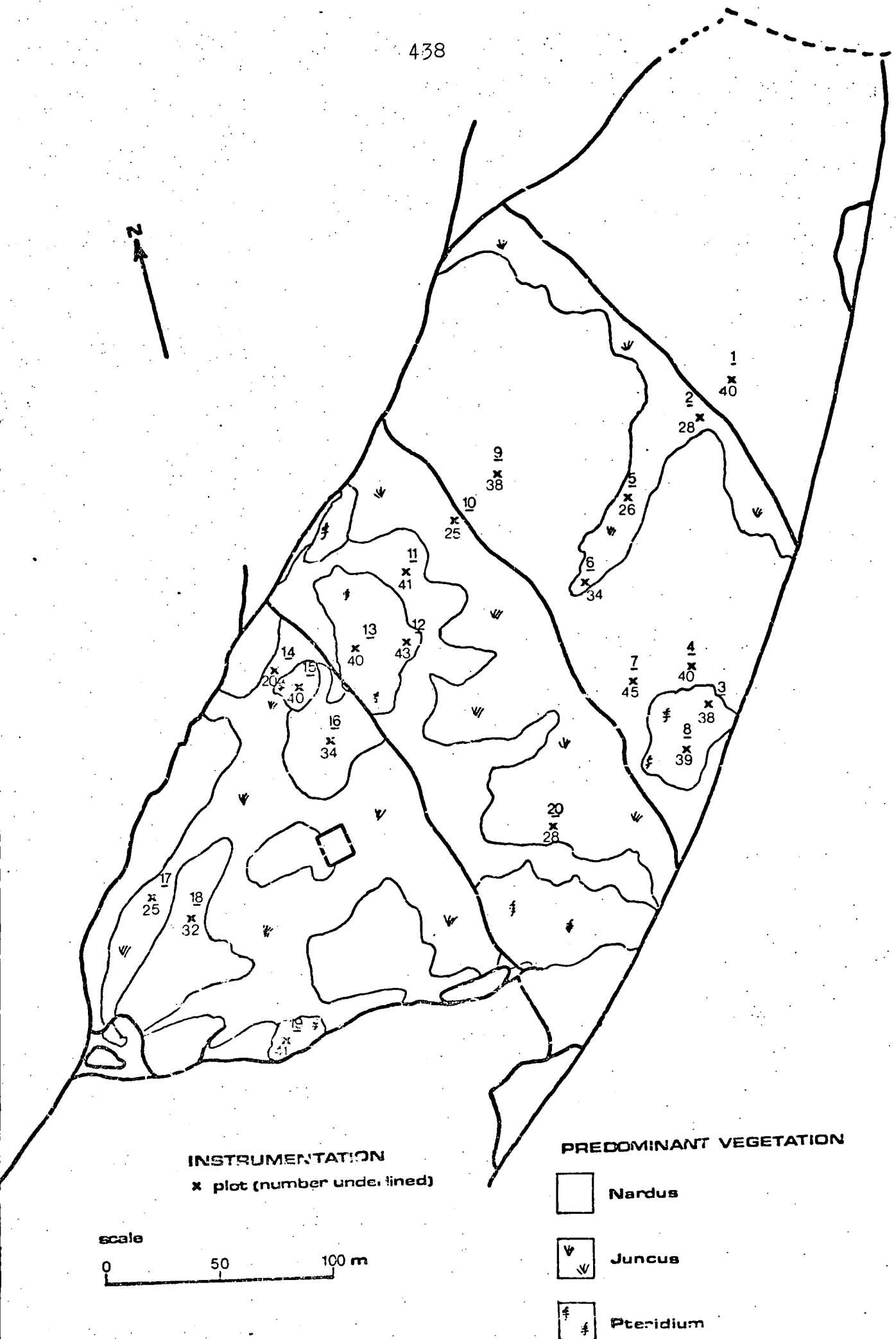


Fig. 12.13 Rookhope Plots: Maximum Angle of Internal Friction ($^{\circ}$)

Plot	8	9	10	11	12	13	14
Maximum angle of internal friction (°)	39	38	25	41	43	40	20
Angle of internal friction (organic) (°)	39	25	20	28	36	31	19

Plot	15	16	17	18	19	20
Maximum angle of internal friction (°)	40	34	25	32	41	28
Angle of internal friction (organic) (°)	30	28	24	20	29	22

The angles are all comparatively steep, but bearing in mind particularly the presence of roots, this is to be expected. Each individual contributing value was averaged from two sets of readings and it is felt therefore that the results are accurate to the limitations already ascribed to the apparatus. A clear distinction emerges from the maximum angle as no reading for the Juncus plots exceeds 30° while neither of the other categories displays as small an angle. A summary for each group might be compared with that for the whole basin.

Table 12.68 Maximum Angle of Internal Friction: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean	26.6	38.6	40.2
Standard deviation	4.2	4.4	1.7

Table 12.69 Maximum Angle of Internal Friction ($^{\circ}$):Basin Summary

Mean	Standard error	Standard deviation
35	1.6	7.2
Minimum	Maximum	Range
20	45	25

It is apparent that the standard deviations are comparatively small and that this variable is particularly suitable for discriminatory purposes when controls of creep are considered.

The angle for the organic horizon cannot be as clearly categorised and, as with apparent cohesion, the importance of roots must be taken into account. Nevertheless, the highest angles were recorded on Pteridium plots and the lowest on Juncus plots, giving a pattern broadly similar to that for the maximum angle. Thus the groupings and trends already distinguished are reinforced by this second value.

By adapting the shear tester so that the dial gauge could indicate movement, it was possible to measure the maximum angle of internal friction while creep was occurring. Thus while shearing was shown on the dial, a steady balance reading recorded the stress during creep. The values obtained were, as would be predicted, somewhat lower than those for the maximum angle already discussed, but tended to vary in the same manner.

To overcome the initial resistance of the soil the largest force or peak stress is required. Once failure has begun the resistance falls to a steady value known as the ultimate stress, which is the force recorded during creep movement (Capper and Cassie, 1969). However for creep to be initiated, peak stress must be achieved and this remains the key variable.

Table 12.70 Maximum Angle of Internal Friction (creep):
Plot Measurements

Plot	1	2	3	4	5	6	7
Maximum angle of internal friction (creep) ($^{\circ}$)	29	21	36	27	21	30	41
Plot	8	9	10	11	12	13	14
Maximum angle of internal friction (creep) ($^{\circ}$)	37	30	24	34	35	35	18
Plot	15	16	17	18	19	20	
Maximum angle of internal friction (creep) ($^{\circ}$)	39	31	20	31	38	20	

Since these measures were taken with only very limited possible observation time and bearing in mind the constraints described for all the shear tester readings, they are seen as a broad indication of resistance rather than a definitive data set. The same pattern of results is again discernible with the highest value on Pteridium plots and the lowest on Juncus plots.

12.4.13. Penetration

Closely related to the foregoing variables is resistance to penetration measured by the hand penetrometer. Penetration has been used to assess shear strength and thereby potential erodibility (Chorley, 1959, 1964) but, as with apparent cohesion, it can also be related to moisture content (Melton 1957). However it is unlike the other measures of resistance to creep used in this study, in that it cannot be directly related to soil movement in the field. It is seen as a technique allowing only approximate comparative indications of resistance. The main advantage

is that readings can be obtained rapidly while the chief limitation concerns the scale which is coarse. Therefore it was decided that, rather than attempt any detailed calibration with the shear test apparatus which, by the nature of the measurements would be of doubtful validity, the printed scale should be used. The results could then be interpreted as giving relative shear strength. However as they were obtained with the soil at its winter moisture condition, they are directly comparative with other similar readings such as the angle of internal friction.

Measurements were made to the nearest 0.05 kg/cm^2 on the scale by pressing the penetrometer probe into the centre of the relevant horizons. To overcome the problems associated with the heterogeneities of soil and also to capitalise on the speed of operation, readings were taken for each horizon until four coincided exactly. In no case were more than seven measurements required and the mode was then accepted as the definitive value. To conform with the pattern established for the other basin factors, internal-plot variation was also measured at the sampling soil pits using the upper horizons.

Table 12.71 Penetration: Plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean (kg/cm^2)	0.94	1.49	1.09
Standard deviation	0.13	0.24	0.15

Since this variable should be compared with the other related measures, the maximum readings (Fig. 12.14) and those for the organic horizon, or in the case of Juncus plots the upper horizon, are both given.

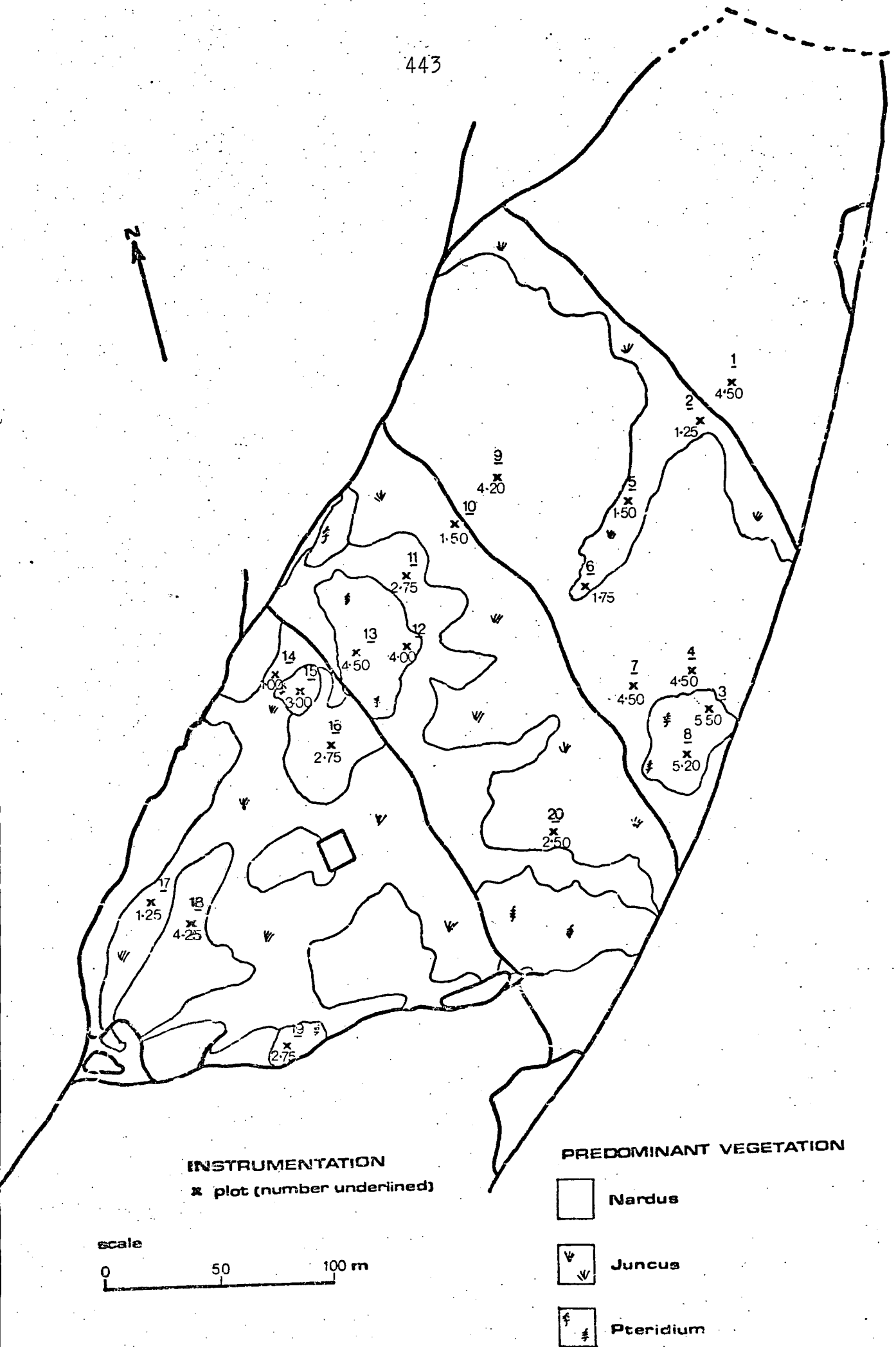


Fig. 12.14 Rookhope Plots: Penetration
 (kg/cm²)

Table 12.72

Penetration: Plot Measurements

Plot	1	2	3	4	5	6	7
Maximum penetration resistance (kg/cm ²)	4.50	1.25	5.50	4.50	1.50	1.75	4.50
Penetration resistance (organic horizon) (kg/cm ²)	1.00	0.65	1.50	1.25	0.95	0.85	1.50

Plot	8	9	10	11	12	13	14
Maximum penetration resistance (kg/cm ²)	5.20	4.20	1.50	2.75	4.00	4.50	1.00
Penetration resistance (organic horizon) (kg/cm ²)	1.65	1.75	0.75	1.25	1.00	1.00	0.50

Plot	15	16	17	18	19	20
Maximum penetration resistance (kg/cm ²)	3.00	2.75	1.25	4.25	2.75	2.50
Penetration resistance (organic horizon) (kg/cm ²)	1.00	0.85	0.75	1.25	1.25	0.85

With the maximum readings, the Juncus plots emerge as a distinctive group, with plot 20 appearing somewhat deviant. However even with the rather higher readings on that plot, there is no overlap with the other categories which include no value below 2.75. The Nardus and Pteridium groups again exhibit a blurred boundary, partly as a result of the lowering of readings down the basin. Thus for the higher tier of plots, the mean for Nardus is 4.42 and for Pteridium 5.35, while for the lower tier the means are 3.50 and 2.87 respectively. It is possible, as was considered for certain earlier variables, that this can be related to the increasing soil water content encountered towards the base of a slope.

The relationship between the mean range for a plot group and the maximum modal values shows a high degree of

constancy throughout the basin. It also illustrates the point that there is distinctive between-plot variation. This conclusion is reinforced when the limited within-plot variation is considered. The readings for the organic or upper horizons display the same pattern among the plot groups as the maximum penetration results, although the distinctions are less clear cut.

If in each case the modal value is treated as the definitive result, the summary statistics for the three categories of plot can be compared with those for the whole basin. Those for the maximum reading only are given.

Table 12.73 Penetration: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean (kg/cm ²)	1.54	3.92	4.16
Standard deviation	0.49	0.81	1.13

These results reinforce the conclusions about the distinctiveness of the Juncus plot penetration readings. The boundary between Nardus and Pteridium plot group variables is less clear cut.

Table 12.74 Penetration (kg/cm²): Basin Summary

Mean	Standard error	Standard deviation
3.16	0.33	1.46
Minimum	Maximum	Range
1.00	5.50	4.50

12.4.14. Unconfined Compression

The two sets of values resulting from this series of measurements were seen as complementary to those obtained for shear strength. They also act as something of a check although the relationship between compression and shear

strength discussed by King and Cresswell (1954) would not be expected as the angles of internal friction are large and also root effects are minimised in measurements involving compression.

Since the variables are related and since the results are of a similar magnitude to those measured for apparent cohesion, it can be assumed that internal-plot variation is much the same for the two variables.

Cores were extracted from the centre of relevant horizons and the mean of two sets of readings taken for each. The maximum reading is tabulated and in every case this was obtained from the organic horizon. Since one results from the other, the strain related to the particular maximum stress (Fig. 12.15) is tabulated for that plot.

Table 12.75 Unconfined Compression: Plot Measurements

Plot	1	2	3	4	5	6	7
Maximum stress (kg/cm ²)	0.95	0.30	0.75	0.95	0.50	0.55	0.70
Strain (cm)	6.25	4.38	7.00	5.00	4.00	4.00	6.75
Plot	8	9	10	11	12	13	14
Maximum stress (kg/cm ²)	0.80	0.95	0.50	0.80	0.80	0.70	0.50
Strain (cm)	8.50	8.50	1.25	5.25	10.75	8.75	3.25
Plot	15	16	17	18	19	20	
Maximum stress (kg/cm ²)	0.80	0.90	0.40	0.90	0.70	0.50	
Strain (cm)	10.25	6.75	3.25	10.00	10.75	2.50	

The values for stress are slightly more discriminatory than those for cohesion, but the trend is reversed and in this case, the Juncus plots exhibit the lowest readings.

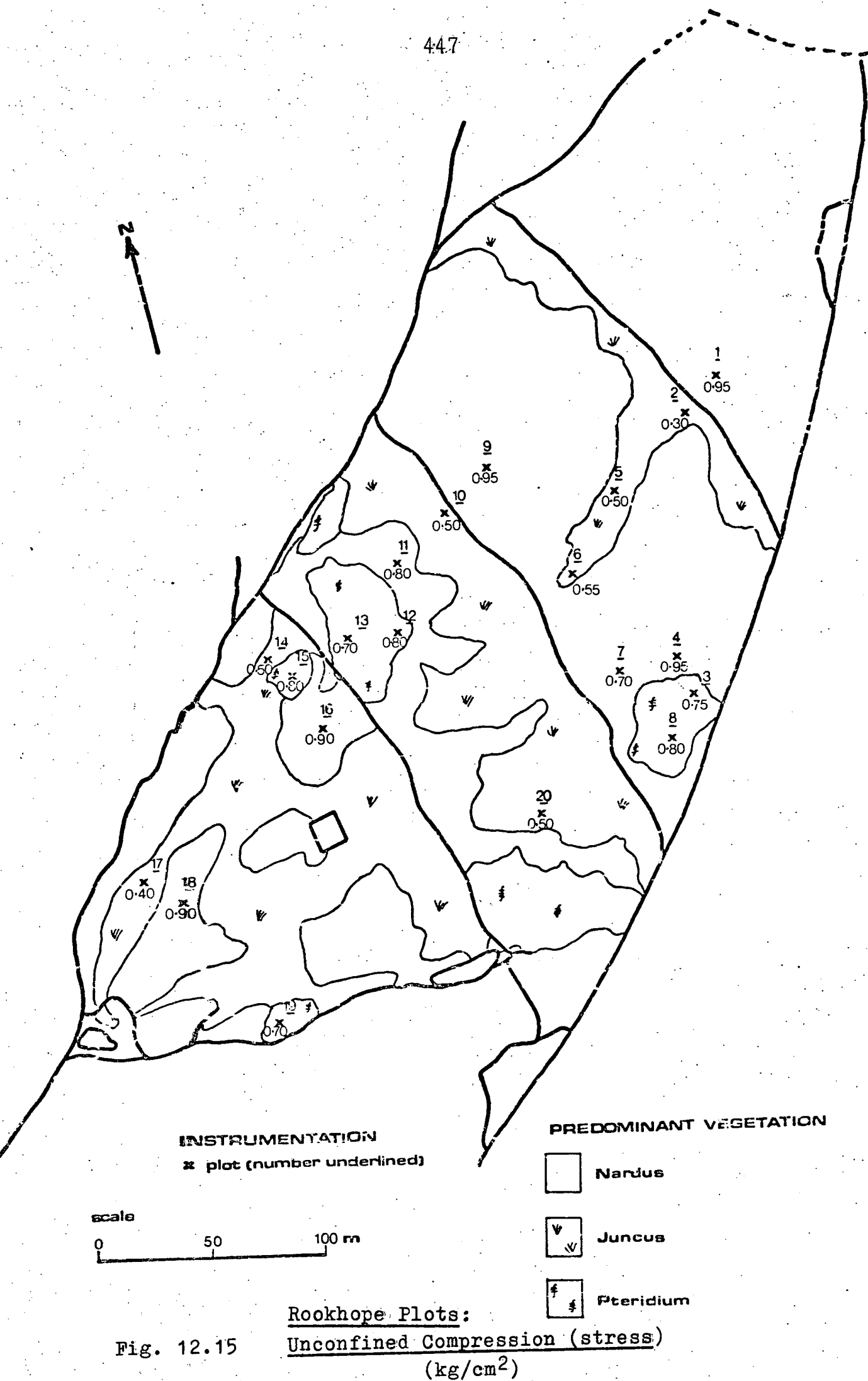


Fig. 12.15

Since unconfined compression can be directly related to the angle of internal friction, this fact would be expected.

From the empirical evidence the major difference during testing for apparent cohesion and unconfined compression is that the former involves pressure across a comparatively small area, i.e. the width of the sample. Therefore the resulting drainage is relatively small whereas that from the unconfined compression test, involving pressure on the complete length of the specimen, is far greater. Thus, in the measurement of apparent cohesion, the greater influence of soil moisture combined with the effect of roots produces a different order of readings. Furthermore, failure from compression appears, like shearing with pressure applied normally, to occur gradually, allowing a degree of continuous repacking under pressure. Shearing with no normal pressure is comparatively sudden with little rearrangement. Reasons for the reversal of the trend can therefore be advanced but it must be realised that in the case of both maximum stress and apparent cohesion, the range of results is very limited and neither variable appears particularly useful for discriminating among possible controls of soil creep.

On the other hand, strain under maximum stress does allow an effective judgment to be made of the compression necessary before failure occurs. Variation throughout the basin is large and differences between the plot groups can be clearly established. This contrast between stress and strain results can be illustrated for the main plot groups.

Table 12.76 Unconfined Compression: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean stress (kg/cm ²)	0.46	0.88	0.76
strain (cm)	3.23	6.93	9.33
Standard deviation	0.09	0.10	0.05
stress			
strain	1.08	1.78	1.51

While the readings for strain show distinctive between-plot group variation, those for stress reveal a degree of overlap between the Nardus and the Pteridium group with the Nardus slightly higher.

Finally, the ranges of the two variables within the whole basin can be constructed.

Table 12.77. Unconfined Compression: Basin Summary

	<u>Mean</u>	<u>Standard error</u>	<u>Standard deviation</u>
Stress (kg/cm ²)	0.70	0.04	0.20
Strain (cm)	6.36	0.65	2.91
	<u>Minimum</u>	<u>Maximum</u>	<u>Range</u>
Stress (kg/cm ²)	0.30	0.95	0.65
Strain (cm)	1.25	10.75	9.50

12.4.15. Texture

In the drainage basin there are fifteen plots with mineral horizons, but in the case of plot 14, as the organic horizon extends well below the depth of the instruments and the seasonal creep zone, measurements were not made. The only Juncus plot with a mineral horizon effective in the context of this study, is plot 6. Within the other two categories, problems arose with certain of the Nardus plots which displayed a degree of stratification within the mineral horizon. In the case of plots 1 and 4 the humus-rich upper part grades into a rather sandier yellow-grey lower layer. The colouring is different on plots 11, 16 and 18 where the upper layer is bleached almost white and the lower exhibits marked iron mottles. It was decided therefore that in these cases the texture should be measured for both strata within the mineral horizon and the final value should reflect the relative thickness of each. This procedure was followed for all the factors which were to be averaged for the profile. On the remaining Nardus plots, 7 and 9, together with all the Pteridium plots, no such differentiation was evident and one

set of readings sufficed for the mineral horizon. Samples for testing were taken in every case from the centre of the particular horizon or layer.

The three techniques for assessing texture have been described, but as the simple settlement and flotation methods were only intended to provide an approximate guide to further work on the physical properties, results quoted refer, with one exception, only to the British Standard pipette procedure (B.S. 1377). The exception concerns the first part of the flotation method in which the coarse and medium sand fraction was sieved off under standard conditions. Data collected at this stage are compared with those produced by the pipette techniques to illustrate through the sand fraction, internal-plot textural variability.

Table 12.78 Texture: Within-plot Variability

Plot	2 (<u>Juncus</u>)	3 (<u>Pteridium</u>)	4 (<u>Nardus</u>)
Mean % of sand fraction	-	28.1	19.8
Standard deviation		2.0	0.5

Although these readings represent only part of the sand fraction, they do indicate the limited variability among samples extracted from one point.

The values for each plot are tabulated but it must be remembered that those for plots 1, 4, 11, 16 and 18 are means from the different strata.

Table 12.79 Texture: Plot Measurements

Plot	1	3	4	6	7	8	9	11
% sand	49.4	55.9	53.0	60.2	57.0	64.8	65.3	58.3
% silt	46.0	40.1	34.5	33.5	29.1	33.5	28.8	30.4
% clay	4.6	4.0	12.5	6.3	13.9	1.7	5.9	11.3

Plot	12	13	15	16	18	19
% sand	77.1	74.9	71.6	60.0	59.0	82.1
% silt	22.2	24.1	25.4	35.1	31.0	14.6
% clay	0.7	1.0	3.0	4.9	10.0	3.3

The Pteridium plots may be distinguished by their generally higher percentage of sand (Fig. 12.16) and lower percentage of clay. This is seen more clearly if the summary statistics for the basin are compared with those for the grouped plots.

Table 12.80 Texture: Statistics for the Drainage Basin and Grouped Plots compared

	Basin	<u>Nardus</u> plots	<u>Pteridium</u> plots
Mean sand (%)	63.5	57.4	71.1
Standard deviation	9.7	5.1	9.4

	Basin	<u>Nardus</u> plots	<u>Pteridium</u> plots
Mean clay (%)	6.0	9.0	2.3
Standard deviation	4.3	3.8	1.3

When the ~~internal~~-plot standard deviations are applied, it is clear that the plot groups and, even neighbouring plots, are distinctive.

12.4.16. Root Factors

For a number of reasons the influence of roots is difficult to assess directly and therefore three separate measurements were made. The only aspect which could be measured with any degree of accuracy throughout the basin was root depth, although even this was complicated by the predominant mode of growth. Nardus plots exhibited a



Fig. 12.16

Rookhope Plots: Percentage Sand

tight well defined turf mat, but for the other two categories the root depth factor was more dependent upon 'sub-dominants'. In places, rhizomes stretched throughout the entire soil profile on the Pteridium plots and the main mat if present, was provided by the other species already listed. In the case of the Juncus plots, the main root system of the dominant species was measured to a mean depth of 11cm, but these were isolated roots and the main plant layer ceased much higher. As the main mat was composed of Sphagnum with occasional Carex tufts, and as under the prevailing conditions, decomposition occurred at a shallow depth, the lower level was taken conventionally at 4.5cm throughout the basin. This seems justified when it is realised that the only reason for the measurement of this factor is to assess its effect on soil movement. It could be seen from the results obtained, that creep certainly occurred just below that depth. For the other two categories, measurements were made in the soil pits to the nearest 0.5cm. The standard deviation for plots 3 and 4 was in each case 0.3cm.

Table 12.81 Depth of Root Mat Base: Plot Measurements

Plot	1	3	4	7
Depth of root mat base (cm)	4.5	3	4	4.5

Plot	8	9	11	12	13
Depth of root mat base (cm)	1	2.5	2	0.5	0.5

Plot	15	16	18	19
Depth of root mat base (cm)	3	2.5	3.5	3

As might be expected, the main root mat is not thick, the deepest layer being under one eighth of the mean soil depth for the basin. While there is an approximate division between the Nardus plots with a more developed, and the Pteridium plots with a less developed root layer, the boundary

is not clear. The influence of roots, as evidenced by their depth, would seem to be of little significance on plots 8, 11, 12 and 13 and only on plots 1, 4 and 7 does it appear important. If the root depth is expressed as a percentage of the organic depth, the position is further clarified. It will be seen later in the study that the organic content is a vital element in constructing a model for creep rates within the basin and therefore this percentage is by no means arbitrary.

Table 12.82 Root Depth as a Percentage of the Organic Depth

Plot	1	3	4	7	8	9
<u>Root depth</u> X 100 <u>Humus depth</u>	50	55	47	85	22	63

Plot	11	12	13	15	16	18	19
<u>Root depth</u> X 100 <u>Humus depth</u>	31	11	13	100	41	78	67

Again, plots 8, 11 and 12 appear as a group within which any counteracting force by roots would seem minimal. However the relative thickness of the root mat is only one factor which may inhibit the movement of the adjacent soil layer. If the density of roots within the mat is considered, then the Pteridium plots appear markedly less dense than the other two categories.

A further measure, and one more directly influencing creep rates in the humus horizon is dry root weight. While it is only possible to remove and weigh the larger roots which can be sieved from the dried soil, it is believed that the results provide a useful guide. However it should be stated that the value of this variable together with those for the depth of root mat and the root strength are so small that the standard deviations appear unrealistic as field measures. They are included for completeness.

Table 12.83 Mean Dry Root Weight: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean dry root weight per 10g of dried soil	0.10	0.12	0.35
Standard deviation	0.03	0.04	0.08

Although the presence of a length of rhizome can give undue prominence to the Pteridium group, it was felt that as the weights were averaged for several plots the values tabulated give a true indication of the possible influence of roots on creep rate.

A further factor is the strength of the root mat, and this was assessed using the shear tester, adapted as described to test cores of 2cm diameter. Ten readings were taken for each vegetation association from the area of plots 2, 3 and 4 and the mean for each was calculated.

Table 12.84 Mean Root Strength: Plot Groups

Plot group	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Mean root strength (kg/cm ²)	0.2	0.3	0.5
Standard deviation	0.02	0.02	0.03

It should be stressed that these values refer to the root mat rather than to large individual roots. The latter were measured separately, producing maximum readings of 1.7kg/cm². Except in the case of plots 13 and 19, these figures are all less than those measured for maximum apparent cohesion. If strength and dry root weight can be related to any inhibiting effect on rates of soil creep then clearly the order of plot groups has been established.

12.5 Variability

For each main basin factor the within-plot variation was measured to provide an indication of what is effectively the intrinsic variability of that factor and also to allow

the distinctiveness of between-plot differences to be judged.

With rather different aims in mind Carson (1967) carried out a similar exercise, sampling four soil characteristics over different lengths of slope and expressing the results as coefficients of variation. His shortest length, a five foot long line, is similar to that used for plot delimitation in this study. The other major difference is the method of measuring the particular variable which was not always the same as that used for Rookhope specimens. Furthermore it must be stated that little information is given about the background to the study area in which the results were obtained. However, bearing in mind these limitations, the variability of factors measured for this study can be contrasted with those reported by Carson.

Dry bulk density was calculated from cores of known volume and measured moisture content.

	<u>Carson</u>	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Coefficient of variation	8	11	11	7

Bearing in mind the different method of deriving the values, these readings are clearly of a similar order. In contrast to the on-site methods of this study, moisture content was found gravimetrically.

	<u>Carson</u>	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Coefficient of variation	12	3	5	11

It is difficult to compare these results since those from the Pteridium plots accord well with those reported but variability in the Rookhope basin appears to be related to plot wetness. Judging by the Exmoor conditions outlined later in Carson's paper, the Pteridium plot reading would appear to provide the most realistic comparison with the Carson value.

The silt/clay fraction was obtained by sieving and therefore provides a comparison with the factor recorded in this study, the sand fraction. It is realised that to make such a comparison assumes no major discrepancy in the proportion of sand to silt/clay between the Exmoor and Rookhope soils.

	<u>Carson</u>	<u>Nardus</u>	<u>Pteridium</u>
Coefficient of variation silt/clay	5		
sand		3	7

It can be seen that the variabilities are of the same order.

The fourth characteristic given in Carson's paper is shear strength, measured by a Vicksburg penetrometer. In the Rookhope basin, various measures of shear strength were taken and two are listed.

	<u>Carson</u>	<u>Juncus</u>	<u>Nardus</u>	<u>Pteridium</u>
Coefficient of variation Penetration	21	14	14	16
Apparent cohesion		18	11	28

Using the same instrument Chorley (1964) produced the following results:

	<u>Mean coefficient of variation</u>
Upper greensand	21.4
Shotover sand	16.2
Kimmeridge clay	19.3
Oxford clay	16.1
Lower greensand	23.1

Thus it can be seen that the internal-plot variability measured for this study is similar to that found by both Carson and Chorley.

In conclusion it would seem that, from the evidence of comparable work, the results for internal-plot variability presented can be accepted as providing an accurate picture and allowing a meaningful assessment to be made of other sources of variation.

12.6. Relationships between the Basin Factors

12.6.1. Introductory

The relationship between the variables measured at each plot within the drainage basin can be clearly displayed in a correlation matrix. For each pair of entries, the relationship is expressed by Pearson's product moment correlation coefficient (significance levels: 95%, 0.56; 99%, 0.44). The twenty basin factors are:

1. Sine of the slope angle
2. Soil depth
3. Organic depth
4. Saturation level
5. Soil moisture under winter conditions (% wet weight)
6. Field capacity
7. Bulk density (dry)
8. Percentage of organic matter
9. Maximum angle of internal friction
10. Maximum apparent cohesion
11. Penetration
12. Maximum unconfined compression (stress)
13. Maximum unconfined compression (strain)
14. Bulk density (field capacity)
15. Creep rates (Inclinometer pegs)
16. Plasticity index (organic horizon)
17. Plasticity index
18. Percentage linear shrinkage
19. Soil moisture under winter conditions (% dry weight)
20. Soil moisture under summer conditions (% dry weight)

It should be noted that for a number of reasons certain variables could not be included. The meteorological readings

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-0.30	-0.46	-0.47	-0.39	-0.43	0.45	-0.41	0.45	-0.38	0.37	0.14	0.29	0.45	-0.44	-0.21	-0.32	-0.32	-0.38	-0.45
2		0.83	0.76	0.91	0.90	-0.85	0.85	-0.80	0.78	-0.79	-0.80	-0.80	-0.75	0.75	0.82	0.85	0.94	0.800	0.86
3			0.59	0.83	0.83	-0.80	0.91	-0.75	0.76	-0.68	-0.80	-0.75	-0.72	0.70	0.63	0.80	0.81	0.81	0.87
4				0.78	0.78	-0.70	0.73	-0.85	0.56	-0.73	-0.62	-0.69	-0.63	0.66	0.74	0.76	0.81	0.74	0.77
5					0.99	-0.95	0.93	-0.89	0.82	-0.83	-0.76	-0.86	-0.84	0.86	0.89	0.94	0.96	0.93	0.92
6						-0.97	0.94	-0.89	0.83	-0.82	-0.75	-0.83	-0.88	0.85	0.83	0.94	0.94	0.92	0.92
7							-0.93	0.85	-0.78	0.83	0.73	0.74	0.92	-0.87	-0.84	-0.92	-0.91	-0.91	-0.90
8								-0.84	0.78	-0.81	-0.84	-0.81	-0.87	0.81	0.81	0.93	0.91	0.94	0.95
9									-0.66	0.77	0.70	0.71	0.78	-0.81	-0.89	-0.90	-0.90	-0.92	-0.91
10										-0.61	-0.54	-0.76	-0.66	0.68	0.68	0.72	0.75	0.70	0.72
11											0.77	0.62	0.76	-0.83	-0.81	-0.85	-0.86	-0.84	-0.82
12												0.63	0.69	-0.63	-0.73	-0.84	-0.83	-0.83	-0.82
13													0.66	-0.70	-0.69	-0.76	-0.82	-0.76	-0.80
14														-0.82	-0.78	-0.87	-0.81	-0.87	-0.84
15															0.77	0.85	0.84	0.88	0.85
16																0.94	0.92	0.89	0.86
17																	0.94	0.98	0.93
18																		0.92	0.94
19																			0.95
20																			

Table 12.85

Basin Factors: Correlation Matrix

do not refer to specific plots and must therefore be considered separately, while distance from the watershed can only be applied, as explained earlier, to certain specific groups of plots. Texture percentage measurements were limited to those with mineral horizons and vegetation cover together with root depth was not thought to be a sufficiently sensitive variable.

Among the major factors are several more minor variables included to provide comparisons. Thus, as explained earlier, it was thought useful to consider bulk density at field capacity alongside the standard characteristic, dry bulk density. As certain of the resistance factors referred to the mineral horizon and others to the organic, correlations with the plasticity index of the organic horizon were included. Finally, since it is of particular importance and is commonly expressed using either of the units, soil moisture was entered in the matrix as percentage wet weight and percentage dry weight. The introduction of the creep rate as a variable at this stage allowed the higher correlation coefficients to be identified so that more relevant correlation diagrams could be constructed.

While the matrix provides an overall guide, the relationships shown are statistical and must be examined further on two levels. Firstly, the more relevant and potentially important correlations must be checked graphically so that the spread of points can be taken into account. Secondly, any such association between variables needs to be explained in geomorphological terms if its true importance is to be appreciated.

It should be noted that there is a degree of dependence already built into many of the variables. For example, where measurements were taken for each horizon, the method of calculating the mean immediately includes the depth factor. Equally obviously many of the variables are clearly related to soil moisture and measurements were made, as described, under clearly defined conditions. Furthermore, autocorrelation would be expected and this is one reason, as explained later, for the general omission of significance levels from the study.

Since in many cases the major contrasts in readings occur between organic and mineral horizons and since the moisture retaining characteristics of organic matter are well known, it might be considered that the major source of variability for most factors measured depended on the organic content of the particular plot. Therefore, as far as possible the organic factor was controlled as a constant by obtaining results for a number of the more important factors only from the organic horizon. The following variables are included in the matrix:

1. Soil moisture under summer conditions (% wet weight)
2. Soil moisture under winter conditions (% wet weight)
3. Maximum angle of internal friction
4. Penetration
5. Bulk density (dry)
6. Field capacity
7. Plasticity index
8. Percentage linear shrinkage

Table 12.86 Correlation Matrix of Basin Factors:

(Organic Horizon)

(significance levels: 95%, 0.71; 99%, 0.83)

	1	2	3	4	5	6	7	8
1.	1.00	0.93	-0.74	-0.76	-0.85	0.92	0.81	0.61
2.		1.00	-0.79	-0.71	-0.83	0.98	0.84	0.64
3.			1.00	0.54	0.61	-0.77	-0.59	-0.37
4.				1.00	0.74	-0.61	-0.62	-0.44
5.					1.00	-0.80	-0.80	-0.61
6.						1.00	0.78	0.62
7.							1.00	0.61
8.								1.00

These correlation coefficients although generally

not so high, follow closely the pattern of those in the main basin factor matrix. While it is realised that there is a variation of the organic percentage within the horizons sampled, none the less, these results indicate strongly that plot differences are not simply a reflection of the proportion of organic matter present. Furthermore it is considered that the matrix makes this general point adequately and it is not necessary to analyse the correlation coefficients in more detail.

From the main basin factor matrix the variables correlating most highly positively and negatively with creep rates, can be identified as the major 'force' and 'resistance' factors respectively. The former is clearly soil moisture and, as the units used exercise little influence on the correlations but affect the linearity, winter moisture measured in percentage wet weight was selected. In fact, as the relationship between percentage wet weight and percentage dry weight becomes, for the higher values, distinctly curvilinear, variables had to be compared using the same units. For the range of results in this study and for later analysis which depends on linearity, percentage wet weight is the more suitable unit. The most highly correlated resistance factor is dry bulk density. Two simple correlation diagrams were then constructed, one based on each of these two variables, selected so that the inter-relationships could be more clearly seen. (significance levels: 95%, 0.44; 99%, 0.56)

12.6.2. 'Force' Factors

The 'force' factor diagram (Fig. 12.17) reveals that a number of variables is highly positively correlated with winter soil moisture although the relationship may not be direct. Since approximately the same rainfall total is likely to be received at any point within the basin, it would be expected that the wetter plots would be those with the highest retention capability or field capacity. However this is closely related to the percentage of organic matter present. Furthermore these plots with their high organic content will obviously register greatest shrinkage on drying and expansion on wetting. The plasticity index depends upon the soil constituents and, since the percentage

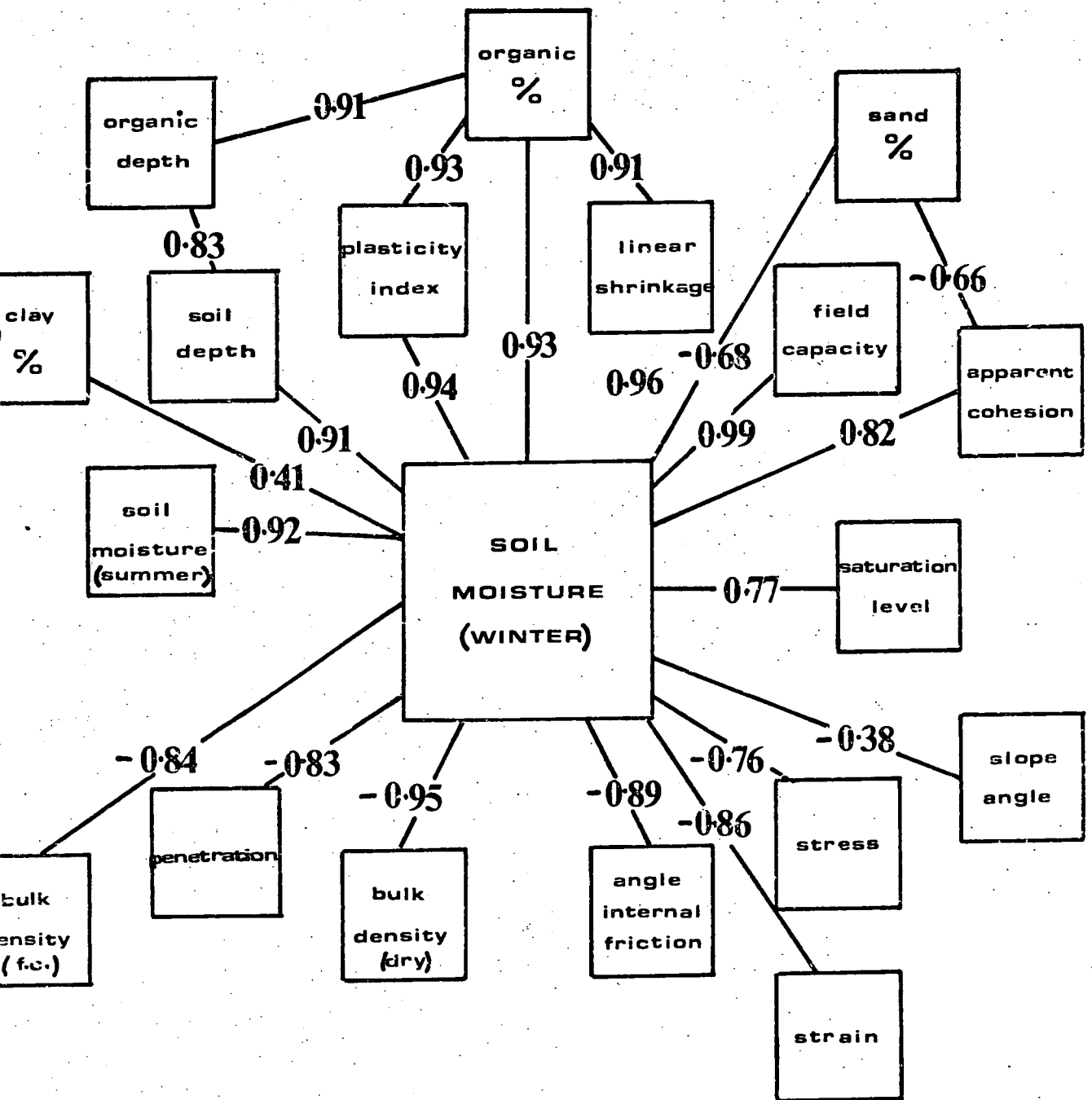


Fig. 12.17

'Force' Factor Diagram

of clay is everywhere low, the organic percentage is again very important. A positive correlation between soil depth and mean moisture content would be expected but this is also closely associated with the depth of the organic horizon, and from this, the organic percentage. As drying conditions vary little within the basin, a high correlation between winter and summer soil moisture content would be predicted, the mismatch resulting largely from local variations in soil, vegetation and meteorological conditions. As discussed earlier, apparent cohesion is largely dependent upon moisture content, exhibiting a positive correlation with the organic percentage and a negative correlation with the sand percentage. It must be remembered that mineral horizons only occur on fourteen plots and the strength of relationship with field capacity and winter moisture content must be seen in this context. The other 'force' factor is saturation level which is likely to vary not only with winter moisture content but particularly with position in the basin. In fact this variable shows the highest correlation in the matrix with slope angle. It should also be noted that although the organic percentage predominates, the clay percentage displays a positive correlation although in this case it is comparatively low. The 'resistance' factors, which will be correlated later, and the angle of slope are negatively correlated with winter moisture content. The correlation between slope and moisture is however so low that the factor cannot be included as important in this discussion.

To check on the validity of these relevant relationships it is necessary to examine the scattergrams so that the disposition of points can be assessed. This involves the identification of deviant plots and the classification of point distributions. The occurrence of plots which do not accord with the trend can be judged by eye on the scattergrams.

To check that the relevant correlations result from the general trend of points rather than from, for example, the position of one deviant result, the scattergrams were classified according to the degree to which they displayed three characteristics:

- (a) overall linear arrangement of points
- (b) lack of lateral spread from the main trend
- (c) lack of clustering

Since the variables tend to fall into three main plot groups, it is considered particularly important that interruptions to the continuous linear spread by marked clusters should be identified. The degrees used to describe the classifications were: high, comparatively high, moderate and low, and although these are subjective, the pattern can be clarified with lack of clustering as an example.

- (a) high: (h) an even trend of points with no obvious gaps (e.g. Fig. 12.18)
- (b) comparatively high: (ch) an even trend but with discernible gaps (e.g. Fig. 12.20)
- (c) moderate: (m) a clear trend but with major gaps (e.g. Fig. 12.25)
- (d) low: (l) some trend but groups predominate
e.g. Fig. 12.19)

Thus (a) and (b) are seen as confirming graphically the statistical relationship, while (c) indicates that the correlation is less clear-cut and (d) means that it is doubtful.

When the 'force' factor scattergrams are categorised and the deviant plots identified, the following table can be constructed.

Table 12.87

Force Factor Diagram AnalysisCorrelation with moisture
(% wet weight)(a) 'Force' variables

	<u>Linear arrangement</u>	<u>Lack of spread</u>	<u>Lack of clustering</u>	<u>Deviant plots</u>
Field capacity (Fig. 12.18)	h	h	h	14
Linear shrinkage (Fig. 12.19)	h	ch	l	17,16,1,4
Plasticity index	h	h	ch	6
Percentage organic (Fig. 12.20)	h	ch	ch	18,14
Summer moisture	h	h	ch	17,10
Soil depth	h	ch	l	14
Apparent cohesion (Fig. 12.21)	h	ch	h	15,11,14,5, 17
Saturation level	h	m	h	14,13,1,8,7

(b) 'Resistance' variables

Dry bulk density (Fig. 12.22)	h	h	ch	-
Angle of internal friction (Fig. 12.23)	h	h	h	18
Compression (strain)	h	ch	h	18,7,3,4
Bulk density (field capacity) (Fig. 12.24)	h	m	ch	15,13,19,1
Penetration	h	ch	h	15,19
Unconfined compression (stress) (Fig. 12.25)	m	m	l	3,7,13,19,16 1,4

The scattergrams of the 'force' variables and winter

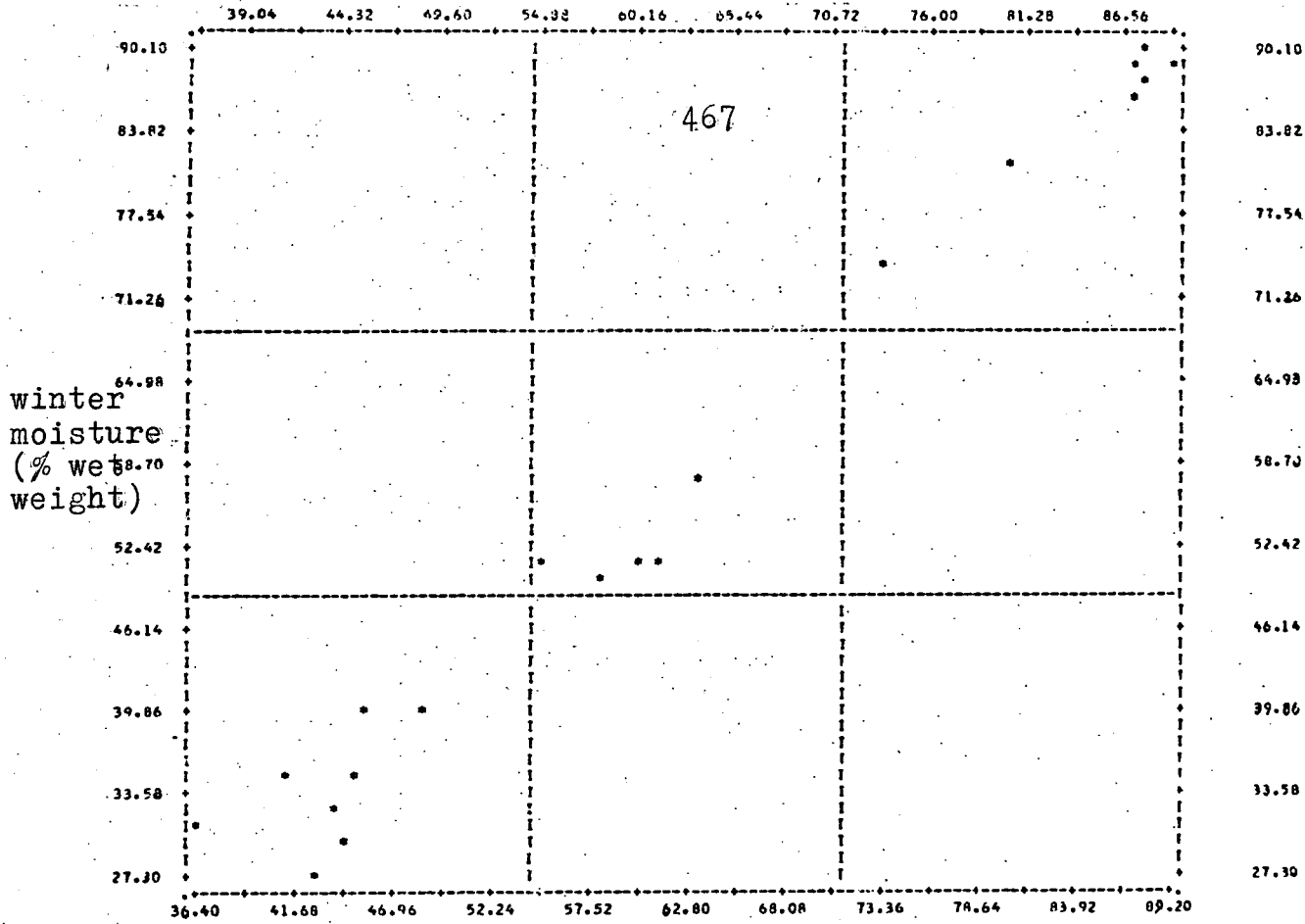


Fig. 12.18 Scattergram: Winter Moisture and Field Capacity

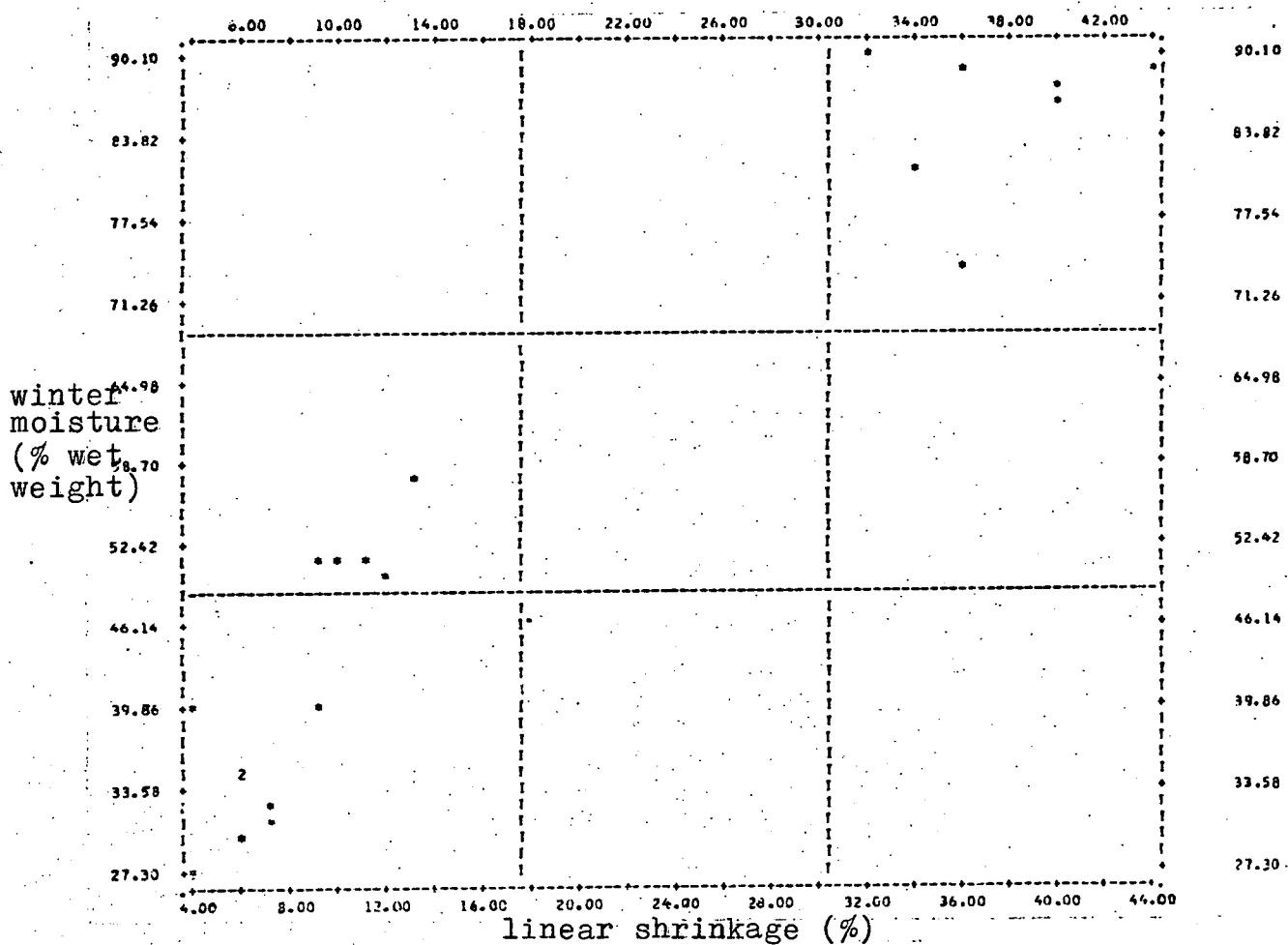


Fig. 12.19 Scattergram: Winter Moisture and Linear Shrinkage

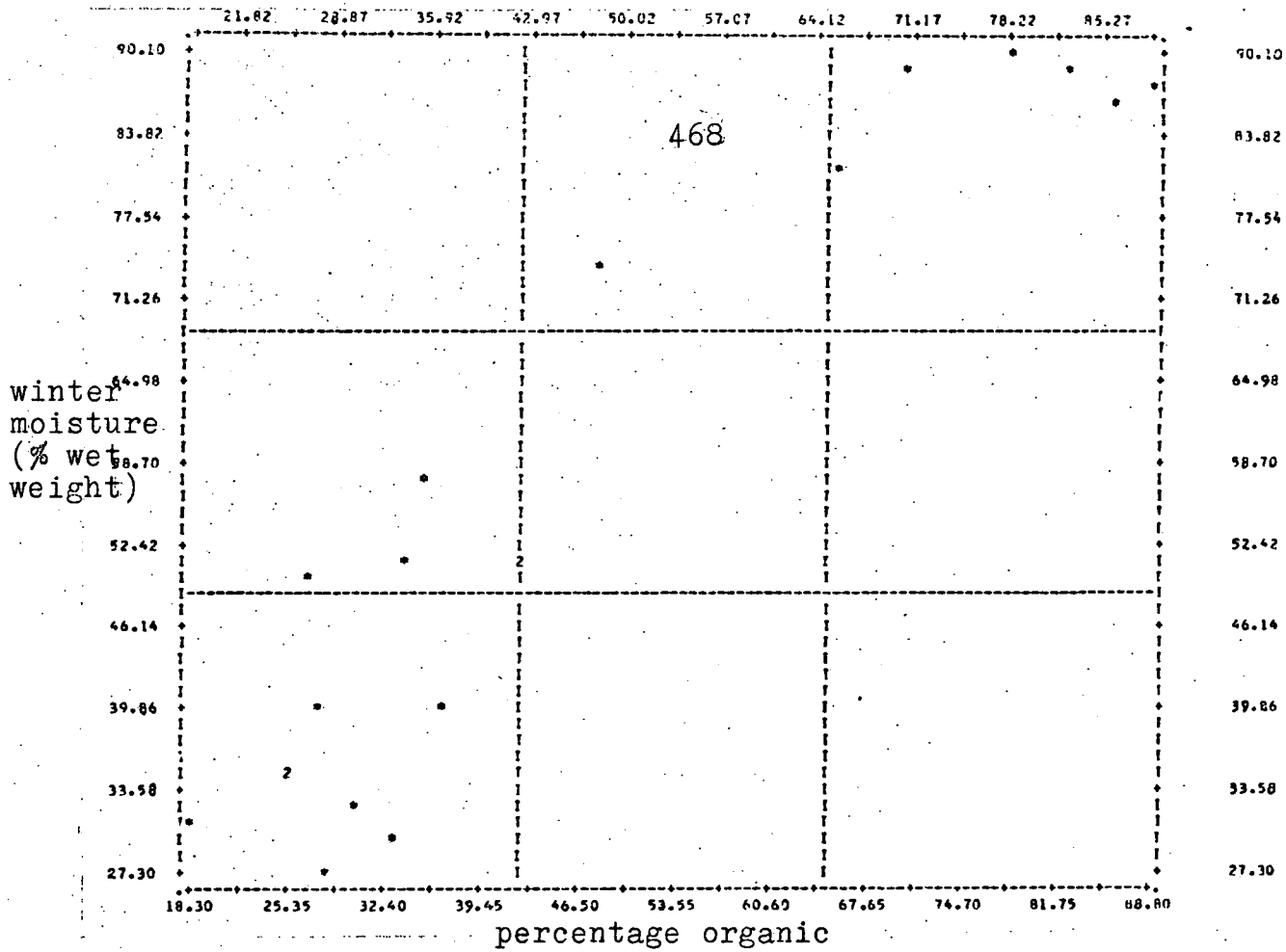


Fig 12.20 Scattergram: Winter Moisture and Percentage Organic Matter

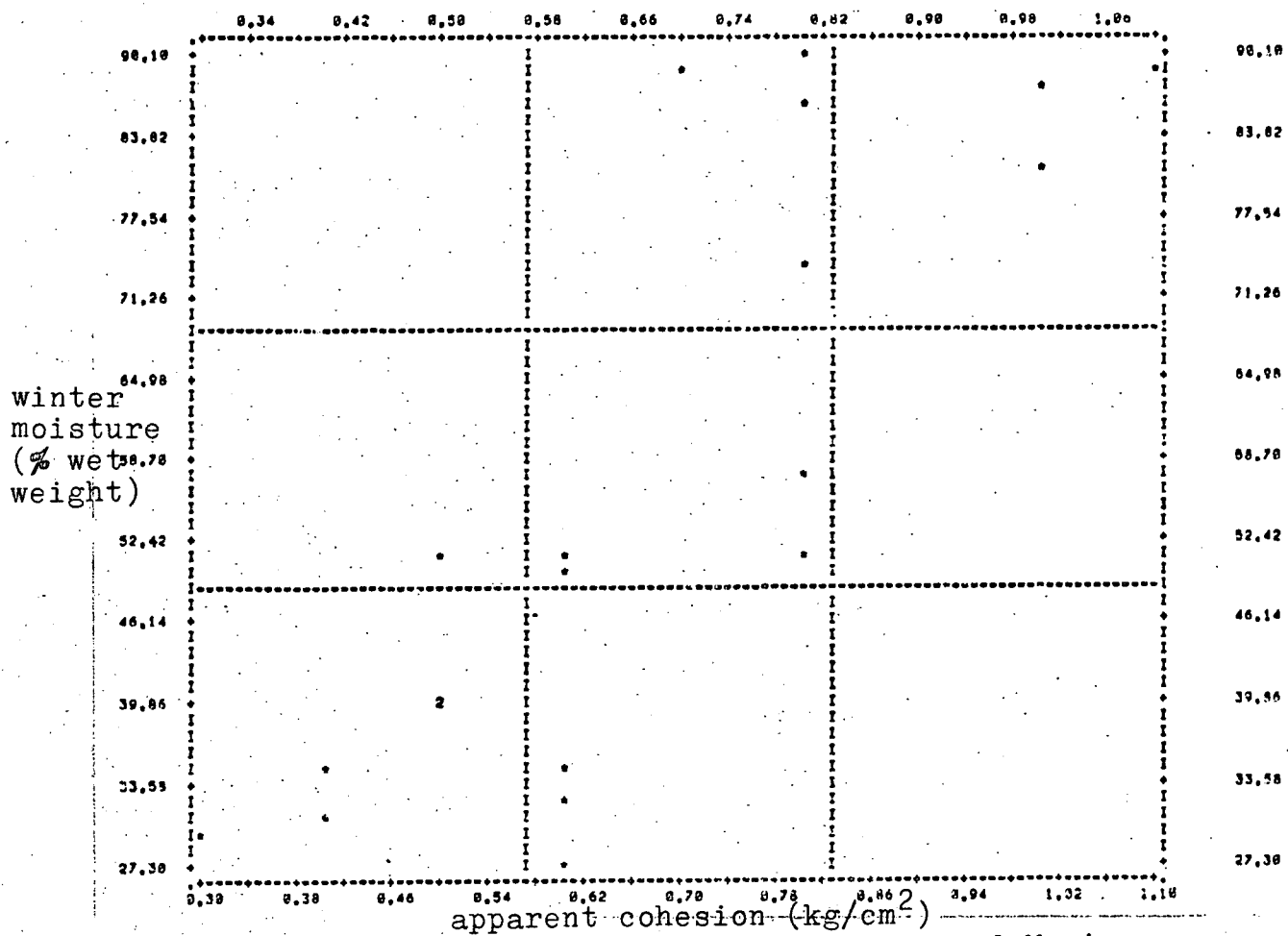


Fig 12.21 Scattergram: Winter Moisture and Maximum Apparent Cohesion

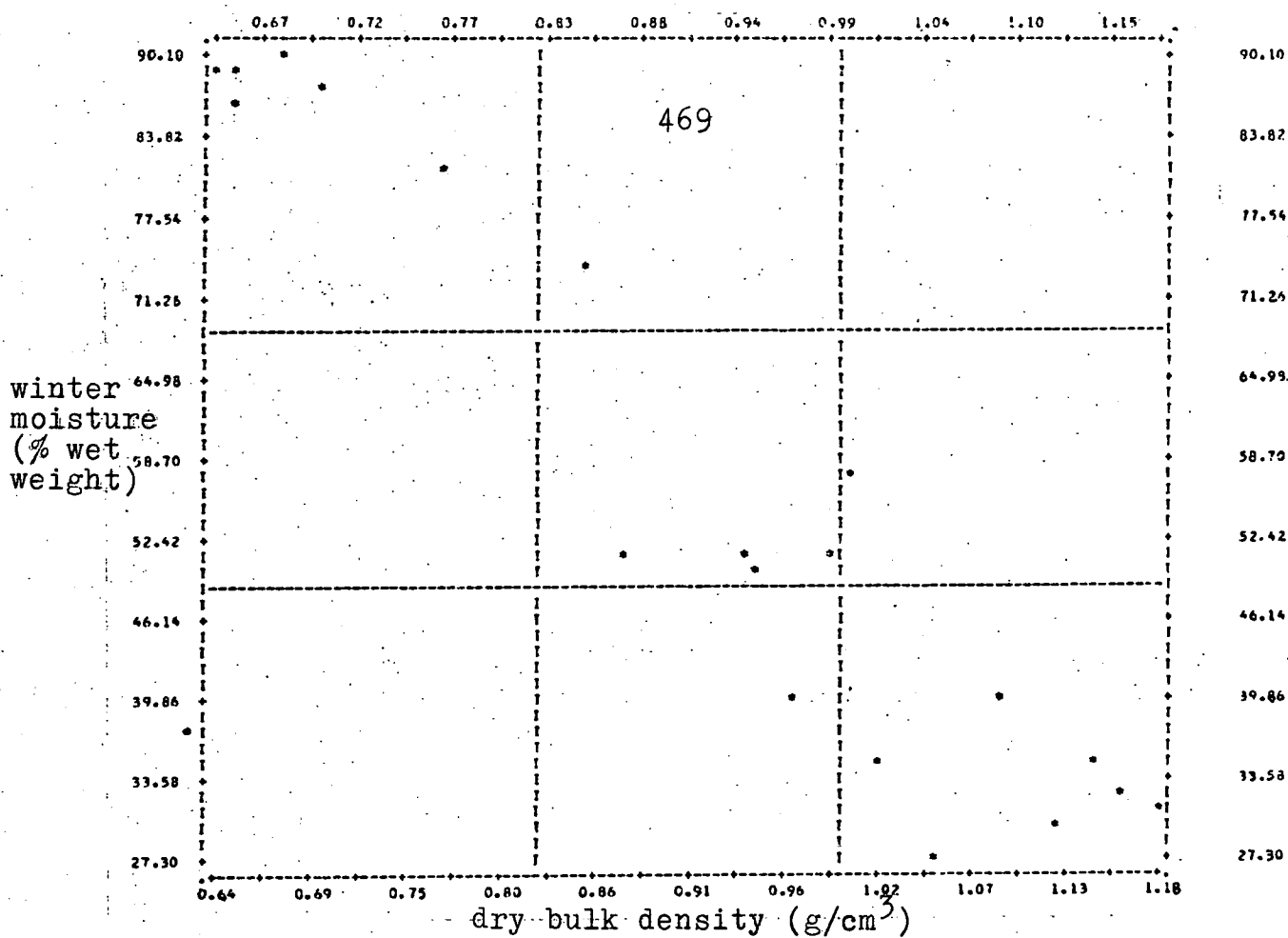


Fig. 12.22 Scattergram: Winter Moisture and Dry Bulk Density

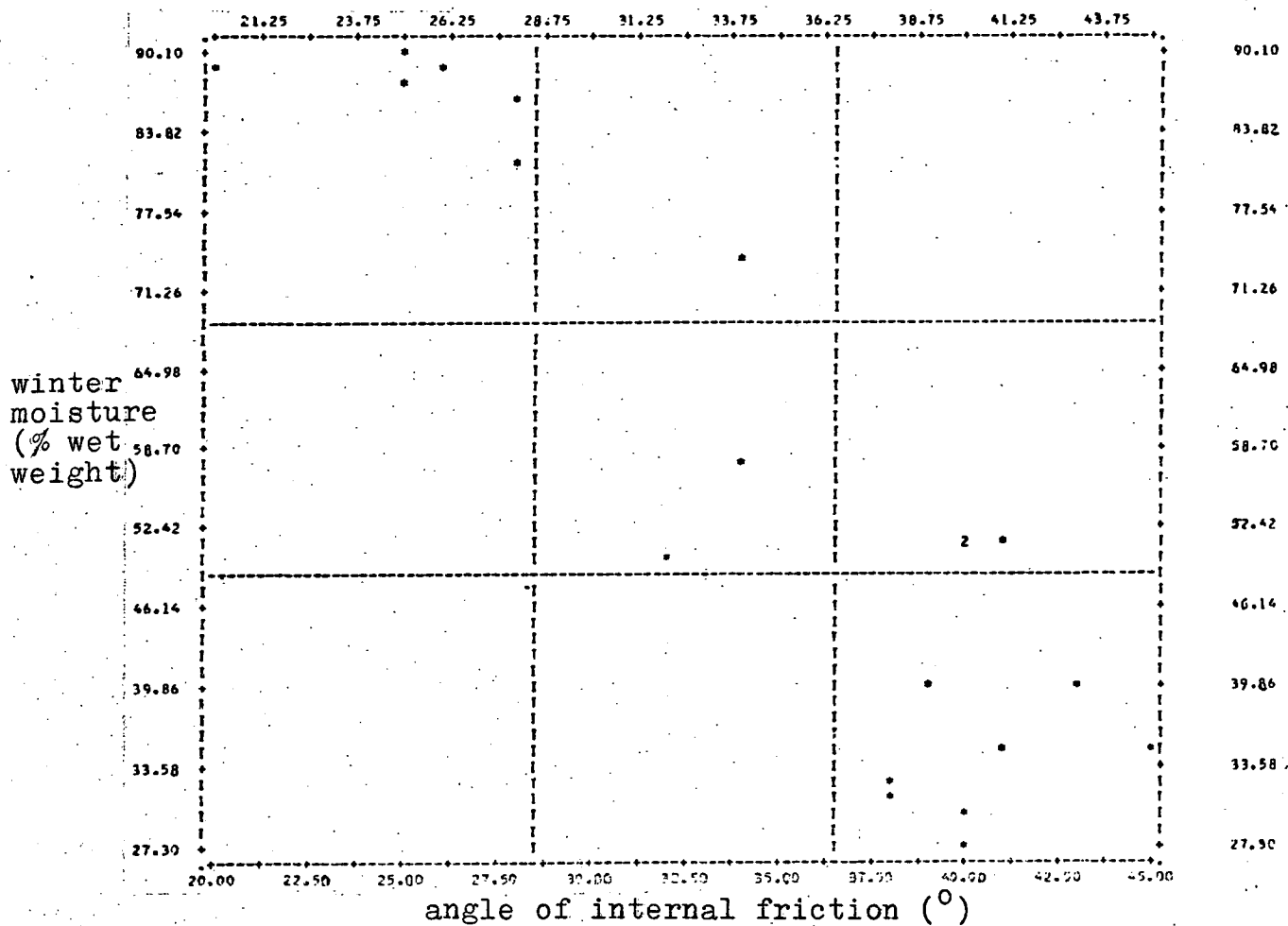


Fig. 12.23 Scattergram: Winter Moisture and Maximum Angle of Internal Friction

winter
moisture
(% wet
weight)

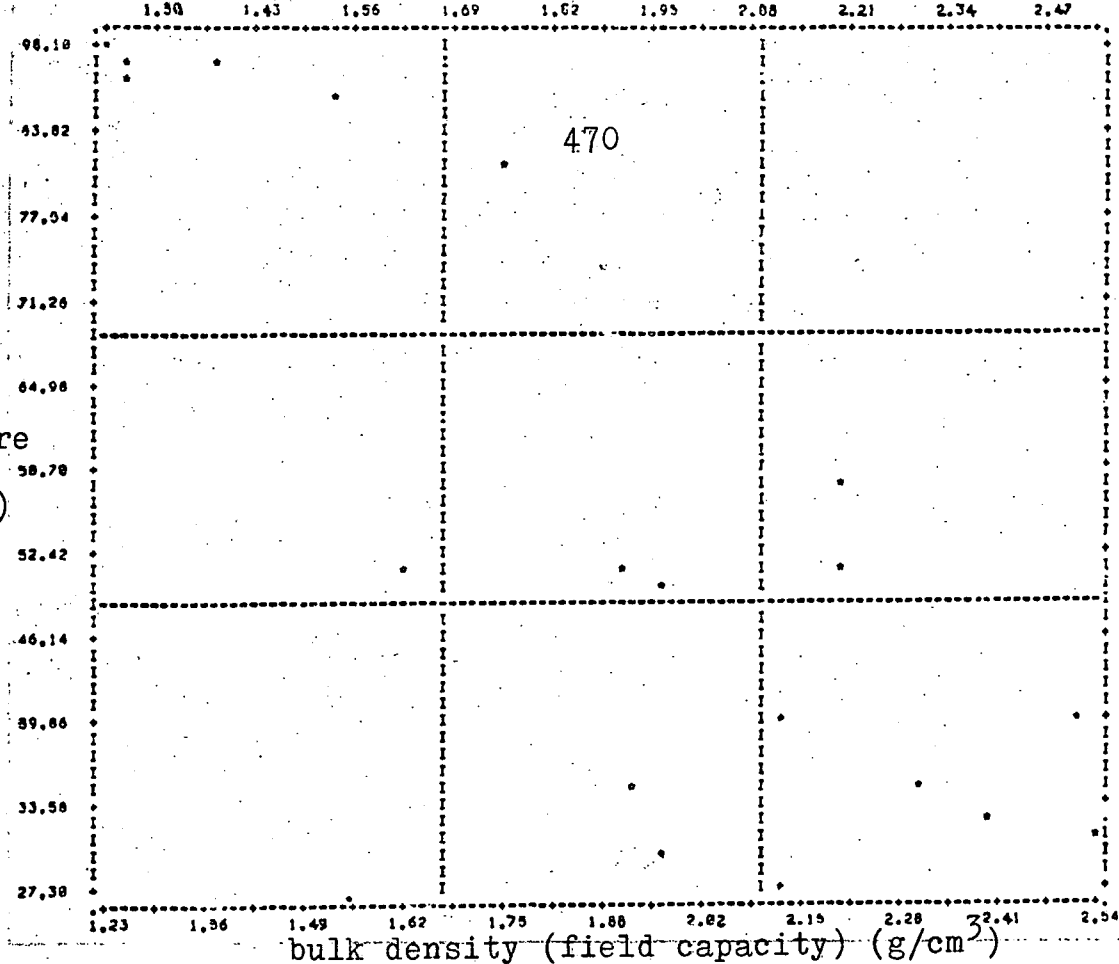


Fig. 12.24 Scattergram: Winter Moisture and Bulk Density (Field Capacity)

winter
moisture
(% wet
weight)

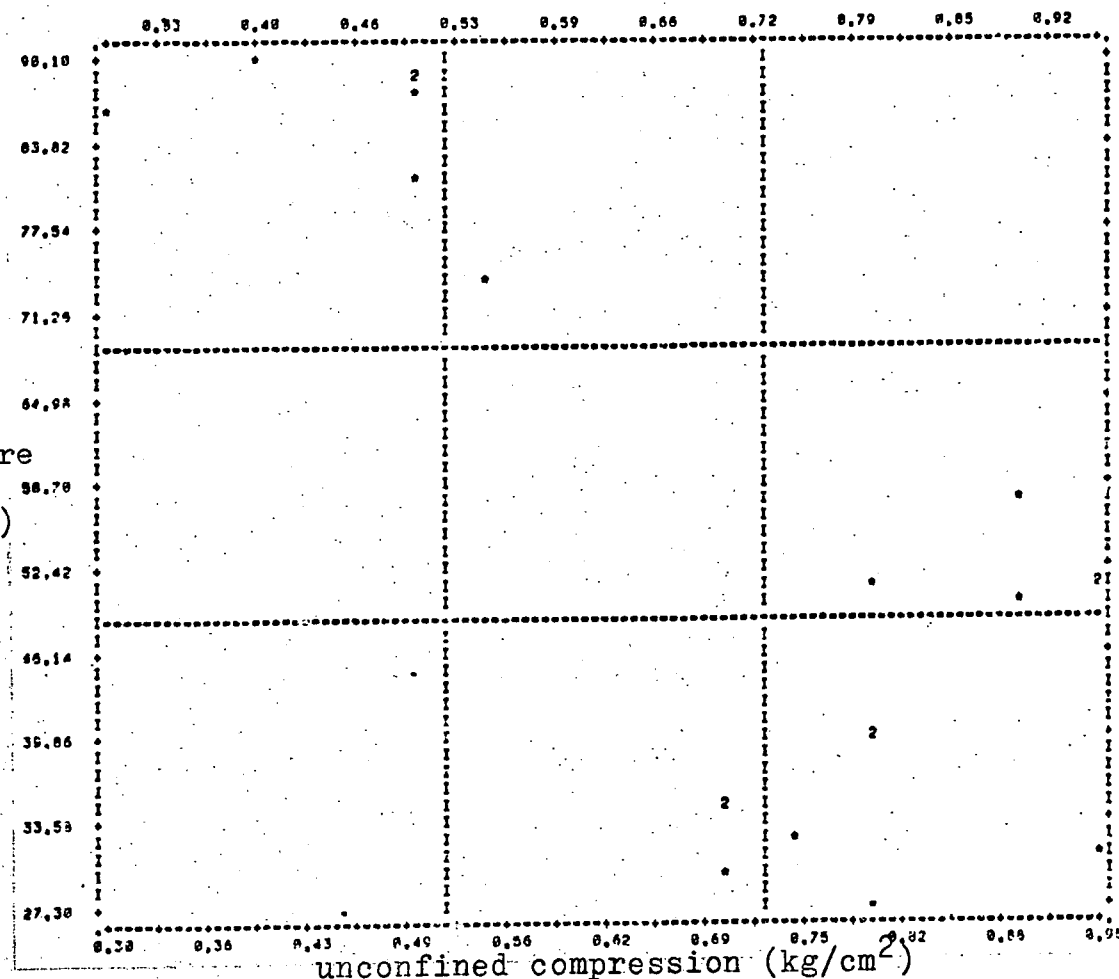


Fig. 12.25 Scattergram: Winter Moisture and Unconfined Compression (stress)

moisture content all show a strong linear trend and only in the case of saturation level is the lateral spread of points marked. However both linear shrinkage and soil depth show a high degree of clustering, indicating that the correlation coefficient must be treated with caution in later analysis and explanation. There are 21 deviant results affecting 14 different plots but it is significant that apparent cohesion (Fig. 12.21) and saturation level, two lower and somewhat ambiguous correlations, account for 10 deviant readings. Only plot 14, which is listed for five variables and plot 17, which is listed for three, tend not to accord with the general trend and these are the wettest plots in the basin.

Among the 'resistance' variables, the correlation coefficient unconfined compression (stress) (Fig. 12.25) can at this stage, be rejected on graphical grounds, while that for bulk density (field capacity) (Fig. 12.24) must be considered somewhat doubtful for later analysis. 18 deviant results are distributed among 9 plots but only plot 19 accounts for more than two variables. The results for the three factors for which plot 19 is listed all tend to be low, but it must be remembered that other evidence has been cited indicating that the correlations for two of these factors must be examined with caution.

12.6.3. 'Resistance' Factors

The 'resistance' factor diagram (Fig. 12.26) is centred on dry bulk density which can be interpreted as a measure of the inertia or resistance to initial movement of a particular plot. The same variable recorded at field capacity would be expected to correlate highly (Fig. 12.27), although under the changed moisture conditions the difference between plots with and without mineral horizons tend to be narrowed. The angle of internal friction (Fig. 12.28) is, as stated earlier, a measure of resistance to sliding or shear while stress (Fig. 12.31) and strain (Fig. 12.30) indicate resistance to failure by compression, and penetration (Fig. 12.29) provides a guide to the intrinsic resistance of the material. Therefore all four are seen as recording some aspect of resistance to movement

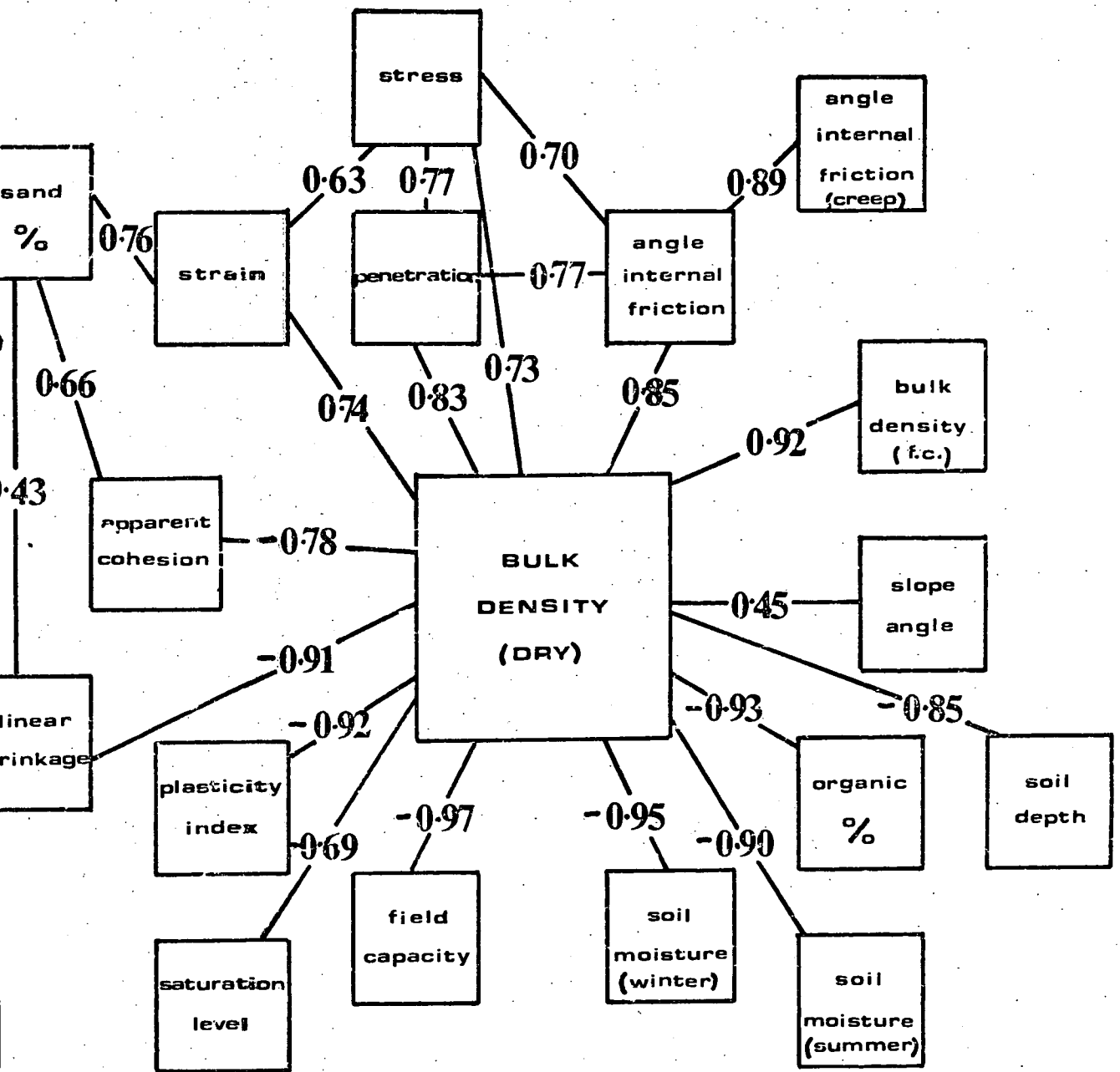


Fig. 12.26 'Resistance' Factor Diagram

and the close relationships between them would be predicted. Once movement is occurring, the resistance changes but the angle of internal resistance during creep is still highly correlated with the peak angle. Strain is a useful guide to movement potential since if in a part of the basin the force downslope is equal, creep will occur first on plots where failure takes place under least compression. That this resistance to failure may be facilitated by the interlocking of particles is indicated by the high correlation with sand percentage. The 'force' factors are all distinguished by high negative correlation coefficients.

The 'resistance' factor scattergrams can be categorised and the deviant plots identified.

Table 12.88 Resistance Factor Diagram Analysis

Correlation with
dry bulk density

(a) 'Resistance' variables

	<u>Linear</u> <u>arrangement</u>	<u>Lack of</u> <u>spread</u>	<u>Lack of</u> <u>clustering</u>	<u>Deviant</u> <u>plots</u>
Bulk density (field capacity) (Fig. 12.27)	h	h	h	13
Angle of internal friction (Fig. 12.28)	h	ch	h	9,3,12,1
Penetration (Fig. 12.29)	h	ch	ch	9,4,1
Compression (strain) (Fig. 12.30)	h	ch	ch	12,18,3,7
Unconfined compression (stress) (Fig. 12.31)	h	ch	m	3,7,13,18,4,1

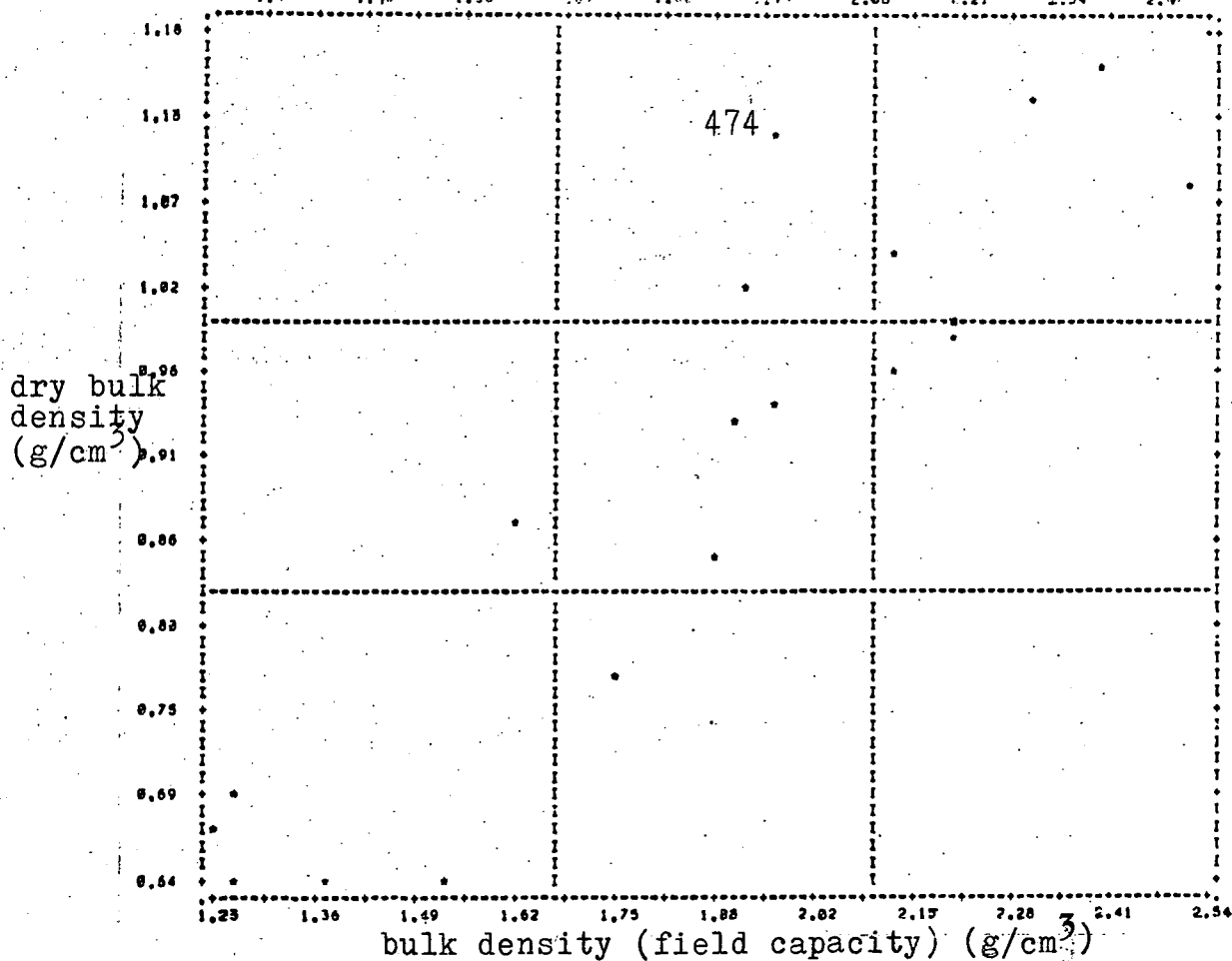


Fig. 12.27 Scattergram: Dry Bulk Density and Bulk Density (Field Capacity)

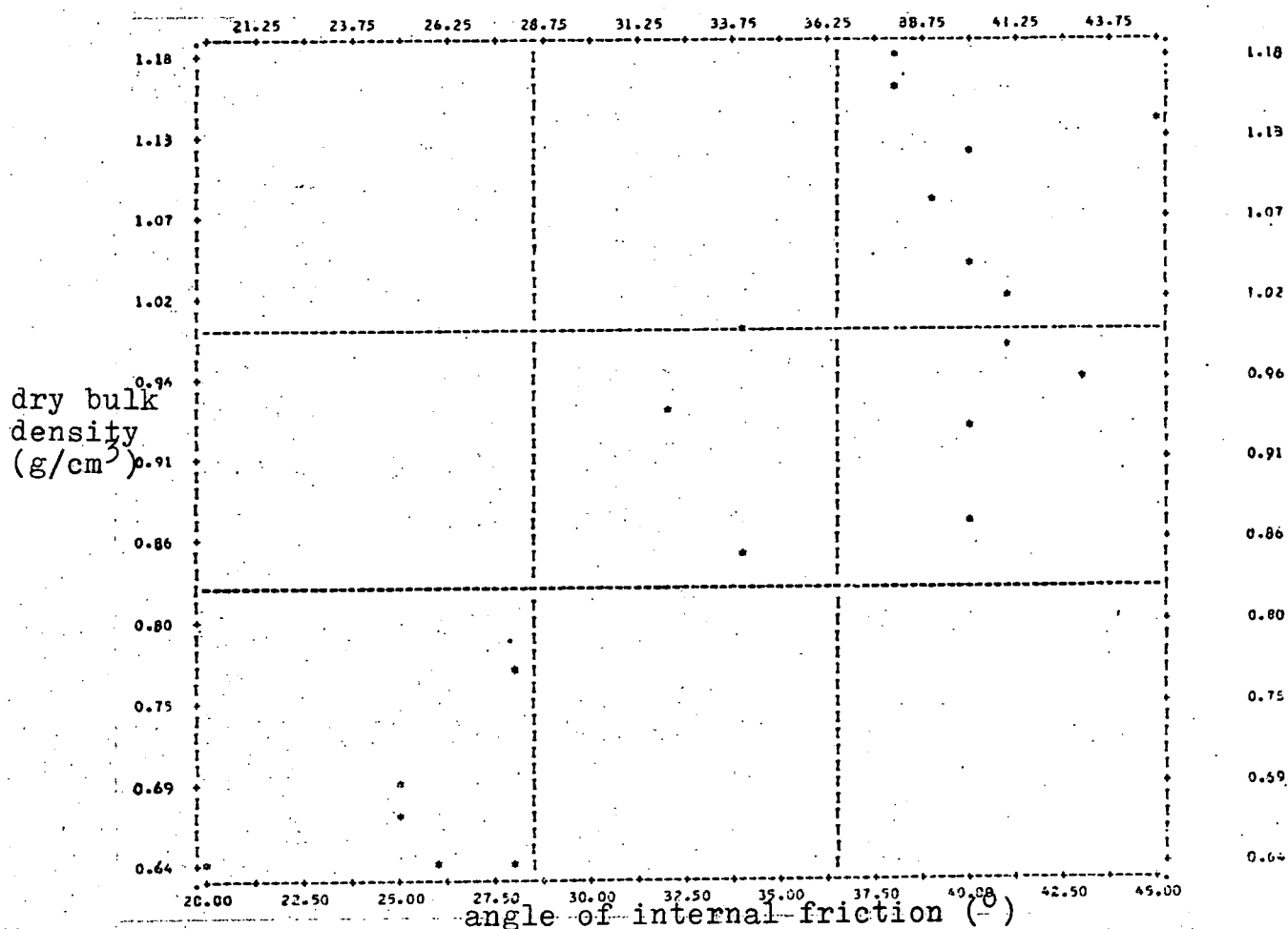


Fig. 12.28 Scattergram: Dry Bulk Density and Maximum Angle of Internal Friction

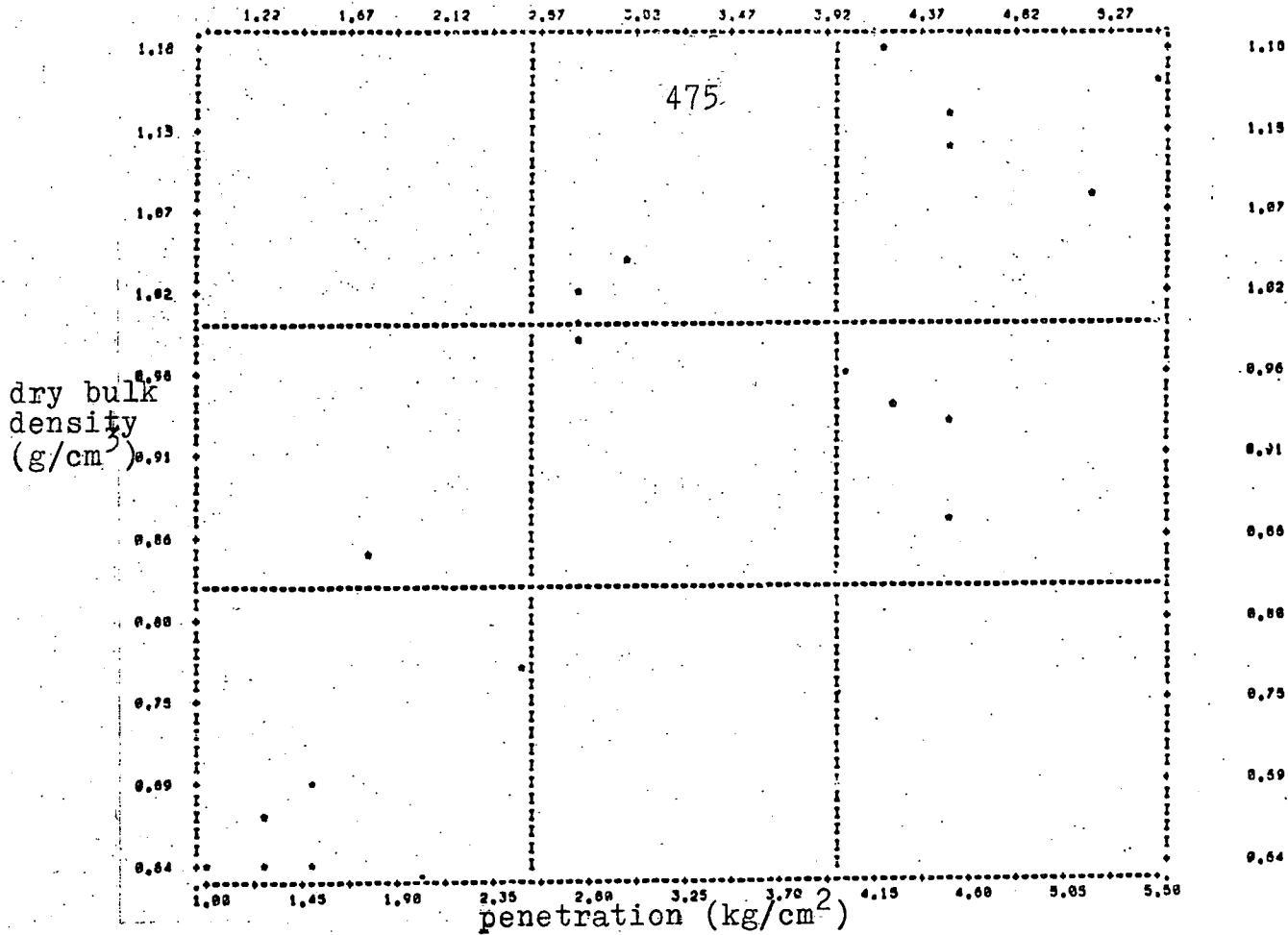


Fig. 12.29 Scattergram: Dry Bulk Density and Penetration

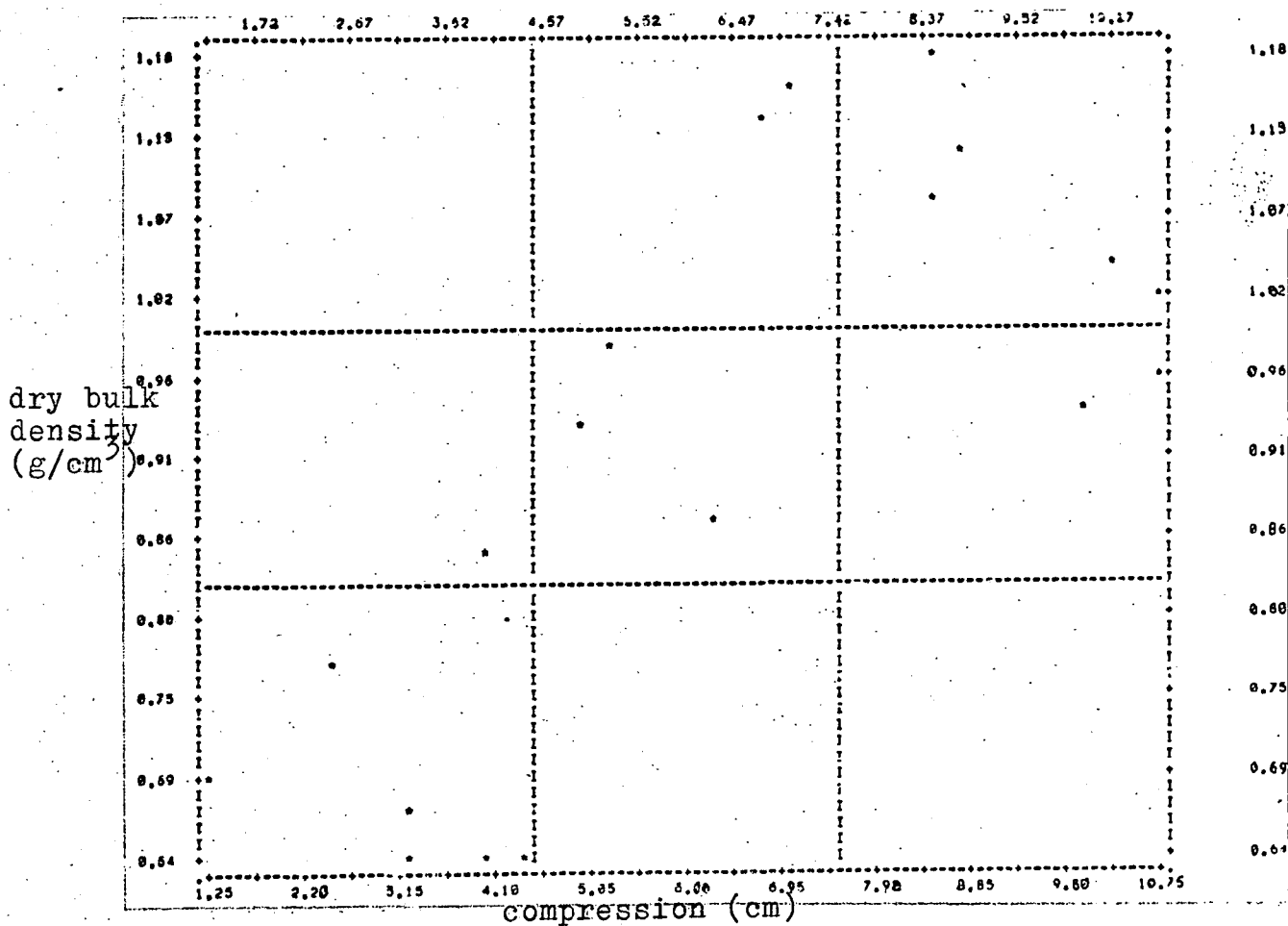


Fig. 12.30 Scattergram: Dry Bulk Density and Compression (strain)

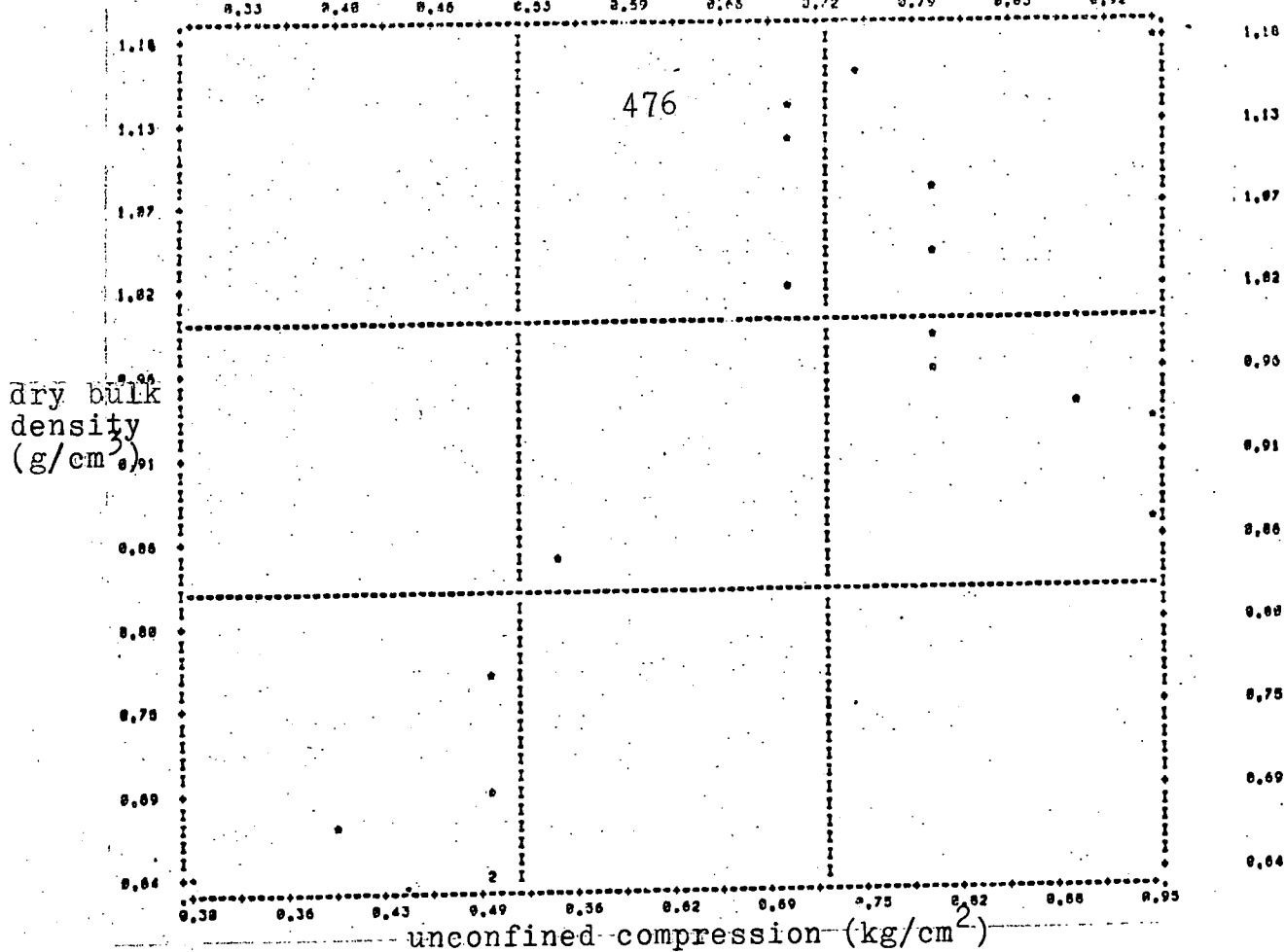


Fig. 12.31 Scattergram: Dry Bulk Density and Unconfined Compression (stress)

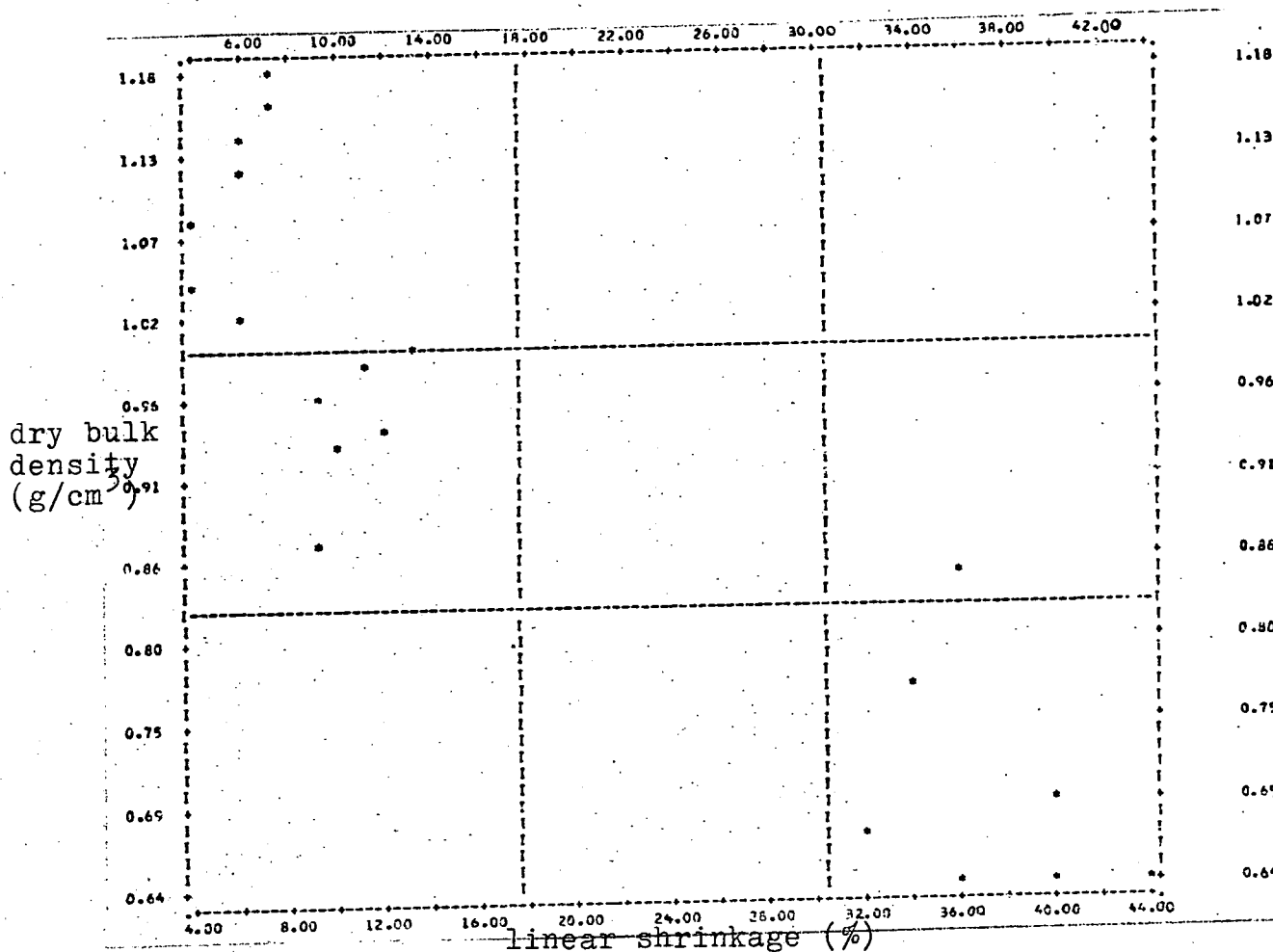


Fig. 12.32 Scattergram: Dry Bulk Density and Linear Shrinkage

(b) 'Force' variables

	<u>Linear arrangement</u>	<u>Lack of spread</u>	<u>Lack of clustering</u>	<u>Deviant plots</u>
Field capacity	h	h	h	-
Winter moisture	h	h	h	15,1
Percentage organic	h	h	h	18
Plasticity index	h	ch	h	1,7
Linear shrinkage (Fig. 12.32)	m	ch	l	6,1,17
Soil depth	m	ch	l	5,14,17,1,6
Apparent cohesion	h	ch	h	3,7,16,14
Saturation level	h	m	ch	1,5,3,9,13

The scattergrams of 'resistance' variables and dry bulk density all display a clear linear arrangement and it is only unconfined compression (stress) (Fig. 12.31) which as a result of definite clustering must be considered of doubtful value in analysis. There are 18 deviant results involving 9 plots but only plots 1 and 3 are tabulated more than twice. It should be noted that both these occur among the 6 plots recorded as deviating from the trend of the unconfined compression correlation. Neither plot is more than marginally deviant, plot 1 having a slightly low dry bulk density for Nardus plots and plot 3 having a higher dry bulk density than normal for Pteridium plots.

Of the 'force' variables, linear shrinkage (Fig. 12.32) and soil depth can be rejected on graphical grounds and the wide spread of points with saturation level must be borne in mind. The remaining factors all relate highly both statistically and graphically. 22 deviant results are distributed among 12 plots, but if the two rejected factors are omitted only 14 remain. Plot 1 alone accounts for more than two variables and as stated earlier, this is attributable to the low dry bulk density reading.

It can be concluded that the high positive and negative correlations with creep rates facilitate a basic division of the basin factors into respectively, 'force' and

'resistance' variables. These can be further examined when grouped in correlation diagrams so that the inter-relationships are clearly seen and can be assessed. This allows certain variables to be questioned using statistical and graphical evidence. As a result of this initial selection, the importance of nearly all the high correlations has been confirmed and only unconfined compression (stress), linear shrinkage and soil depth need be rejected in the context of these particular correlation diagrams. Additionally, saturation level must be treated with caution. It has also been shown that humus depth, bulk density (field capacity), plasticity index (organic horizon) and angle of internal friction on creep are redundant being subsumed in other variables. Furthermore, in the earlier discussion it was seen that unconfined compression and apparent cohesion were not very satisfactory discriminating characteristics. For the main stages of analysis and modelling which follow it was decided to omit certain of the redundant variables but to retain all factors, such as linear shrinkage, which measured a different property. However before any assessment can be made of the factors controlling rates of creep, the evidence presented in the initial analysis must be taken into account.

CHAPTER THIRTEEN

BASIN FACTORS AFFECTING RATES OF SOIL CREEP

13.1. Introductory

13.2. Data Analysis

13.2.1. Correlation Diagrams and
Graphical Analysis

13.2.2. Principal Components Analysis

13.3. Model Construction

13. BASIN FACTORS AFFECTING RATES OF SOIL CREEP

13.1. Introductory

A geomorphic process is a distinctive mechanism or group of mechanisms for the transportation of debris (Carson and Kirkby, 1972). Movement occurs when the forces involved are greater than the resistances. Therefore as both forces and resistances vary in space and time, so the processes and their interactions will also vary. Thus in the present study, rates of creep differ according to the factors operating on a particular plot and also according to changes, principally meteorological, occurring through time. The problem is therefore by nature multivariate.

As an initial simplification, two groups of measurements, the response and the controlling variables, can be identified. In fact, process studies may be defined as those which involve an attempt to link system responses to controlling characteristics (Caine, 1971). In the case of mass movement, the response variables involve strains such as movement as a result of physical or chemical processes. The controlling variables comprise elements of the geomorphological system in which the strains occur, such as morphometric, geological, biological and climatic factors.

A further simplification is possible as many of the controlling factors, especially the soil properties, do not vary independently. Thus a change in one is likely to be associated with a change in others and the degree to which they vary together can be measured. It is therefore possible to select those factors displaying the greatest independence of variation from each other.

In the Rookhope basin, the controlling variables were initially selected as a result of a theoretical appraisal, practical studies reported, previous work (Anderson, 1971) and the pilot study. They were then further sieved following the production of the correlation diagram which facilitated the identification of the strongest correlations.

The response variable, in this study soil creep, was monitored by six different types of instrument. Six measurements of annual rate were thus obtained for each plot and selection from these was based on the following criteria:

- (a) The rate recorded by each instrument compared with the control comprising the mean of the remaining five results.
- (b) The sensitivity of measurement.

Bearing in mind these considerations, the Inclinator pegs seemed to provide the best overall indication of creep rates. Furthermore since a similar device had already been successfully validated (Anderson, 1971) and since the technique of using a comparatively sophisticated measuring instrument with simple inserts approaches the optimum (Carson and Kirkby, 1972), the original experimental design had to a degree anticipated this decision. As a result, other advantages include:

- (a) the degree of replication
- (b) the possibility of direct comparison with results from other experiments in the study
- (c) the limited soil disturbance during installation, minimizing any backward action.

It should be pointed out however, that should the results have dictated the selection of another instrument, the fact that pegs were in each plot would still have allowed comparison, admittedly less direct, with readings from the plot at Brandon and laboratory programme.

13.2. Data Analysis

Using in each case the variables selected, the aim was to examine the relationship between the rates of creep and the controlling factors. This involved a statistical strategy of firstly data analysis in two stages and then modelling. The general intent of data analysis is to seek through a body of data for interesting relationships and to exhibit results in such a way as to make them recognisable. It can therefore be seen as an exploratory

process including principally summarization and exposure (Tukey and Wilk, 1966). The stages of the analysis were:

- (a) the production of a correlation structure, scattergrams and graphs of peg movement
- (b) principal components analysis

The computing for this chapter was completed on the N.U.M.A.C. system (IBM 370/167) at the University of Durham using SPSS package programs (Nie et al, 1970).

The complete statistical procedure consisted of an initial exploration of the data followed by bivariate analyses through scattergrams and then a multivariate analysis using loadings. This allowed certain variables to be discarded so that the main controlling or independent factors and the best measure of the response factor (dependent) could be used to produce a simple predictive model. Finally the structure of the residuals was examined (Fig. 13.1).

13.2.1. Correlation Diagrams and Graphical Analysis

The first stage of analysis was the production of a diagram from the correlation matrix* in which creep rates were represented by Inclinator peg readings (Fig. 13.2). The external, or climatic, factors, vegetation coverage and distance of a plot from the watershed, together with the element of time could not be quantified in the same way within the matrix and are discussed separately later in this section.

The diagram shows clearly that, among the variables displaying a high correlation with creep rates, it is possible to make a fundamental division. The basin factors showing a positive correlation mostly involve some aspect of soil moisture and are therefore connected with forces affecting strain and facilitating creep. Conversely, the negatively correlated variables include various measures linked with shear strength and are generally concerned with resistance. Exceptions are apparent cohesion which most obviously of all the variables combines elements of resistance and moisture; soil depth, which also gives a high positive correlation, and the sine *(significance levels: 95%, 0.44; 99%, 0.56)

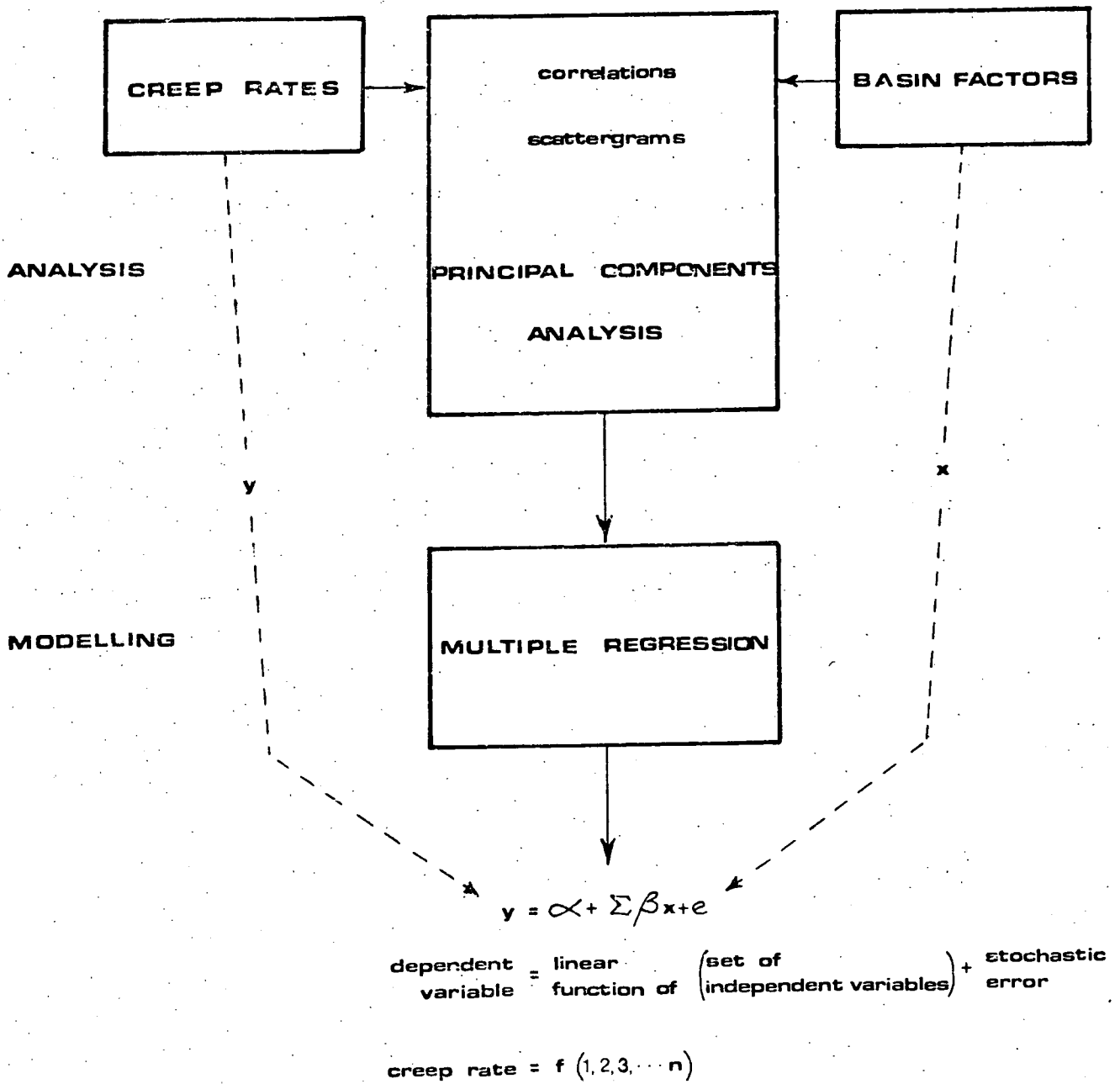


Fig. 13.1

Statistical Procedure

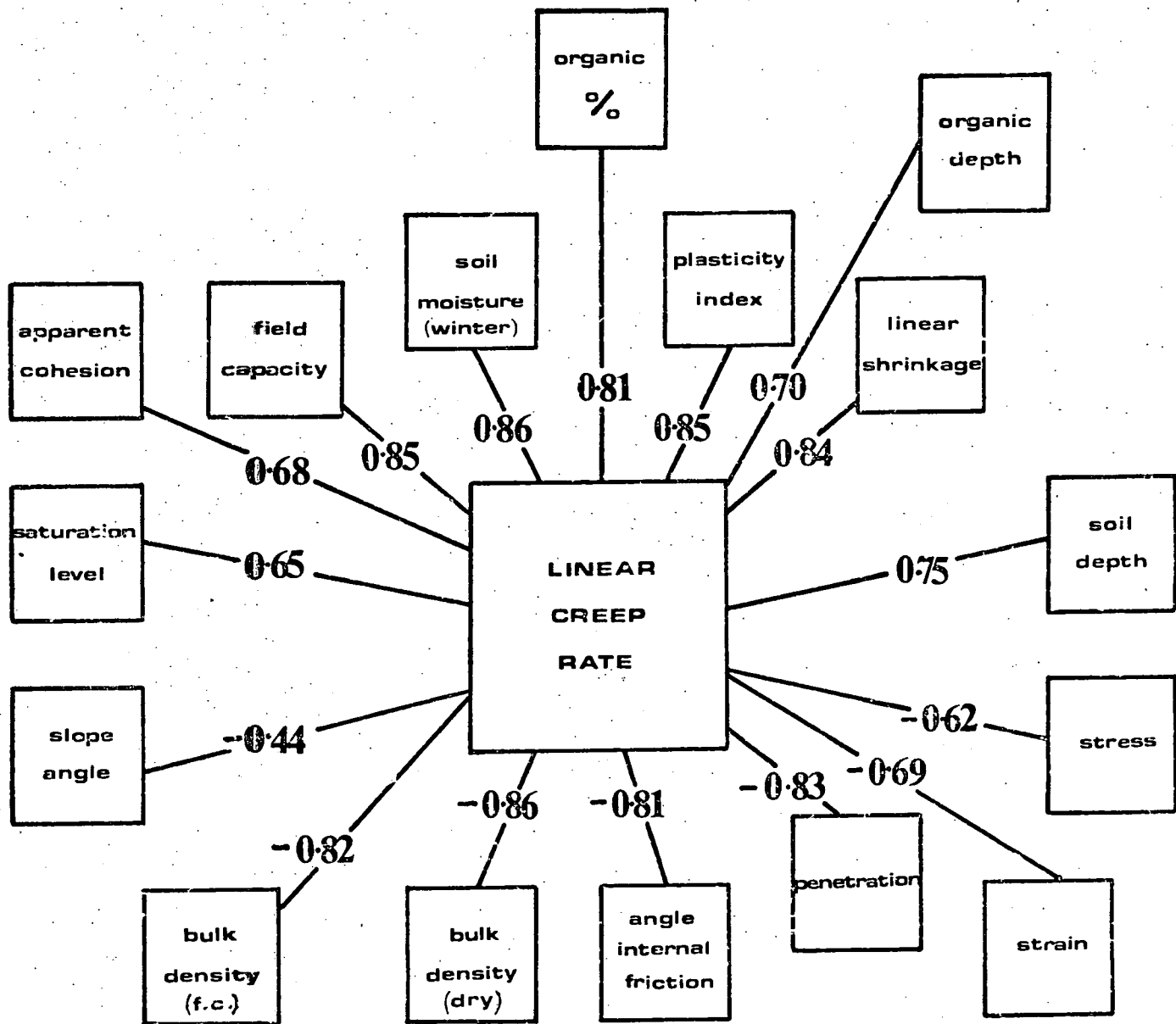


Fig. 13.2 Correlation Diagram: Linear Creep Rate and Basin Factors

of the slope angle which indicates a low negative correlation.

It should be stated at this point that significance tests were applied throughout this study and the levels are quoted. However, it is felt that these can only act as a guide, and limited weight should be attributed to them for two reasons. The approach adopted is exploratory rather than one of deciding between null and alternative hypotheses at arbitrary significance levels. Secondly, spatial autocorrelation in the data invalidates the use of standard significance tests on Pearson's product moment correlations (Moran, 1973).

Before any definite conclusions can be drawn it is considered particularly important to inspect the scattergrams for the variables showing strong correlations with rates of creep. Graphical displays can constitute a most useful tool in analysis, attracting attention to what is often most valuable (Tukey, 1972). In this study, they were generated to examine the spread of data in relation to the correlation coefficient. For example, a seemingly high correlation could result from the position of one or two isolated points rather than indicating a basically linear arrangement. Furthermore it is possible to identify and discuss any deviant results.

To classify the scattergrams, the criteria already identified were used:

- (a) the overall linear arrangement of points
- (b) the lack of lateral spread from the main trend
- (c) the lack of clustering

It should be noted that while the creep rates themselves (in mm) are not uniformly distributed between the lowest, 0.33, and the highest, 2.44, there is little evidence of clustering. Therefore a perfect correlation would produce a comparatively even distribution of points.

The application of these criteria allowed certain broad distinctions to be made and these are tabulated. Examples of the scattergrams are included (Figs. 13.3-13.17).

Table 13.1 Scattergram Classification: Linear
Creep Rates and Basin Factors

<u>Degree</u>	<u>Characteristic</u>		
	<u>linear arrangement</u>	<u>lack of spread</u>	<u>lack of clustering</u>
high	saturation level winter moisture (% wet weight) field capacity dry bulk density angle of internal friction penetration unconfined com- pression (stress) compression (strain) bulk density (field capacity) plasticity index	dry bulk dens- ity angle of int- ernal friction	saturation level dry bulk density penetration compression (strain) bulk density (field capacity)

<u>Degree</u>	<u>Characteristic</u>		
	<u>linear arrangement</u>	<u>lack of spread</u>	<u>lack of clustering</u>
comparat- ively high	apparent cohesion plasticity index (organic) summer moisture (% dry weight) winter moisture (% dry weight)	saturation level winter moisture (% wet weight) field capacity penetration bulk density (field capacity) plasticity index (organic) plasticity index linear shrink- age summer moisture (% dry weight) winter moisture (% dry weight)	winter moisture (% wet weight) field capacity angle of inter- nal friction plasticity index (organic)

<u>Degree</u>	<u>Characteristic</u>		
	<u>linear arrangement</u>	<u>lack of spread</u>	<u>lack of clustering</u>
moderate	percentage organic linear shrinkage	percentage org- anic apparent cohes- ion unconfined com- pression (stress) compression (strain)	percentage or- ganic apparent cohes- ion unconfined com- pression (stress) plasticity index linear shrink- age summer moisture (% dry weight) winter moisture (% dry weight)

<u>Degree</u>	<u>Characteristic</u>		
	<u>linear arrangement</u>	<u>lack of spread</u>	<u>lack of clustering</u>
low	slope angle soil depth organic depth	slope angle soil depth organic depth	slope angle soil depth organic depth

This table illustrates the fact that to quote a correlation coefficient without examining the scattergram can give rise to misleading conclusions. While the boundary decisions involved must be partly subjective, it is clear that of the variables showing a strong positive correlation with creep rates, soil moisture, field capacity and mean plasticity index can be confirmed as also valid graphically. Similarly the variables with a strong negative correlation, dry bulk density, angle of internal friction, penetration and strain can also be accepted. Percentage organic and linear shrinkage are not as clear-cut when viewed in graphic display but must also be considered. Saturation level does not correlate as highly as many of the other factors but the scattergram dictates its inclusion in the analysis. Finally, while the resistance variables

generally emerge more strongly from this stage of analysis, it must be remembered that the strain variables are all closely related to soil moisture and this must give rise to a degree of clustering, since the plots are either very wet or comparatively dry with no gradation between.

However, despite the graphical evidence, it was decided to check on the major variables using readings from plots in the most distinctive vegetation community only. The following correlation coefficients were calculated for creep rates and the selected variables on Juncus plots:

winter moisture	0.83
field capacity	0.74
bulk density	-0.75
angle of internal friction	-0.89

(significance levels: 95%, 0.75; 99%, 0.87)

These results further confirm that the correlations are not merely a result of having two plot groups, Juncus and Pteridium at virtually opposite extremes with regard to most of the variables measured.

Although the main aim of the study was to investigate the effect of basin factors on linear rates of creep, the correlation coefficients were also calculated using volumetric rates and the more important variables, and the comparative results can be tabulated (significance levels: 95%, 0.44; 99%, 0.56).

Table 13.2. Correlation Coefficients: Volumetric Creep Rates and Basin Factors

	<u>Linear rate</u>	<u>Volumetric rate</u>
Winter moisture	0.86	0.91
Plasticity index (mean	0.85	0.90
Linear shrinkage	0.84	0.88
Field capacity	0.85	0.84
Organic	0.81	0.82
Soil depth	0.75	0.80
Saturation level	0.66	0.71
Organic depth	0.70	0.69

	<u>Linear rate</u>	<u>Volumetric rate</u>
Apparent cohesion	0.68	0.61
Bulk density (dry)	-0.87	-0.88
Angle of internal friction	-0.81	-0.86
Penetration	-0.83	-0.83
Slope angle	-0.44	-0.42

It is seen that for the more important variables the correlations are even stronger when calculations are made with volumetric rates. This is particularly the case among the force factors with plasticity index, linear shrinkage and winter moisture. The resistance factors are also strengthened, especially the angle of internal friction. When the results are added to the other evidence discussed, it is clear that a number of key variables correlate highly with creep rate.

Thus the use of scattergrams to check for possible problems, rather than relying on numerical results above has confirmed the importance of certain variables and considerably clarified the picture. Scattergrams were also used to identify deviant plots

Table 13.3. Correlation Coefficients: Linear Creep Rates and Basin Factors

<u>Correlation with annual creep rate</u>	<u>Deviant plots</u>
(a) <u>Force variables</u>	
Winter moisture (% wet weight) (Fig. 13.3)	5, 15, 9
Field capacity (Fig. 13.4)	5, 7, 9
Linear shrinkage (Fig. 13.5)	17, 1, 16, 9, 6
Plasticity index (Fig. 13.6)	9, 5, 16, 1
Percentage organic (Fig. 13.7)	14, 9
Summer moisture (% dry weight) (Fig. 13.8)	9, 12, 1, 16
Soil depth (Fig. 13.9)	6, 17, 14, 9
Apparent cohesion (Fig. 13.10)	14, 17, 3, 5, 20
Saturation level (Fig. 13.11)	13, 3, 18, 20, 7, 16

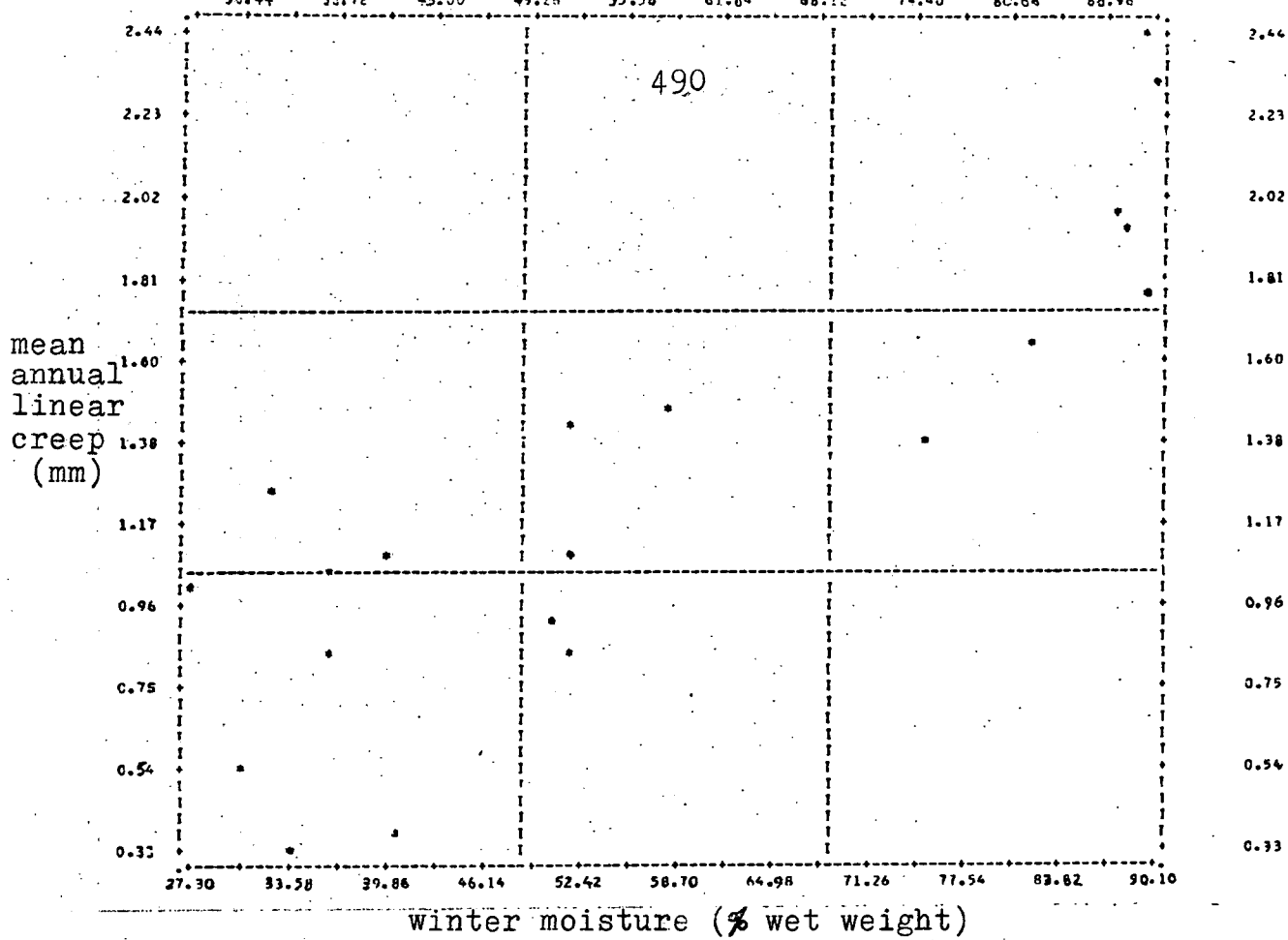


Fig. 13.3 Scattergram: Mean Annual Linear Creep and Winter Moisture

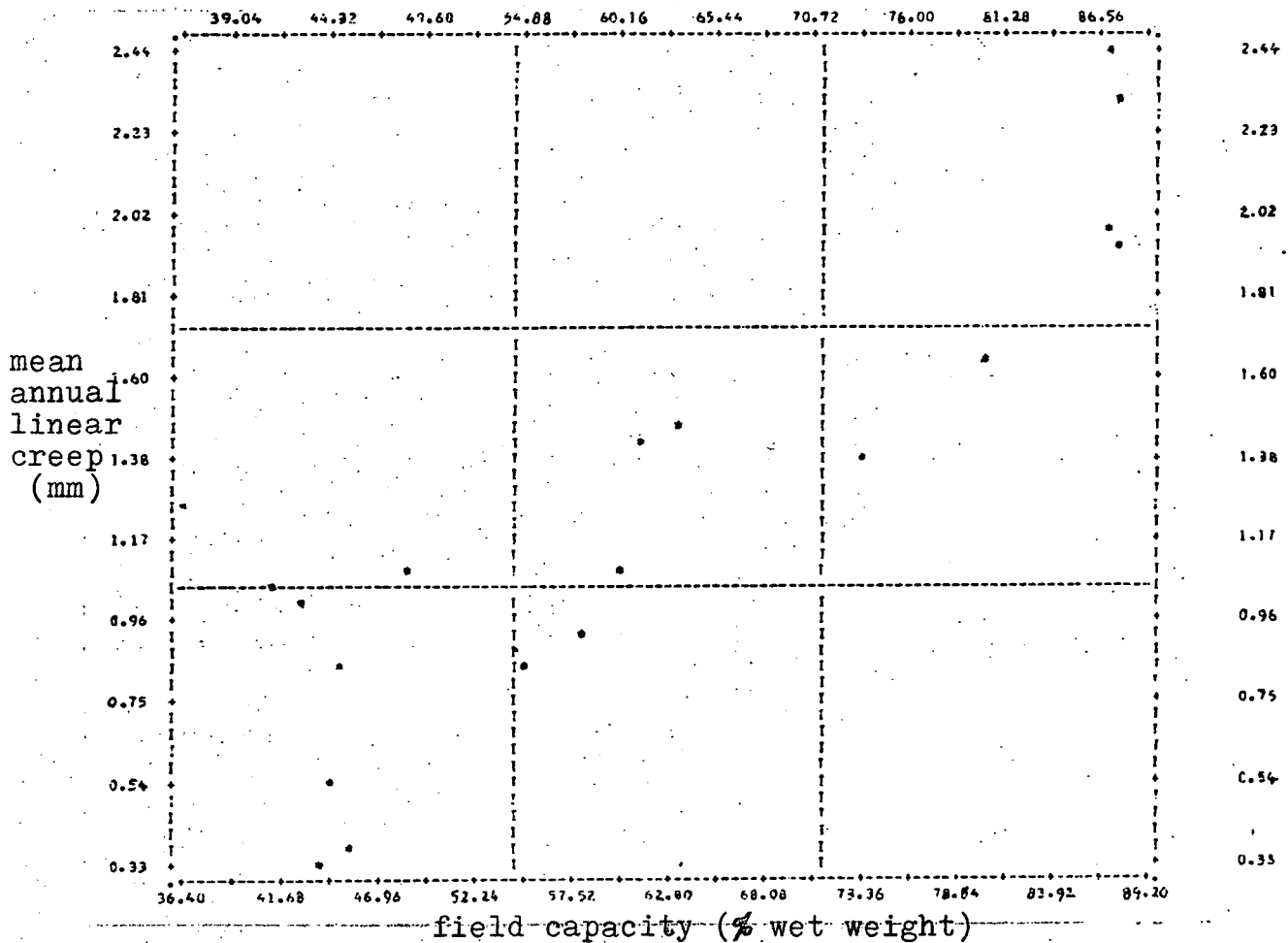


Fig. 13.4 Scattergram: Mean Annual Linear Creep and Field Capacity

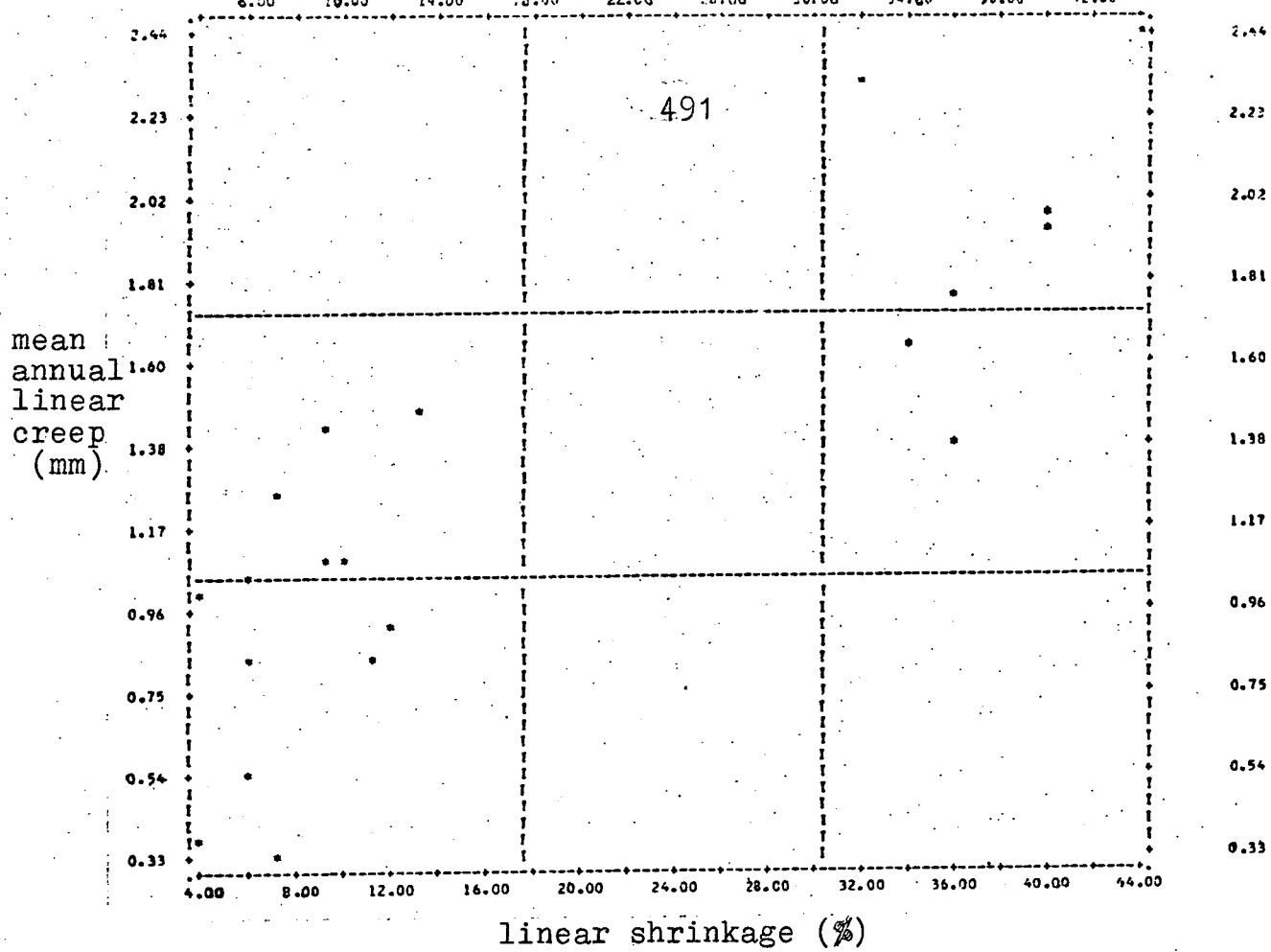


Fig. 13.5 Scattergram: Mean Annual Linear Creep and Linear Shrinkage

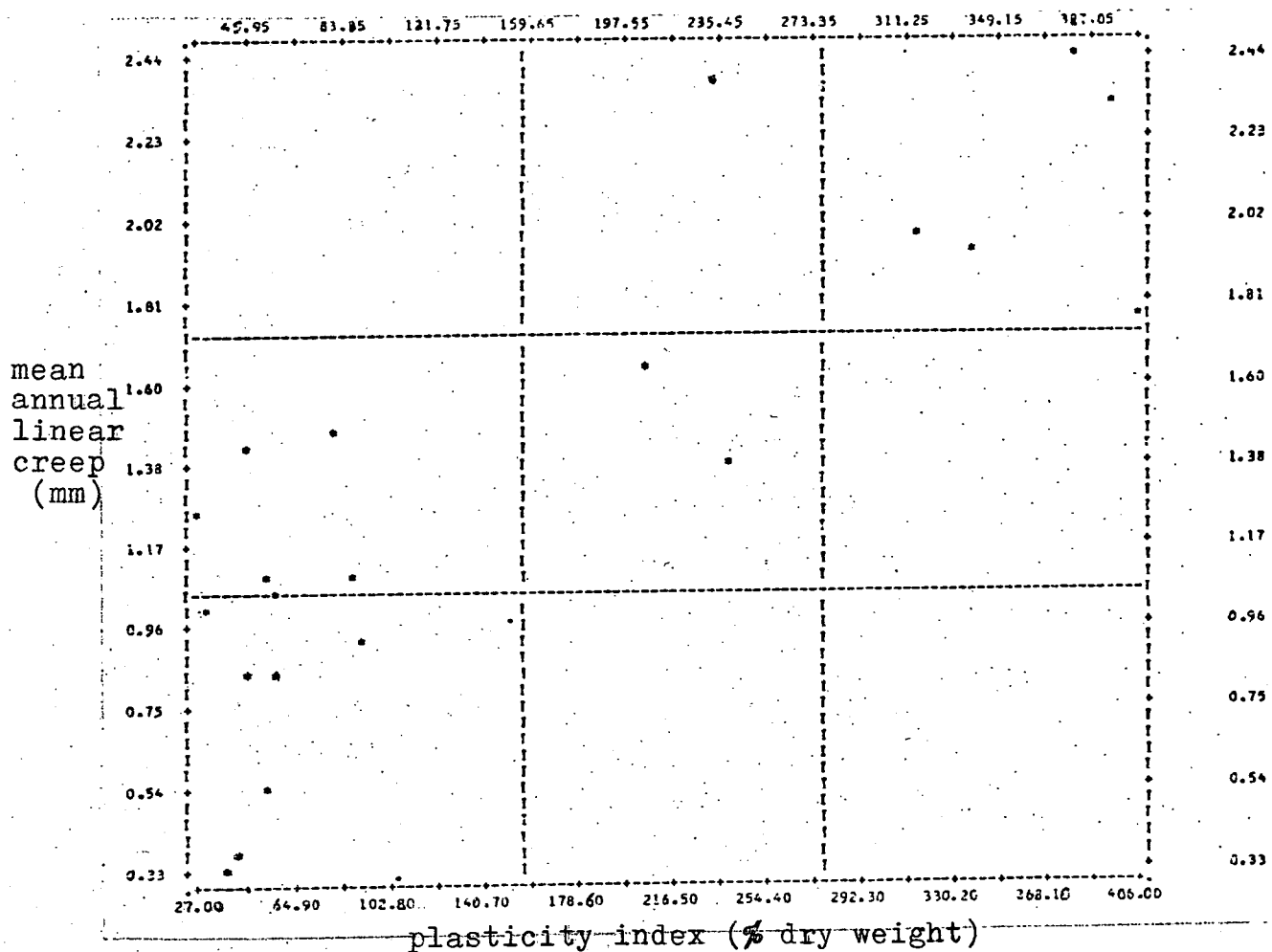


Fig. 13.6 Scattergram: Mean Annual Linear Creep and Plasticity Index

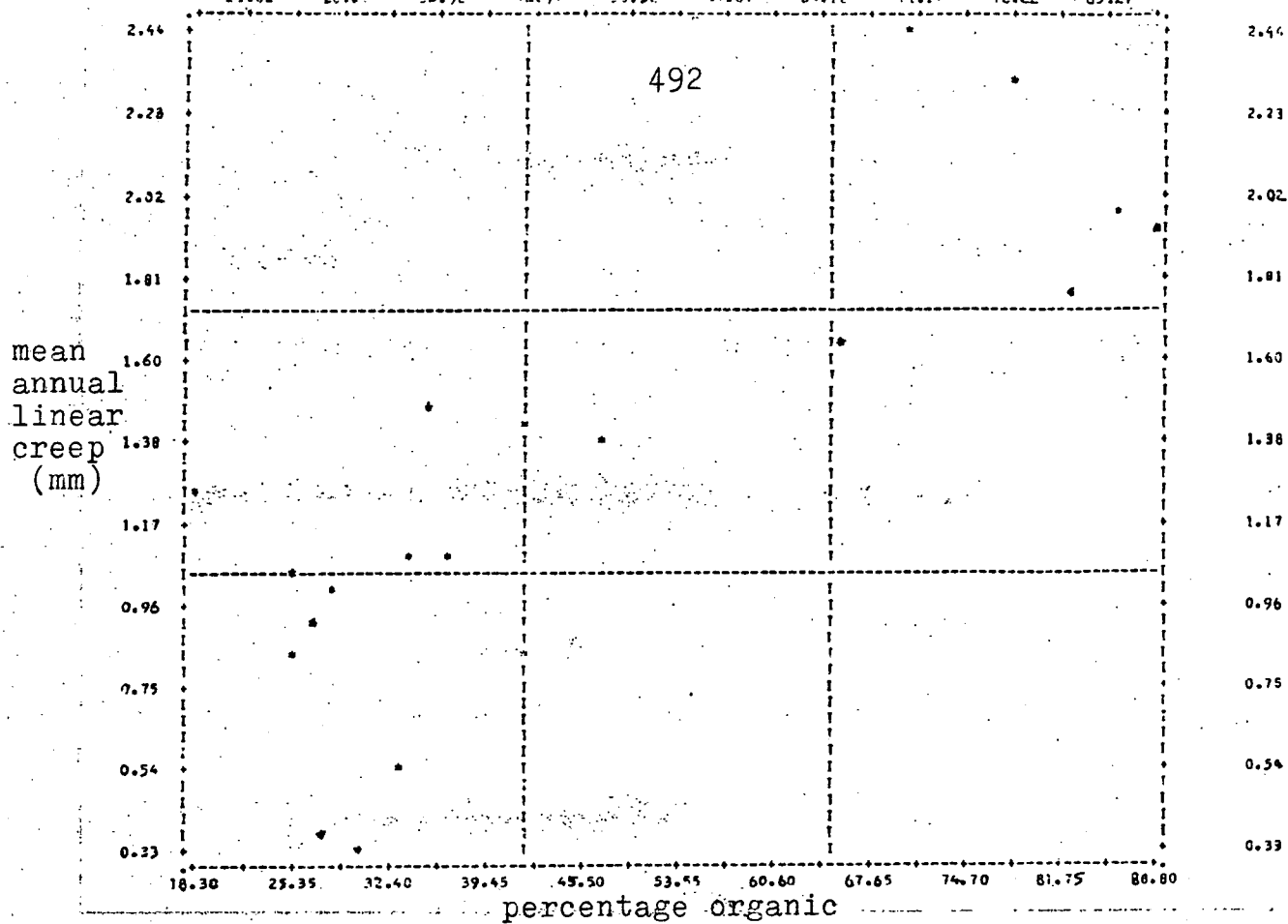


Fig. 13.7 Scattergram: Mean Annual Linear Creep and Percentage Organic Matter

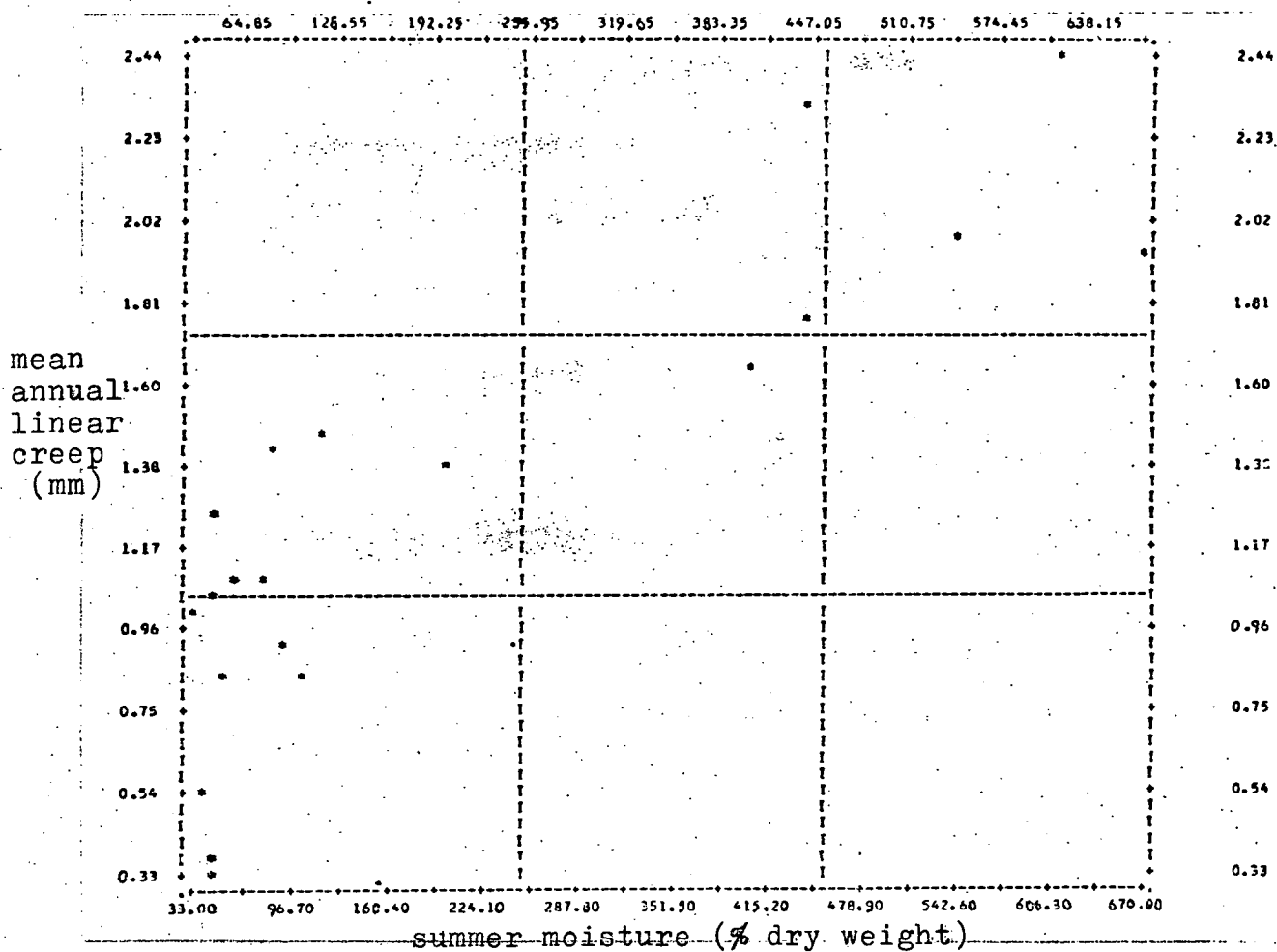


Fig. 13.8 Scattergram: Mean Annual Linear Creep and Summer Moisture

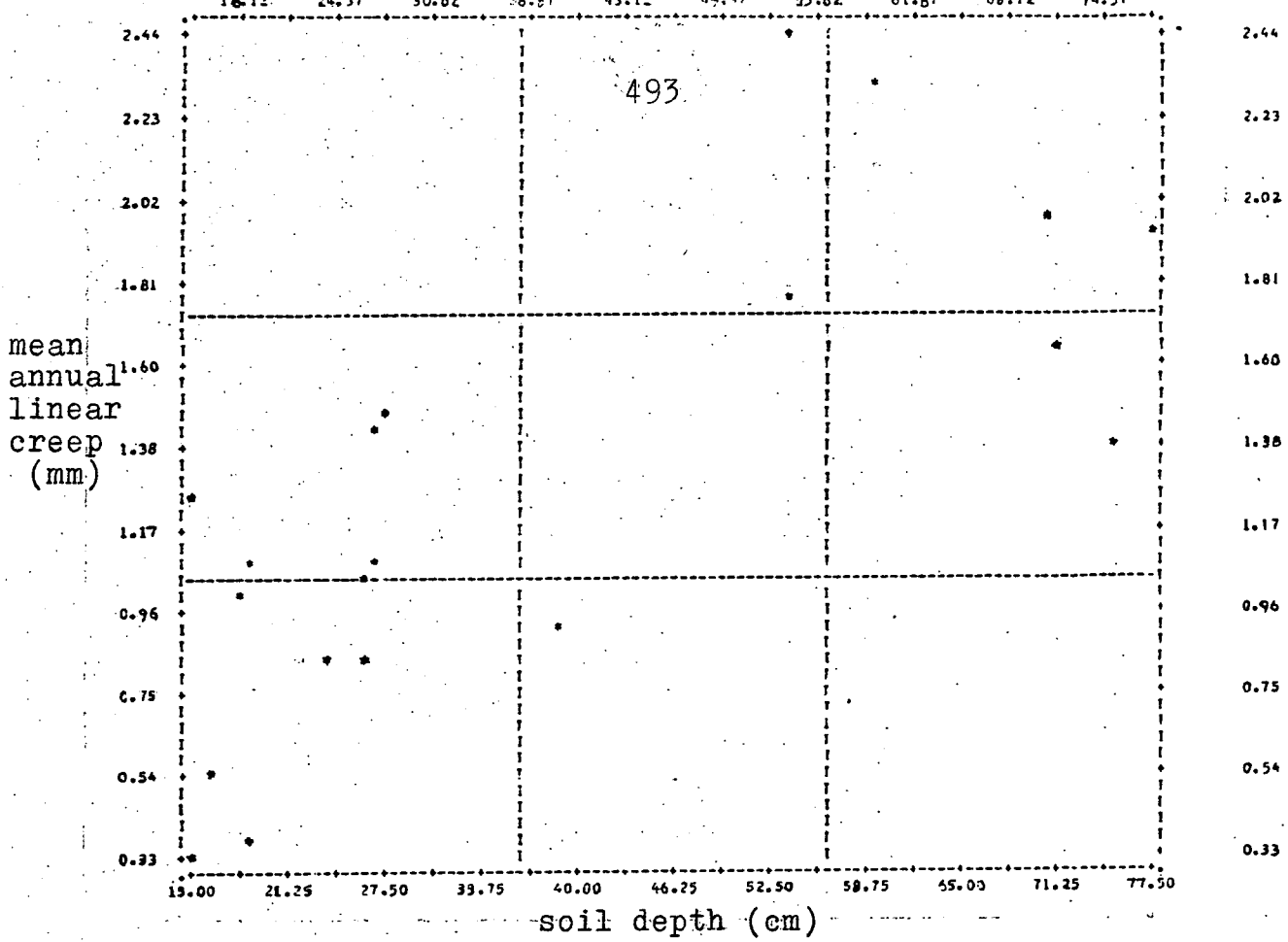


Fig. 13.9 Scattergram: Mean Annual Linear Creep and Soil Depth

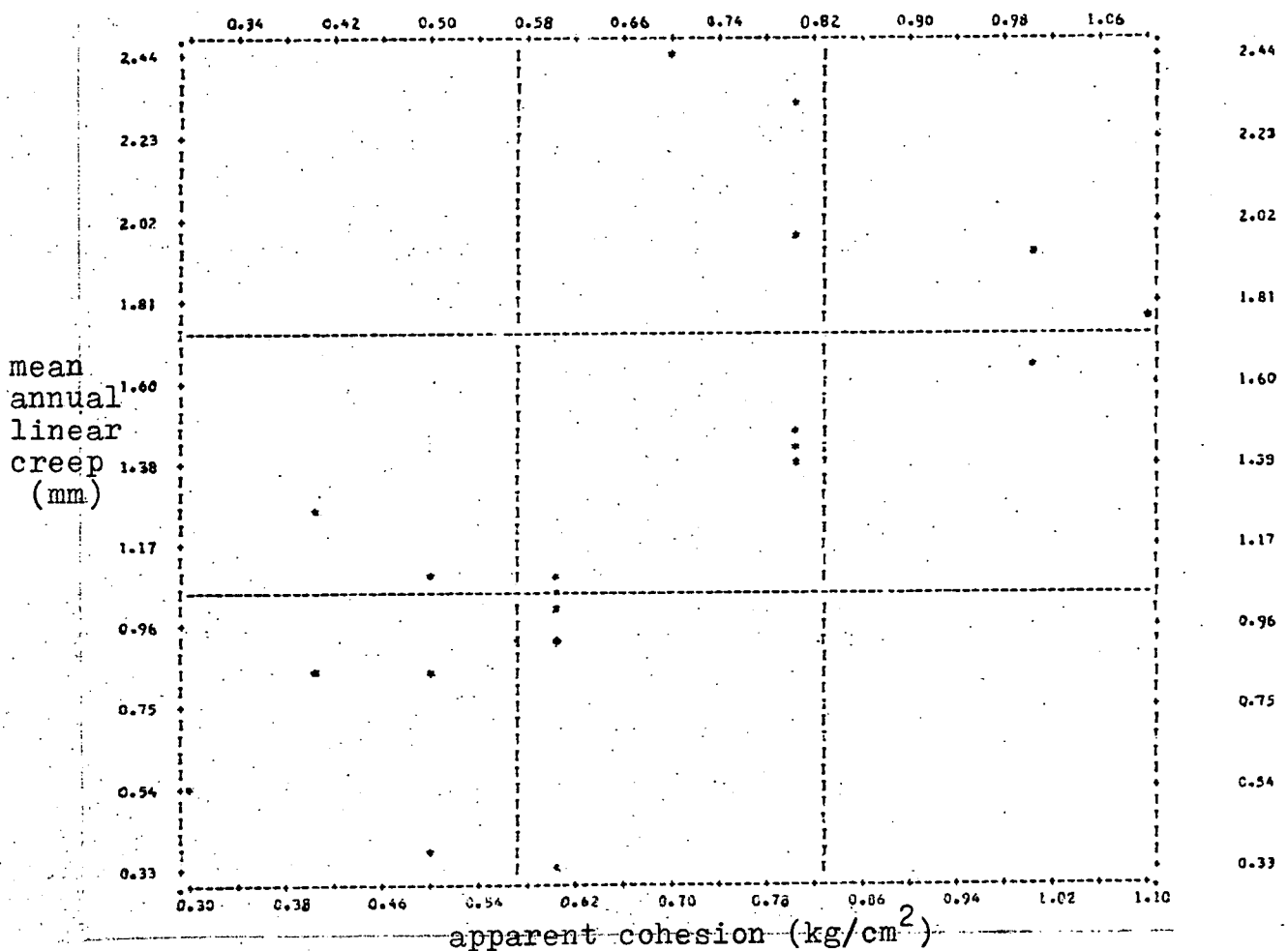


Fig. 13.10 Scattergram: Mean Annual Linear Creep and Maximum Apparent Cohesion

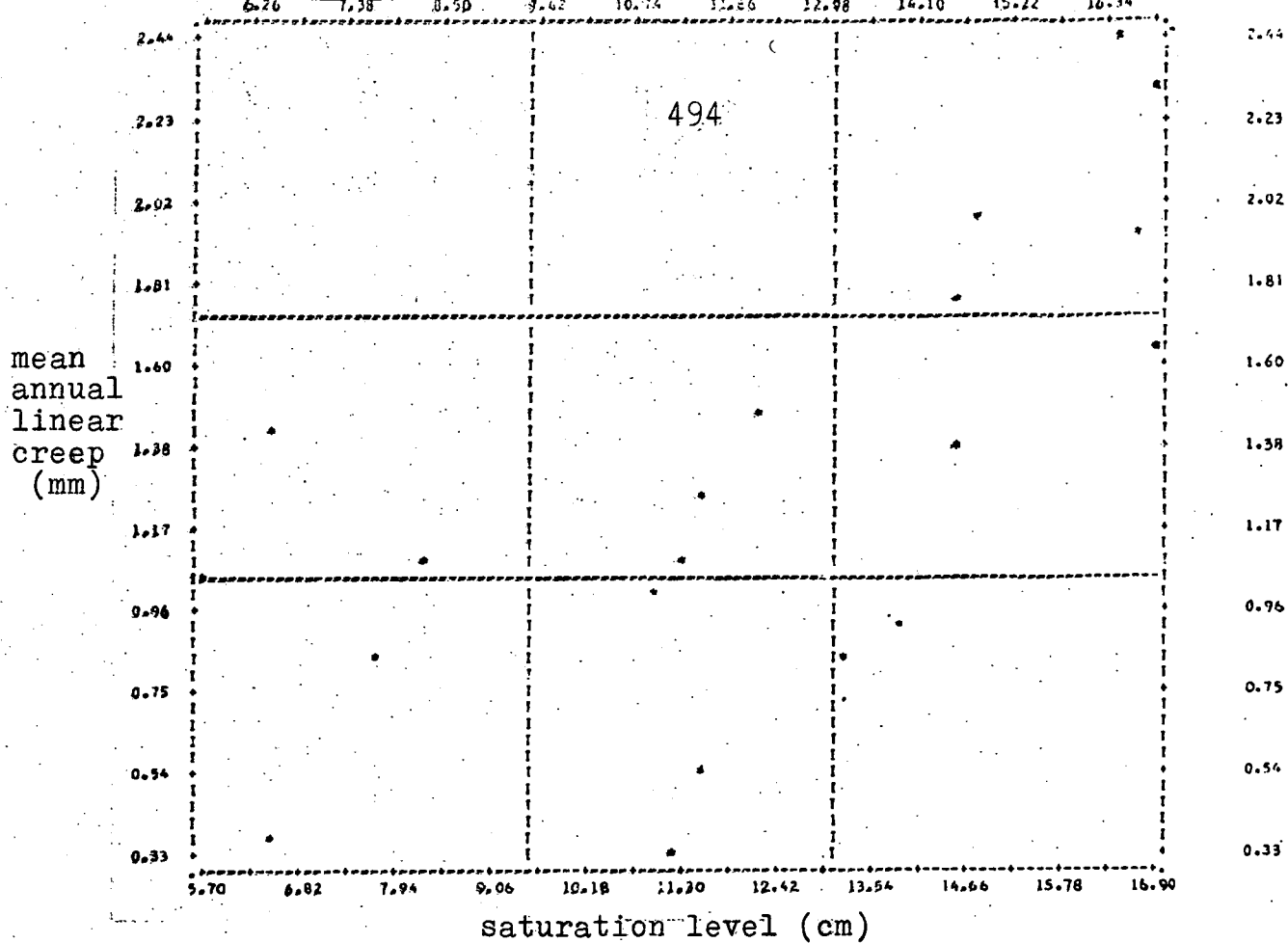


Fig. 13.11 Scattergram: Mean Annual Linear Creep and Saturation Level

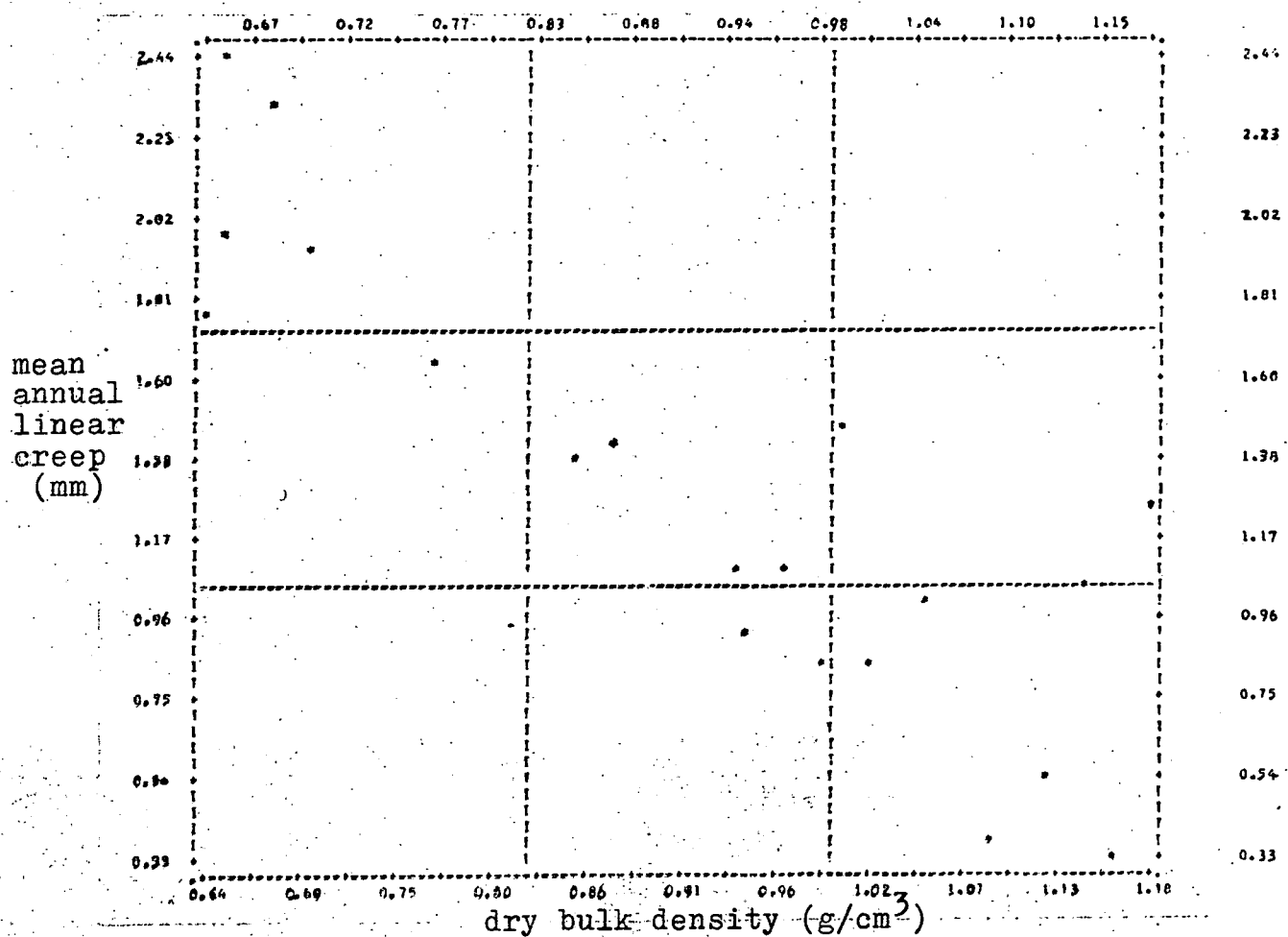


Fig. 13.12 Scattergram: Mean Annual Linear Creep and Dry Bulk Density

Correlations with annual creep rateDeviant plots(b) Resistance variables

Dry bulk density (Fig. 13.12)	7, 9, 5
Angle of internal friction (Fig. 13.13)	7, 11, 1, 18
Compression (strain) (Fig. 13.14)	12, 14, 3, 8, 11
Bulk density (field capacity) (Fig. 13.15)	9, 16, 13
Penetration (Fig. 13.16)	1, 6, 11, 19
Unconfined compression (stress) (Fig. 13.17)	14, 1, 9, 16, 4, 3, 13, 2

Using a strict interpretation of deviance it is possible to isolate the basin factors conforming less strongly to the pattern of correlation. The force variables show 37 deviant results but 16 of these are accounted for by only three factors: saturation level, apparent cohesion and linear shrinkage. In the analysis of basin factors, the first two of these also included a high number of deviant plots. When the scattergram of linear shrinkage and creep rates was examined it could be concluded that the relationship was somewhat weak graphically. Only three plots, 9, 5 and 16 are listed for three variables each, plot 9 appearing seven times. However it will be recalled that this particular plot has tended to be an isolate throughout the discussion of basin factors. It is a Nardus plot but the moisture-related variables tended to accord more with the trend apparent for Pteridium plots. On the other hand, the annual rate of creep is among the highest for Nardus plots. Plot 16 is in the same vegetation group but is the wettest plot in the group and also the one recording the highest annual creep rate. However many of the other positively correlated variables are relatively low. Plot 5, a Juncus plot, exhibits high values for the force factors but a comparatively low creep rate.

The resistance variables show only 26 deviant results and of these 8 were recorded for one variable, unconfined compression (stress). It has already been stated that this factor must be regarded with great caution. No plots

mean
annual
linear
creep
(mm)

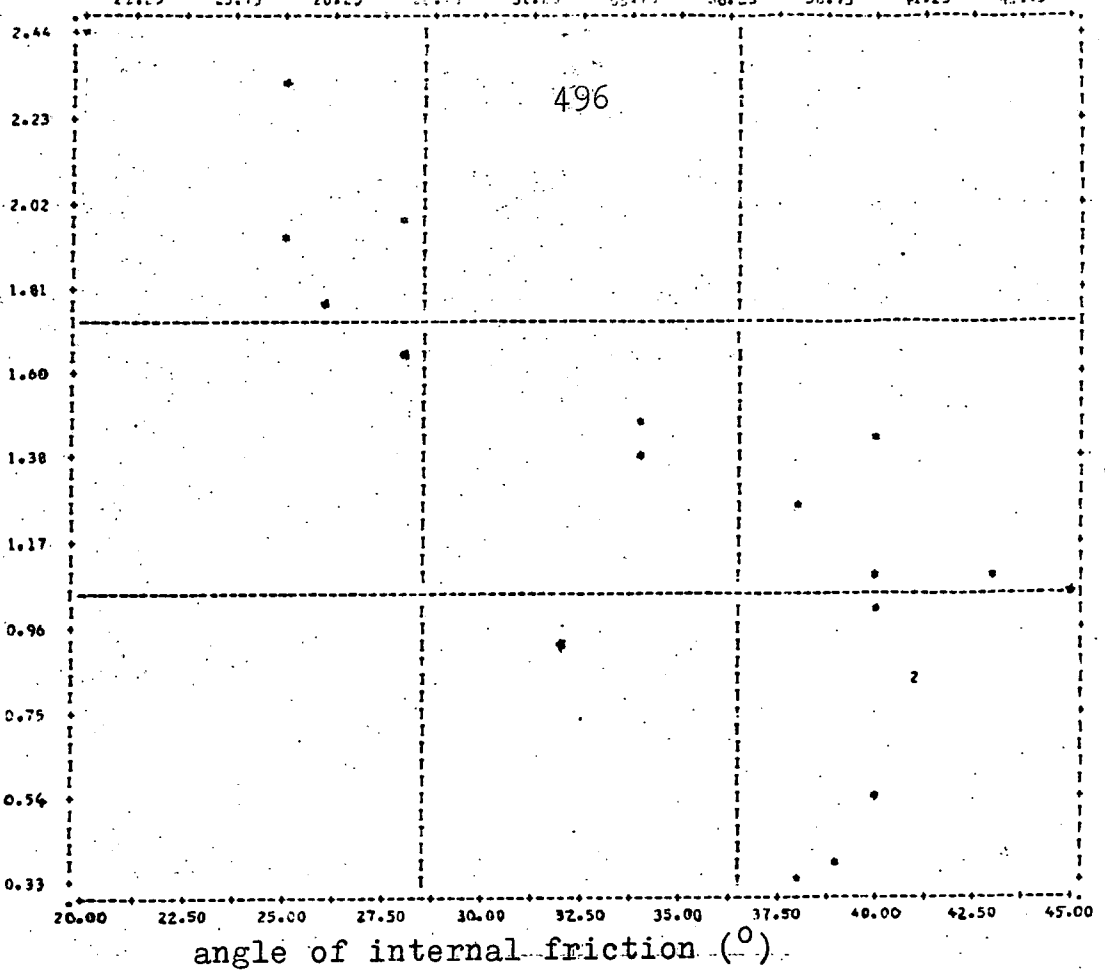


Fig. 13.13 Scattergram: Mean Annual Linear Creep and Maximum Angle of Internal Friction

mean
annual
linear
creep
(mm)

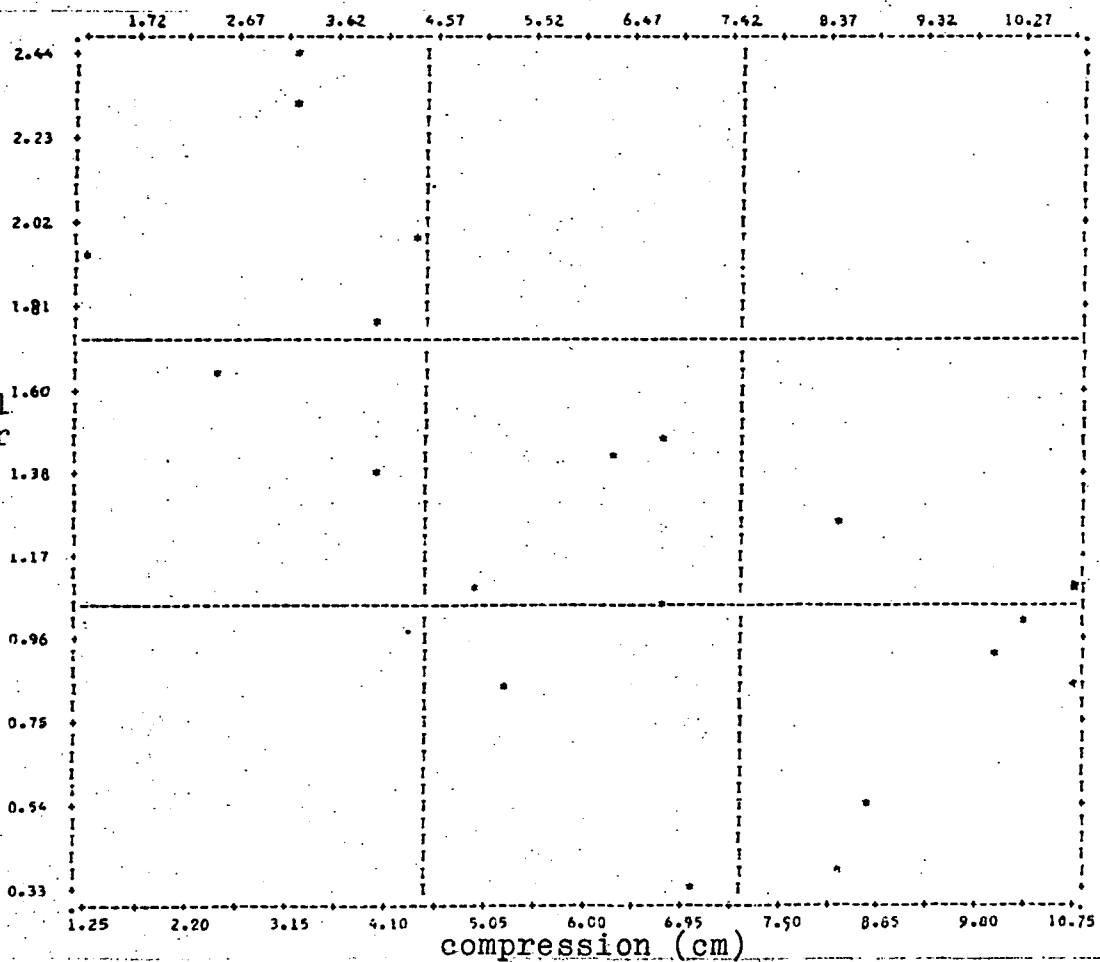


Fig. 13.14 Scattergram: Mean Annual Linear Creep and Compression (strain)

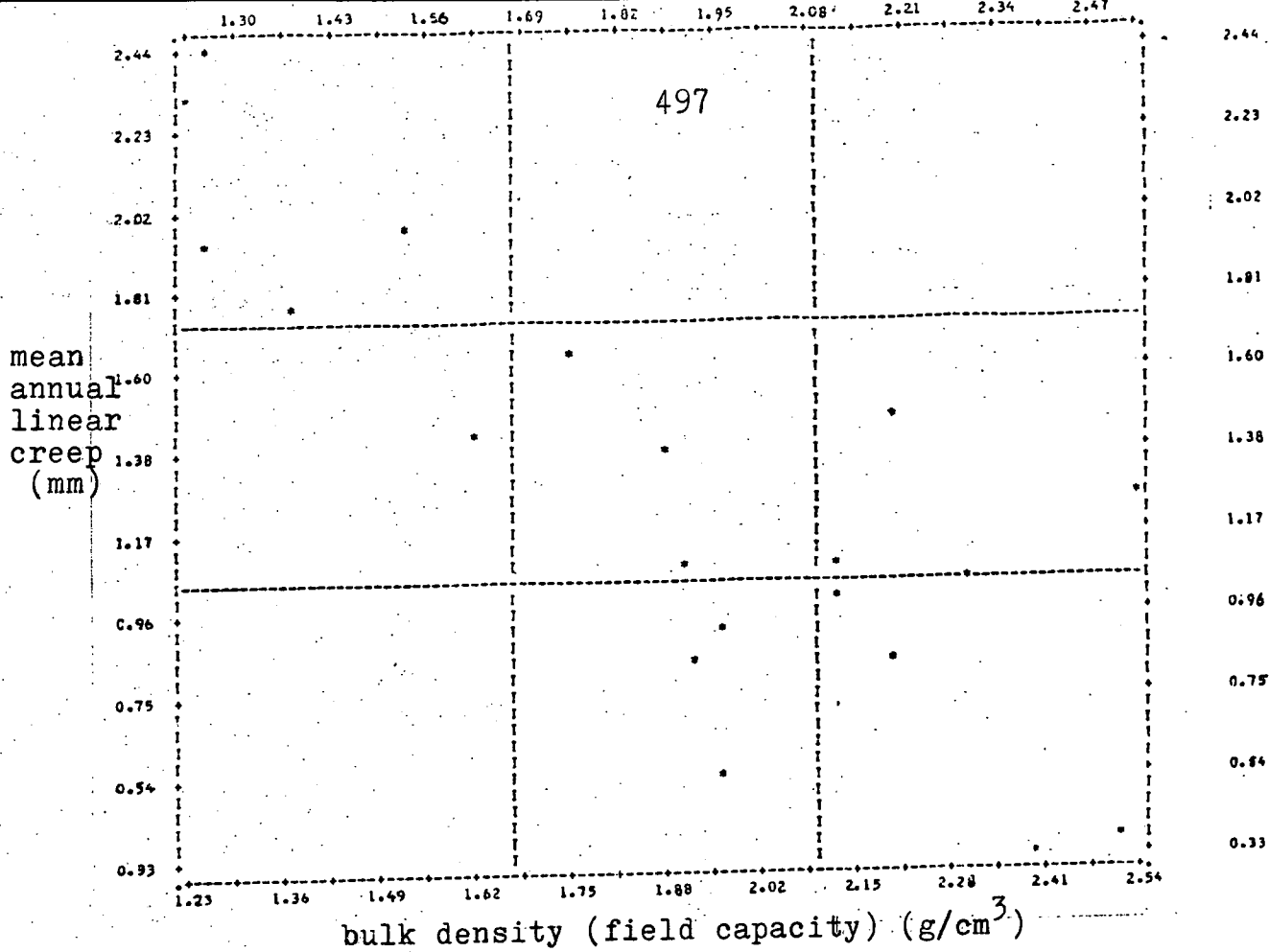


Fig. 13.15 Scattergram: Mean Annual Linear Creep and Bulk Density (Field Capacity)

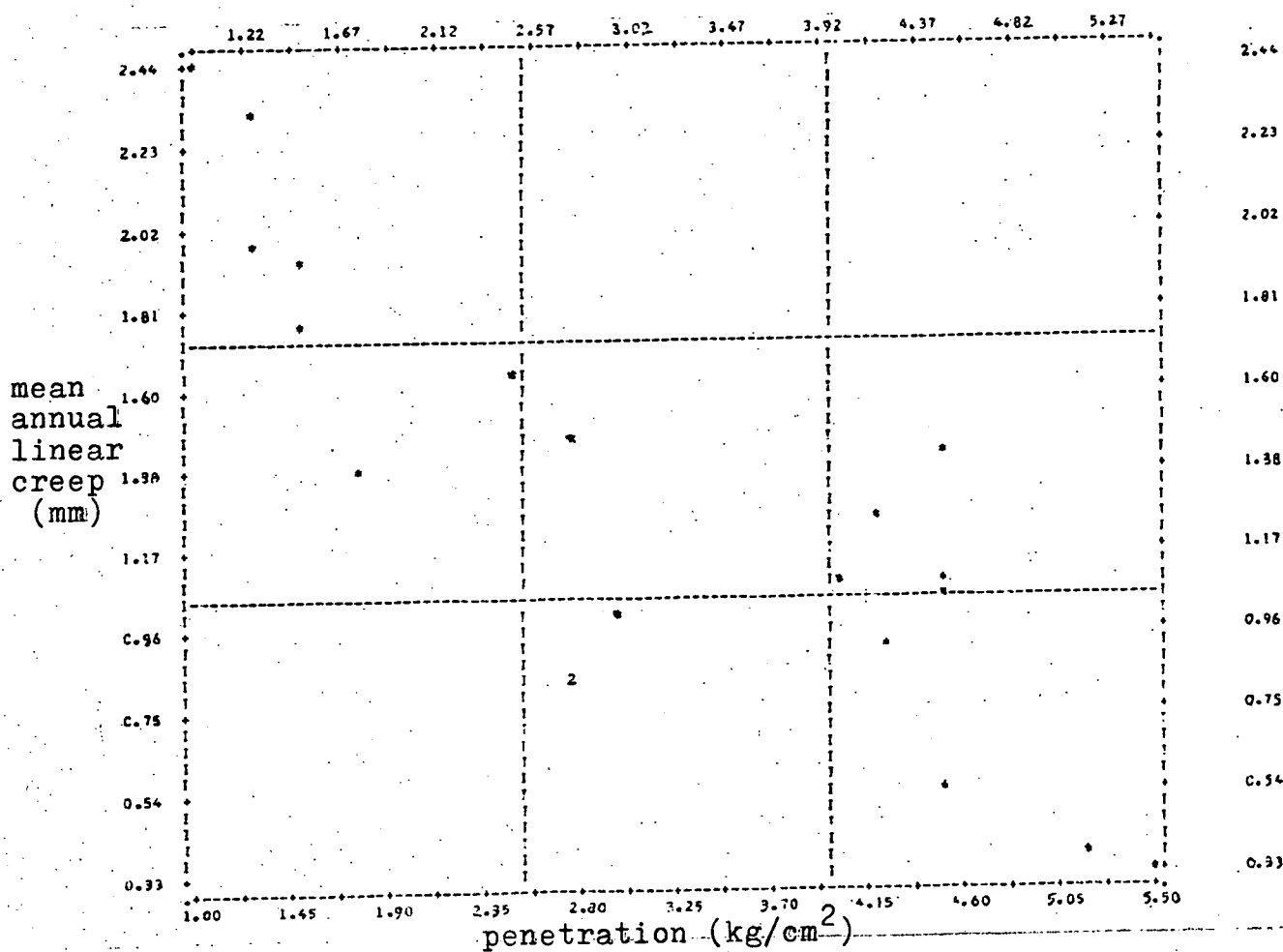


Fig. 13.16 Scattergram: Mean Annual Linear Creep and Penetration

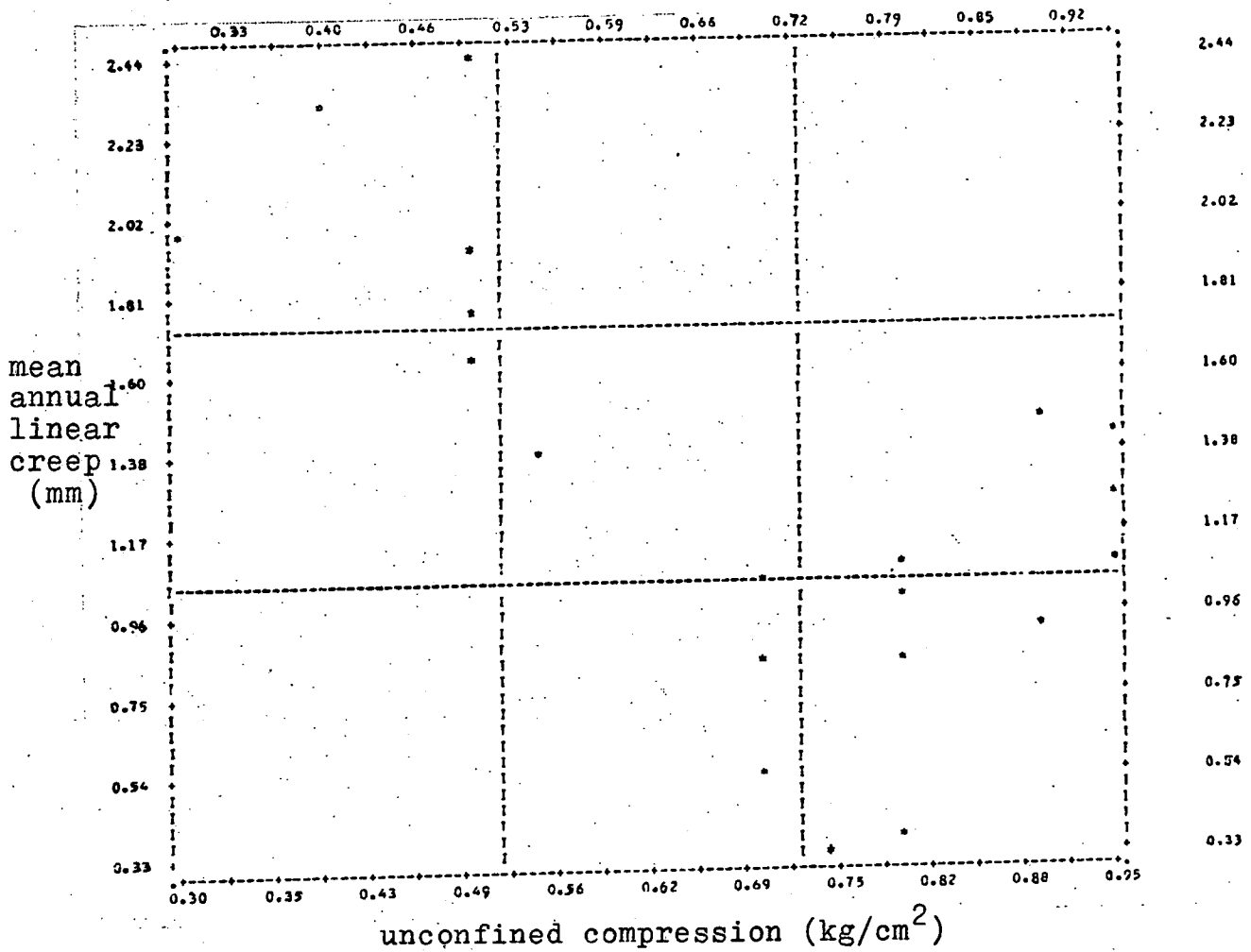


Fig. 13.17 Scattergram: Mean Annual Linear Creep and Unconfined Compression (stress)

are listed for more than three variables.

Thus, the general pattern of correlations to emerge statistically can, with few exceptions, be confirmed graphically.

Bearing in mind the foregoing discussion, the correlation diagram can now be interpreted in a more meaningful way. The positively correlated variables relating to force and facilitating creep are all closely related to soil moisture. Clearly the wetter plots tend to be more mobile and in general these plots will also have a major percentage of organic matter in their profiles. This must also be seen in the context of the soil capacity for holding moisture over any period, its field capacity. The high correlations between field capacity, percentage organic matter and winter moisture would therefore be expected. However it is not moisture content alone but change resulting from wetting and drying cycles which provides the 'triggering action' for creep. This is illustrated clearly by the correlation with linear shrinkage, indicating that those plots which shrink more on drying are also those with the highest creep rates. Finally, another major effect of the moisture is shown by the plasticity index which indicates the range of water content over which the soil behaves as a plastic. These five variables which all correlate highly with creep rates also show strong correlations with one another. In fact the inter-relationships exhibit well the multivariate nature of the problem.

Among the negatively correlated variables the main resistance to creep is expressed by dry bulk density. When the samples are saturated clearly the distinction between the organic and mineral soils is reduced since the former absorbs larger weights of water. Resistance to shearing is closely related to soil texture and therefore to bulk density with the predominantly mineral soil displaying a high bulk density and a comparatively large angle of internal friction. While shearing is in many ways similar to normal field processes, penetration is seen as basically a measure of resistance but one which

is in no way analogous to natural events. It shows a high correlation with the other resistance variables, particularly dry bulk density. Unconfined compression is similar to penetration since both involve compression. However in the former it is difficult to judge the actual moment of rupture especially with the organic soils which tend to bulge rather than break, and therefore the two are not as highly correlated as would be expected from a theoretical consideration. Of greater importance in this study is the compression variable (strain) which indicates that on the more mobile plots comparatively little compression is required before rupture occurs. As with the force variables, those representing resistance to creep show high correlations with one another and again present a multivariate problem.

Five variables, either because they correlate less strongly with creep rates or as a result of problems revealed by the scattergram analysis must be considered separately. Clearly it would be expected that organic depth would correlate highly with the percentage of organic matter. However the former was susceptible to less precise measurement and also is less directly related to soil moisture content. It is on the other hand strongly positively correlated with soil depth although, since on no plot was movement measured throughout the profile, depth itself cannot be a limiting or important factor with regard to creep rates. As explained earlier, apparent cohesion subsumes the effects of soil moisture together with the packing of particles and the effects of roots. Therefore it can be classified as a resistance variable but the significance of water is the comparatively high positive correlation. Similarly the measurement of saturation level is obviously closely allied to that of soil moisture but in this case the highest point recorded may be an isolated occurrence. Therefore the position of a plot within the basin exercises an important influence and one which tends to mask other relationships. The fifth variable, the sine of the slope angle, shows a low negative correlation with creep rates, a result similar

to that recorded by Evans (1974). It must be stressed again that the range of angles is very limited and that many other factors display large variations. To investigate further the effects of slope angle, it was controlled by grouping the plots into the three angular groups. The creep rates for plots within each group were then correlated with a range of basin factors and the following correlation coefficient resulted.

Table 13.4 Correlation Coefficients for Plot Groups:
Linear Creep Rates and Basin Factors

	<u>Slope angles</u>		
	<u>Low</u> (2.5° - 8.0°)	<u>Medium</u> (9° - 12.5°)	<u>High</u> (20.5° - 23.5°)
Number of plots	8	8	4
<u>Force variables</u>			
Soil depth	0.89	0.84	0.86
Organic depth	0.88	0.55	0.87
Saturation level	0.78	0.55	0.46
Winter moisture (% wet weight)	0.97	0.82	0.75
Field capacity	0.97	0.81	0.71
Organic percentage	0.91	0.71	0.63
Apparent cohesion	0.73	0.52	0.85
Plasticity index	0.97	0.84	0.82
Linear shrinkage	0.90	0.89	0.81
<u>Resistance variables</u>			
Dry bulk density	-0.98	-0.77	-0.69
Angle of internal friction	-0.85	-0.93	-0.28
Penetration	-0.91	-0.65	-0.86
Unconfined compression (stress)	-0.79	-0.66	-0.89
Compression (strain)	-0.74	-0.68	-0.96
Significance levels	0.71	0.71	0.95
95%	0.83	0.83	0.99
99%			

While these results are not used for future analysis, they do illustrate the point that high positive correlations with force variables and high negative correlations with resistance variables are recorded independently of slope variation. The effect of slope on the factors within the main basin correlation matrix therefore appears negligible.

Other variables which could not be included in the diagram were all the external or climatic factors, distance from the watershed and vegetation. While the climatic factors can be more precisely illustrated from the Brandon plot data and the laboratory experiments, certain general relationships can be identified and discussed.

However, before creep variations within the basin as a whole can be examined in the context of meteorological factors, the regularity of movement must be established. This is important since unless there is a definite uniformity of movement among the pegs, seasonal variations will not be discerned. Therefore the changes recorded by all 73 pegs were plotted for the sixteen occasions on which readings were taken. It was then possible to see whether a particular peg indicated upslope or downslope movement during the fifteen periods between measurements. Since in the original experimental design the basin was sampled by plots so that relatively homogeneous conditions could be expected, deviations from the general trend are listed by plots. For each of the fifteen periods the number of pegs showing movement in the opposite direction to the majority of pegs on that plot is given. No account is taken of the amount of movement registered since rates have already been considered at length. Any peg for which the reading remained constant is judged to be in agreement with the general trend. Only 71 such readings were obtained from the total of 1095.

Table 13.5. Peg Movement during Periods between Measurements:
Total of Pegs Moving in a Direction Opposed to
the Plot Trend

*Plots with only 3 pegs

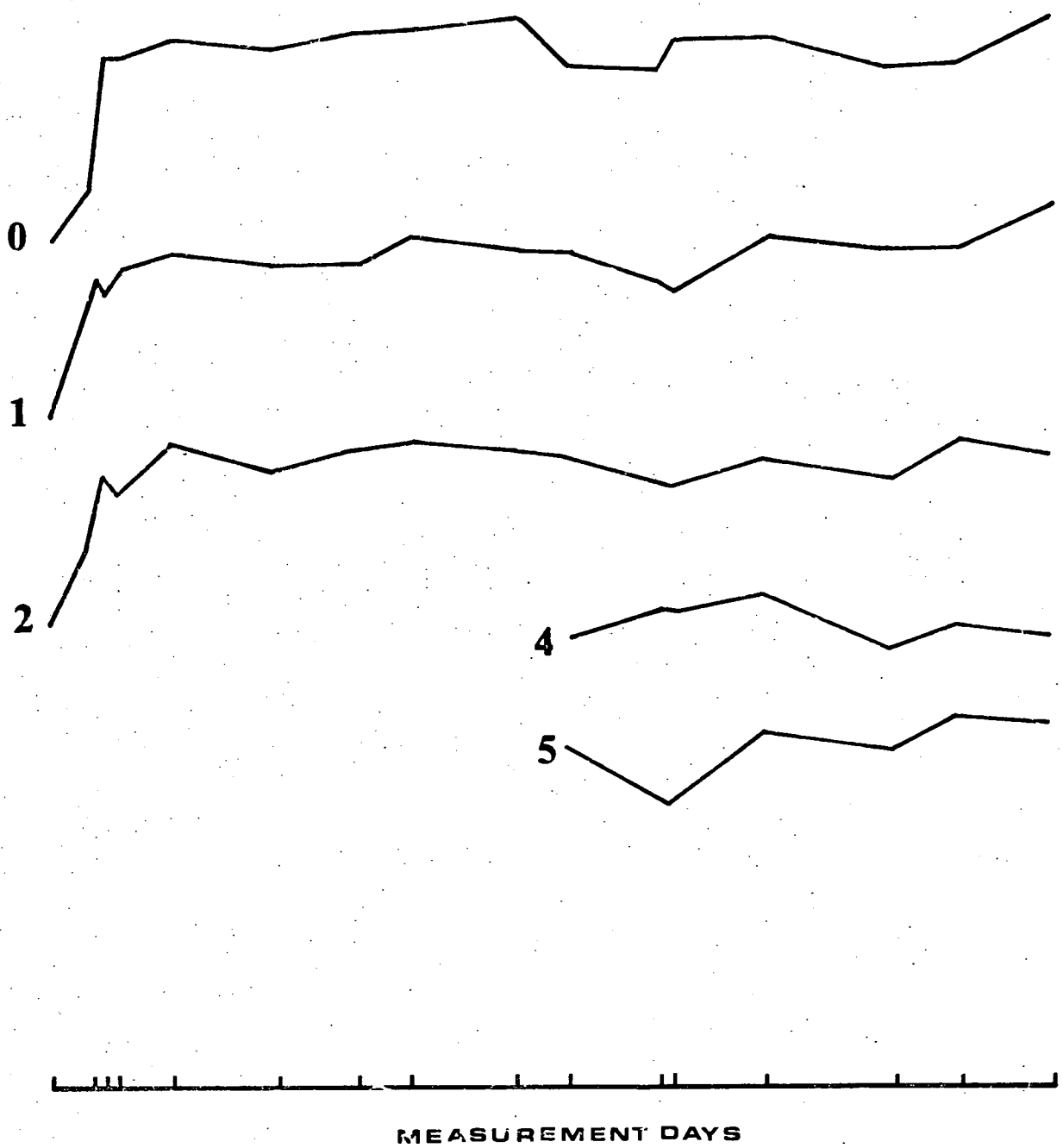
Plot	Periods between measurements															Total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1*		1	1					1			1				1	5
2		1			1	2		1	2		1					8
3	1	2	2	2			1	1				2	1			12
4*		1	1							1		1	1			5
5				1	1	1	1	1			1			1		7
6	1	1	1		1			1			1		1			7
7		1	1			1					1			1		5
8	2	1		1	1	2				1	1					9
9		1	1	1	1	1	1			1	1	1	1			10
10		2	1		1	1	1	1		2	2			1		12
11		1	1							1	1					4
12*		1	1	1	1	1										5
13			1	1			1		1	1			1			6
14*						1		1						1		3
15		1	1		1				1		1					5
16			2	1	1	1			1	1	1		2			10
17*				1				1	1		1			1		5
18*		1		1			1				1					4
19*				1	1						1			1		4
20				2		2		2			1	2			1	10
Total	4	15	14	13	10	13	6	10	6	8	16	6	7	6	2	

Within this matrix are 300 cells, each representing one measurement period per plot. On only 119 such periods was any lack of uniformity recorded and certain parts of the measurement year emerge showing marked regularity of movement. These are periods 1, 7-10 and 12-15. However it must be emphasised that the direction of movement is not tabulated. Furthermore on 17 occasions two pegs are listed and this means that half the instruments were indicating creep in each direction. For 73 pegs therefore a total of 36 irregular results in any one period would indicate that there was no trend. In fact the highest total was 16, recorded in period 11.

It can be concluded that, using the plots as units, there is a definite regularity in the movement of the Inclinator pegs. This is particularly so during the early stages of the measurement year, from late February to mid June and from June until November. This general regularity has been offered (Evans, 1974) as evidence to refute the basic idea of random movement advanced by Culling (1963). However, while the net effect of Culling's theory might be questioned, his concern was with the microscale which could not be detected by any creep rate measurements yet devised.

To relate these creep variations to the climatic variables tabulated earlier, it is necessary to examine the direction of movement during each period for the whole basin. To allow this, each movement of every peg was plotted and the total number of movements upslope and downslope totalled. Examples are given for three plots (Figs. 13.18.A,B,C.) and the remainder are included in Appendix 3.* Two measurements are given for moisture, the general moisture state indicated by the mean daily rainfall during the measurement period, and the total rainfall for the preceding 24 hours. However it must be emphasised that, from the Brandon results, the lag is short and therefore it is the latter reading which is the more significant. The general moisture state can only provide a very loose guide. In a similar way a number of freeze-thaw cycles during a period of measurement can only

*The aluminium peg is numbered 4 and the red painted wooden peg 5.



movement
(mm)

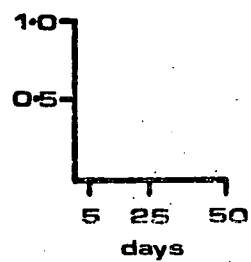


Fig. 13.18A

Peg Movements: Plot 1

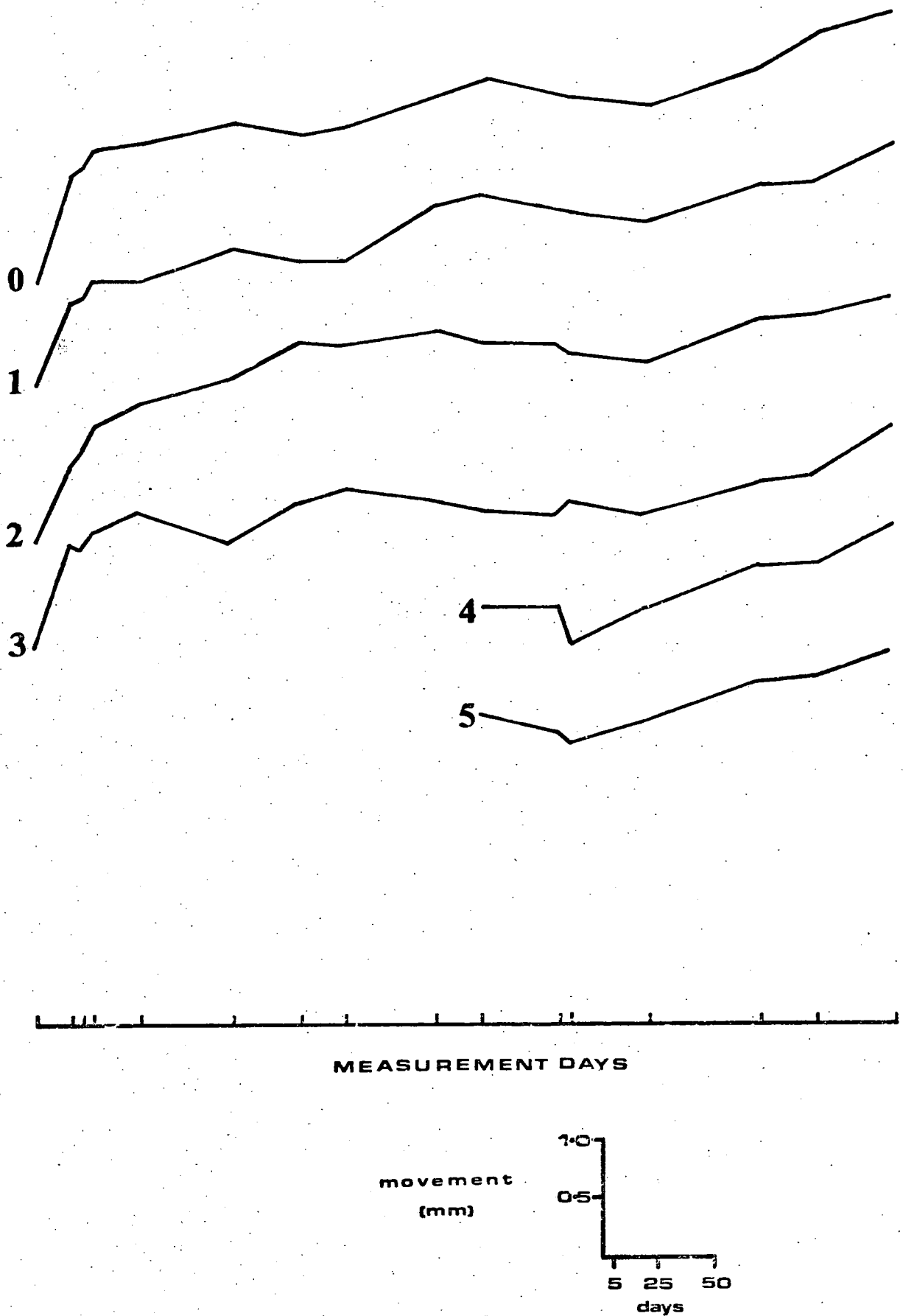
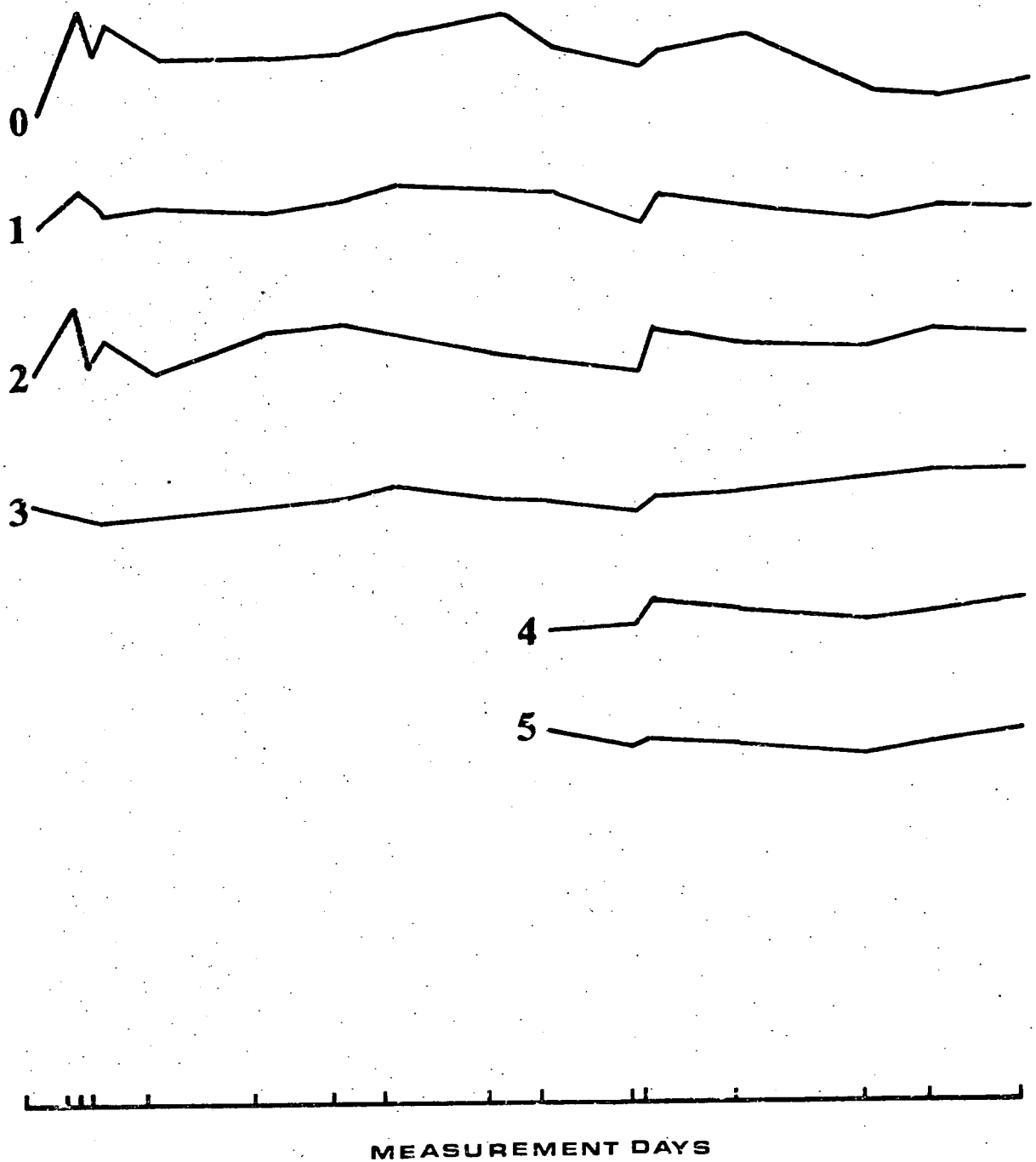


Fig. 13.18B

Peg Movements: Plot 2



movement
(mm)

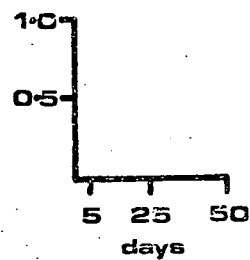


Fig. 13.18C Peg Movements: Plot 3

give an approximate indication of potential impetus for creep since frost penetration varies in time and also according to the exact location within the basin. Even if the readings were taken under freezing conditions, the distribution of frost is very irregular even on the scale of one plot. Therefore when meteorological controls are considered, undoubtedly the most important reading is that for rainfall during the previous 24 hours.

On the scale of the basin within which variations in factors such as altitude, exposure, slope, vegetation association and soil type occur, complete regularity of soil movement would not be expected. The effects of moisture and freezing, the principal forces causing expansion, will obviously differ according to, for example, whether the soil is predominantly sandy or organic, whether the vegetation cover is high or low and whether the soil is already moist or dry.

Furthermore the fact that readings were taken at irregular intervals and with comparatively long time periods between them, at least compared with the lag already identified, means that any conclusions can only be general and tentative. On the other hand, since the other variables controlling creep rates have been assessed in the basin, the meteorological factors should also be examined.

The expected relationship is that increased moisture and freezing cause soil expansion while drying causes contraction. Clearly the effect of rain is similar to that of adding to the moisture content and thereby facilitating downslope movement. If the soil is already wet, rainfall will therefore have less effect while freezing is likely to cause even greater expansion. Annually, downslope movement would consequently be predicted in the winter half-year as a result of the high level of moisture and freeze-thaw while summer drying should produce contraction and upslope movement. However it must be remembered that the basin does not dry out evenly in summer and many plots, particularly those with a Juncus association, have a high summer moisture content.

Table 13.6. Total Peg Movements within the Basin
and Meteorological Cycles

<u>Periods</u> <u>between</u> <u>Measurements</u>	<u>Number of peg</u> <u>movements</u>		<u>Rainfall</u> <u>(mm)</u>		<u>Freeze-thaw</u>	
	<u>Upslope</u>	<u>Downslope</u>	<u>Mean</u> <u>daily</u>	<u>Total for</u> <u>previous</u> <u>24 hours</u>	<u>Number</u> <u>of</u> <u>cycles</u>	<u>Freeze -</u> <u>Thaw +</u>
1	4	69	1.4	5.2	4	
2	28	45	2.7	2.3	1	
3	19	54	1.1	0.2	3	+
4	14	59	1.3	3.8	6	-
5	35	38	3.3	0.6	9	-
6	17	56	5.2	0.6	10	+
7	9	64	1.4	4.8	5	+
8	55	18	1.2	0	9	
9	64	9	1.6	0	2	
10	43	30	1.7	1.0	2	
11	36	37	1.4	0	0	
12	14	59	2.7	1.8	0	
13	29	44	3.0	0.4	0	
14	9	64	3.5	3.0	3	
15	8	65	2.4	7.1	10	

It can be seen that high rainfall in the previous 24 hours is associated with predominantly downslope movement. This can be observed for periods 1, 2, 4, 7, 14 and 15. Upslope movement dominates when the soil is comparatively dry and rainfall during the previous day has been low. These conditions occurred in periods 8, 9 and 10. Period 3 coincided with the thaw stage of a cycle so that the soil was very wet, while readings for period 5 were taken during freezing temperatures and the irregularity resulting from frost action is apparent. Measurements after period 6 were also taken during thaw and following a large number of freeze-thaw cycles. For period 11, a very short time interval, the basin was comparatively dry and there was no rain in the previous 24 hours. However these results were deliberately obtained only five days after the previous

set as, following a dry period, 7.1mm of rainfall had been recorded on 18th June. Thus with a heavy fall and two days of drying, marked variation would have been expected. Periods 12 and 13 both record significant downslope movement despite only modest rainfall in the previous 24 hours, but in these cases the basin was comparatively wet.

Therefore it can be concluded that seasonal variations in creep can be discerned within the complete basin and a pattern related to changing meteorological conditions can be seen. However it must be stressed that the results from the Brandon plot were obtained to investigate this relationship in detail.

Plots of movements recorded by the Inclinator pegs were also used to test in more detail the time which should be allowed for adjustment. As discussed earlier, the pattern of peg movement exhibits a definite regularity and therefore it is possible to compare this with the results plotted for pegs installed later to find the time elapsing before they record the same pattern. This procedure has already been considered as part of the experimental design and, as a small pilot study, three aluminium pegs were inserted, one each on plots 11, 12 and 17, on 11th December 1973. The complete instrumentation for this occurred on 12th May 1974 when each plot was equipped with a wooden peg and an aluminium peg. It should be mentioned that the aluminium pegs were of exactly the same dimensions as the others but it was thought that a contrast should be provided between metal and wood.

While the assessment of patterns must be somewhat subjective it is comparatively easy to compare trends and tabulate the number of measurement periods occurring before the peg movement coincided with the pattern of the plot.

Table 13.7. Time Factor: Number of Periods between Measurements until Pegs followed Plot Trend

<u>Plot</u>	<u>Number of measurement periods</u>	
	<u>wooden peg (5)</u>	<u>aluminium peg (4)</u>
1	1	-
2	1	-
3	1	-
4	-	-
5	1	1
6	-	-
7	-	-
8	-	-
9	1	1
10	-	1
11	1	-
12	-	1
13	-	-
14	-	-
15	-	1
16	1	-
17	-	1
18	-	-
19	-	2
20	-	-

For 26 of the 40 pegs adjustment took place within one measurement period of approximately one month. Among the remainder, 13 pegs showed accordance with the general pattern of the plot after one period and only 1 peg required two periods. Thus the evidence supports that advanced as a result of preliminary work that readings can be taken as representative of creep after one month. In fact this point was anticipated during the instrumentation of the basin with all the devices for monitoring soil movement. The number of periods required is evenly distributed between the two types of peg.

To examine the possible influence of distance from the watershed on creep, the plots were ranked in a series of transects down the basin and the resulting order correlated with the annual rates for each of the plots. None was significant.

Table 13.8. Correlation Coefficients: Plot Position
Related to the Watershed and Annual Creep Rates

<u>Plots in transect</u>	<u>Correlation Coefficient</u>
1,2,5,6,10,11,13,14,17	0.12
4,7,11,16,18	0.05
4,7,20,19	-0.06
3,8,20,19	0.60

From these results it is clear that there is no evidence to support a relationship between creep rates and distance from the watershed. It would hardly be expected, given the heterogeneous nature of the plots within the transects. Furthermore, the temporary base levels occur at the foot of each scarp and these must influence any dependence between plots in a transect.

The vegetation coverage within any one plot was quantified by quadrat and therefore the predominance of the major species can be examined in relation to creep rates. The percentage coverage of the major genera on each plot was correlated with creep rates and the results for the three plot groups are given. None was significant.

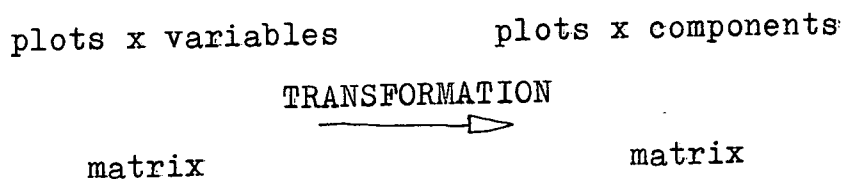
Table 13.9. Correlation Coefficients by Plot Groups:
Percentage Coverage of Major Genera per
Plot and Annual Creep Rates

<u>Vegetation % (major genera)</u>	<u>Correlation Coefficient</u>
<u>Juncus</u>	0.27
<u>Nardus</u>	0.41
<u>Pteridium</u>	-0.19

The actual effect of the genera on creep can therefore be discarded and it can be assumed that it is the total complex of vegetation and soil characteristics which are important. These have, of course, already been analysed in detail. For the Pteridium plots a coefficient of 0.51 was calculated for the relationship between creep and percentage of bare ground. While this is low, it provides some support for evidence already described on this subject. The correlation with root depth, which could not include Juncus plots yielded a coefficient of only 0.42. Thus, in this study, vegetation variables cannot in general be considered in isolation as important controls, but must be seen more as indicators of a total complex. The possible exception is root strength, although evidence on this subject is limited. The mean figures quoted indicate possible impedance of movement by roots with Pteridium rhizomes being the most effective in this and Juncus roots offering least resistance.

13.2.2. Principal Components Analysis

The second stage of analysis was principal components analysis which can be briefly summarized:



The components are new variables which are linear functions of the original variables and they have special properties:

- (a) they are orthogonal and therefore independent of each other
- (b) the first component is the linear function of the variables which accounts for the maximum possible proportion of total variance
- (c) the second component is the linear function of the variables which accounts for the maximum possible proportion of the remainder, after the effect of the first component has been removed
- (d) the remaining components from third to last may be defined in a corresponding manner

The number of components is equal to the number of variables but since variance is usually concentrated in the first few components, these provide a parsimonious summary of the basic features of the data matrix. It should be emphasised that linearity is a central feature and it is important therefore to check for any possible curvilinear relationships or threshold effects. In the case of the Rookhope data, as already implied in the earlier part of the analysis, these are not in evidence.

The basic inputs for the SPSS package (Nie et al, 1970), were the correlation matrices already generated, consisting of Pearson's product moment correlation coefficients. As stated earlier, evidence from the matrix of creep rate readings from the six instruments strongly supports the selection of the Inclinator peg results as those most closely indicating actual creep rates in the basin. However as a final check on this, principal components analysis was used to produce a matrix of which an extract is given. The loadings listed are the correlations between the variables and the components.

Table 13.10. Principal Components: Annual Creep Rates

	<u>Component 1</u>	<u>Component 2</u>	<u>Component 3</u>
Inclinometer pegs	0.98815	-0.00728	-0.02327
Aluminium rods	0.96136	-0.13826	-0.07895
Young's Pits	0.97242	0.02190	-0.16345
Cassidy's Tubes	0.88975	0.44488	0.08748
Dowelling pillars	0.94784	-0.23035	0.20535
Anderson's Tubes	0.98789	-0.05941	0.01483

Component 1 accounts for 91.9% of the total variance in the data matrix and can therefore be seen as the basic 'creep' component. All the instruments load strongly on this component and only Cassidy's Tubes show any sizeable loading on component 2. These points therefore indicate

that all the instruments except the Cassidy's Tubes measure basically the same variable. Cassidy's Tubes are more complex and seem to include at least one further dimension. However component 2 accounts for only 4.6% of the variance and no other instrument loads highly on to it. Since neither of the other devices which records a velocity profile (dowelling pillars and Young's Pits) accords, the component may be identified with the design of the tubes themselves rather than the mode of measurement. However the fact that Cassidy's Tubes load relatively lowly on the first component and relatively highly on the second, indicated again that they are out of step with the other instruments. From all the arguments advanced it is a reasonable assumption that they are less accurate, although this should not be over-emphasised since the second component accounts for so little of the total variance. These conclusions are congruent with the interpretation of the data. Certainly, if there were any grounds for considering Cassidy's Tubes to be the best and the other instruments less accurate, these would have been reinforced by the results.

In examining component 1, the 'creep' component, it can be seen that although the loadings are all high, the highest is attributed to the Inclinator pegs. Furthermore 96% of the total variance of the peg data is accounted for by component 1. It can be concluded that the Inclinator peg results are those most closely identified with the creep component, a point which can therefore be justified on both instrumental and statistical grounds. Statistical conclusions also reinforce those already made on other grounds, that Anderson's Tubes are overall the next most accurate for monitoring creep rates.

The principal components matrix using all the basin factors measured again, identifies in component 1 the division between force and resistance variables.

Table 13.11. Principal Components: Basin Factors

	<u>Component 1</u>	<u>Component 2</u>	<u>Component 3</u>	<u>Component 4</u>
Slope angle	-0.43266	0.87525	0.07183	-0.06697
Soil depth	0.91487	0.11975	0.16521	0.12123
Organic depth	0.86846	-0.09272	0.27480	0.10142
Saturation level	0.81169	-0.13161	-0.12499	0.48714
Winter moisture (% wet)	0.97851	0.02316	0.07456	-0.03047
Field capacity	0.97847	-0.02564	0.06514	-0.07697
Bulk density (dry)	-0.95311	0.06430	0.02818	0.21281
% Organic	0.96170	0.00706	0.08352	-0.05868
Angle internal friction	-0.92114	0.05947	0.15525	-0.14222
Apparent cohesion	0.80059	-0.09451	0.45012	-0.14929
Penetration	-0.87113	-0.03603	0.26776	-0.00281
Unconfined compression	-0.82481	-0.32328	0.05072	-0.12591
Compression	-0.83171	-0.04847	-0.37247	-0.09439
Bulk density (field capacity)	-0.88063	0.09665	0.13787	0.29629
Creep rate (pegs)	0.88231	-0.10787	-0.14576	-0.22078
Plasticity index (organic)	0.89946	0.22106	-0.18376	-0.00276
Plasticity index (mean)	0.96754	0.13059	-0.11574	-0.04572
Linear shrinkage	0.97260	0.12949	-0.01171	0.07726
Winter moisture (% dry)	0.96291	0.05275	-0.13483	-0.06212
Summer moisture (% dry)	0.96549	-0.01669	-0.03206	0.03299

Component 1 accounts for 79.6% of the total variance and, from the high positive loadings, can be considered basically a 'moisture' component. The winter moisture variable itself shows a loading of 0.98 and the lowest positive loading is recorded by apparent cohesion which, as previously explained, can also be seen as a resistance. The clearly defined resisting variables all display high negative loadings which would be the expected association with a 'moisture' component. All the variables load most highly on component 1 except for the sine of slope angle which alone shows a strong loading on component 2. Of particular importance are the loadings with creep rates which are also highest on component 1. This confirms the importance of moisture as a variable affecting creep rates. Throughout the analysis, evidence has pointed towards moisture as a key factor, while the high positive correlations between it and the other force variables have already been discussed.

Component 2 which accounts for 5.2% of the total variance is dominated by one variable, the sine of the slope angle, and can therefore be considered a 'slope' component. This is interesting since the importance of this variable accords with several theoretical appraisals; for example, (Kirkby (1967)). From a consideration of the basic mechanism of soil creep, it would appear that the sine of the slope angle must be an important control of rates (Chapter 1). However it has been observed by Evans (1974) that the angle is only likely to predominate where a slope displays homogeneity of characteristics throughout its length. Furthermore Young (1972) has pointed out that no conclusive field evidence has been advanced in support of the pre-eminence of this variable. In this matrix no other loadings appear high and creep rate displays a very low negative loading. However it must again be emphasised that these results are specific to the assemblage of slopes at Rookhope where there is a limited angular range. It is also more likely and seems theoretically appropriate that in the long term, slope angle must be more predominant.

Component 3, accounting for 3.4% of the total variance, is more difficult to categorize since it contains no high

correlations and all the variables are loaded highly on the previous components. However, apart from compression, all the soil mechanics loadings are positive, with apparent cohesion and penetration as the highest. This can therefore be considered a 'mechanics' component, particularly as creep rates show a negative loading. Similarly component 4, accounting for 2.7% of the total variance, shows a negative loading with creep rate. The most significant positive correlations, and for each the second highest loading, are indicated for saturation level, bulk density (dry) and bulk density (at field capacity). Component 4 can thus be categorized as a 'density' component.

Component 5 is almost as important as component 4, accounting for 2.6% of the total variance, and can be classified as an 'organic/mechanics' component, since the high loadings are with unconfined compression, which was in each case measured for the organic horizon and plasticity index (organic). No other component accounts for more than 2% of the total variance.

This analysis illustrates the point made earlier that percentage variance and therefore interpretability fall away rapidly and it is the first few components which reveal the basic features.

It can be concluded that component 1 is by far the most important, illustrating the significance of moisture variables. However it is realised that this could, in part, result from the fact that a large number of basin factors measured are associated with moisture. The consistency of the components could be tested by varying the data. A second principal components analysis was therefore completed, after the elimination of a number of variables closely related to moisture. It was decided that these should be the variables contributing the six highest positive loadings on component 1 after winter moisture.

Table 13.12. Principal Components: Basin Factors
(Six Major Moisture Variables Eliminated)

	<u>Component</u> <u>1</u>	<u>Component</u> <u>2</u>	<u>Component</u> <u>3</u>	<u>Component</u> <u>4</u>	<u>Component</u> <u>5</u>
Sine of slope	-0.45474	0.86846	0.01276	-0.07659	0.10159
Soil depth	0.92432	0.16218	0.12022	0.09331	-0.03061
Organic depth	0.86940	-0.04907	0.27040	0.15377	-0.31648
Water level	0.82382	-0.11489	-0.14152	0.44957	0.22231
Winter moisture (% wet)	0.97792	0.05443	0.05718	-0.05121	0.07889
Bulk density	-0.95081	0.04021	0.04458	0.21464	0.05200
Angle of internal friction	-0.91818	0.04963	0.14612	-0.11402	-0.18382
Apparent cohesion	0.81361	-0.03865	0.44397	-0.17951	0.11717
Penetration	-0.87540	-0.04821	0.30616	0.01884	0.08507
Unconfined compression	-0.81012	-0.33908	0.08543	-0.18363	0.39530
Compression	-0.83348	-0.09625	-0.36351	-0.06694	-0.16651
Bulk density (saturated)	-0.87750	0.08111	0.14534	0.28244	0.11938
Creep rate (pegs)	0.88427	-0.09317	-0.14193	-0.25567	0.04146
Plasticity index (organic)	0.89049	0.22548	-0.19889	-0.04913	0.22314

The resulting pattern is very similar to that in the previous analysis with winter moisture again showing a loading of 0.98. The soil depth variable has a slightly increased loading as have saturation level and apparent cohesion, the component accounts for 73.7% of the total variance and the loading with creep rate is again high. Component 2 is dominated by the loading for sine of the slope angle but the loading with creep rates is low.

Thus, despite the bias against the moisture factor introduced in preparing the matrix, the moisture component still emerges strongly as the most critical with regard to

variance in the data matrix and also as that with which creep rate is most highly correlated. This second principal components matrix of basin factors therefore confirms the stability of the relationships revealed by the first. This completes the data analysis.

13.3. Model Construction

To allow prediction and application and to facilitate greater comprehension, it is necessary to construct a mathematical model. This can be produced through multiple regression analysis for which the input is again a data matrix. With this technique it is possible to examine the linear relationship between the basin factors, which can be considered the independent variables, and annual creep rates, the dependent variable. As a result of the principal components analysis, the independent variables could be selected as those controlling creep while being approximately uncorrelated with each other. The dependent variable was chosen on instrumental and statistical grounds. The necessity for linearity has already been stressed. The aim is therefore to produce a linear combination of the basin factors which correlates as highly as possible with measured creep rates. The postulated model is:

dependent variable = linear function (set of independent
variables) +
stochastic error

$$\text{or } y_i = \alpha + \sum_{j=1}^k \beta_j x_{ij} + \epsilon_i$$

where y_i , $i=1, \dots, n$ is the dependent variable measured for each of n plots

x_{ij} , $i=1, \dots, n$; $j=1, \dots, k$ are independent variables, k in number, measured for n plots

the α and β_j 's are unknown parameters

ϵ_i , $i=1, \dots, n$ is the stochastic error consisting of any combination of:

- (a) measurement error
- (b) sampling error
- (c) other variables

In practice, the data, comprising measured dependent and independent variables, are available and it is therefore necessary to estimate the unknown parameters. This is usually done through least squares by varying the parameters and selecting those values which minimize the sum of squared differences.

$$S = \sum_{i=1}^n \left[y_i - \left(\alpha + \sum_{j=1}^k \beta_j x_{ij} \right) \right]^2$$

The estimates of the parameters can then be substituted in the equation

$$\text{est } y_i = a + \sum_{j=1}^k b_j x_{ij}$$

where a and b_j minimize S and the residuals are then given by:

$$\begin{aligned} \text{residual} &= \text{observed} - \text{estimated} \\ &= y_i - \left(a + \sum_{j=1}^k b_j x_{ij} \right), i=1, \dots, n \end{aligned}$$

By this means therefore the best prediction of creep rate can be made, the difference between the actual and the predicted rate being the residual. The residuals are thus estimates of the stochastic errors.

Clearly one problem in applying this technique to the present study is the comparatively large number of independent variables, although this was overcome in part by selection using the principal components analysis. To complete the process a variation in the basic analysis, stepwise multiple regression, was used so that the best possible prediction with the fewest independent variables could be obtained. By this means the equation is produced one variable at a time starting with the independent variable which is the single best predictor. This is followed by the selection of the second independent variable which, in conjunction with the first, provides the best prediction.

Thus at each step the best variable is selected bearing in mind the other variables in the equation so that the best overall result is achieved. The process is continued until no additional variable makes a major contribution. It must be stated that this procedure is not necessarily optimal (Moran, 1973). If the controlling variables are correlated with each other, there is the problem of multicollinearity. However in this study, attempts have been made to avoid both these difficulties by checking on the residuals and by using principal components analysis to indicate redundant variables.

For the stepwise multiple regression, eight basin variables were selected according to the principal components analysis loadings. The independent variable with the highest from each of the first eight components was chosen so that each cluster within the data was represented and the set was not weighted towards the moisture variables. By definition, creep was omitted as a variable and there was an implicit lower loading limit of 0.2. The regression of creep rate with the eight variables produced, at the first step, winter moisture which accounted for 74.2% of the total variance in the dependent variable. The equation is:

$$\text{creep} = 0.05472 + 0.02191 (\text{winter moisture})$$

At the second step, penetration was selected, accounting for a further 4.4% of the total variance. The next two steps produced the only other variables, accounting for a reasonably high percentage of the total variance, the four together accounting for 82.7% of the total variance in creep rate.

Table 13.13. Stepwise Multiple Regression: Variables and Percentage Variance

<u>Variable</u>	<u>% of Variance</u>
Winter moisture	74.2
Penetration	4.4
Bulk density (field capacity)	2.1
Unconfined compression	2.0
Water level	0.4

This gives a prediction equation of:

$$\text{creep} = 1.47203 + 0.01159 (\text{winter moisture}) - 0.16926 (\text{penetration}) - 0.41357 (\text{bulk density at field capacity}) + 0.70647 (\text{unconfined compression})$$

Before any summary of this final equation is made, it is important to examine the residuals.

A negative rule is that a model is not adequate if pattern is discernible in the residuals, but the converse may not be true (Nelder, 1972). Since they are assumed to reflect a number of sources already listed, the errors act in an unbiased random fashion. The main purpose therefore was to check on the adequacy of the model together with the realism of the assumptions made and to look for any further ideas. Since the first two variables contain such a high proportion of the total variance, it was decided to exclude these and to correlate the residuals with the remaining variables. For this the residuals from the equations were defined:

$$\text{Residual 1} = \text{creep rate} - 0.05472 - 0.02191 (\text{winter moisture})$$

$$\text{Residual 2} = \text{creep rate} - 0.99627 - 0.01393 (\text{winter moisture}) + 0.15415 (\text{penetration})$$

No pattern was discernible in the thirteen scattergrams produced (e.g. Fig. 13.19) and the highest correlation coefficient was: $r = -0.23$. Therefore it appears that no other major

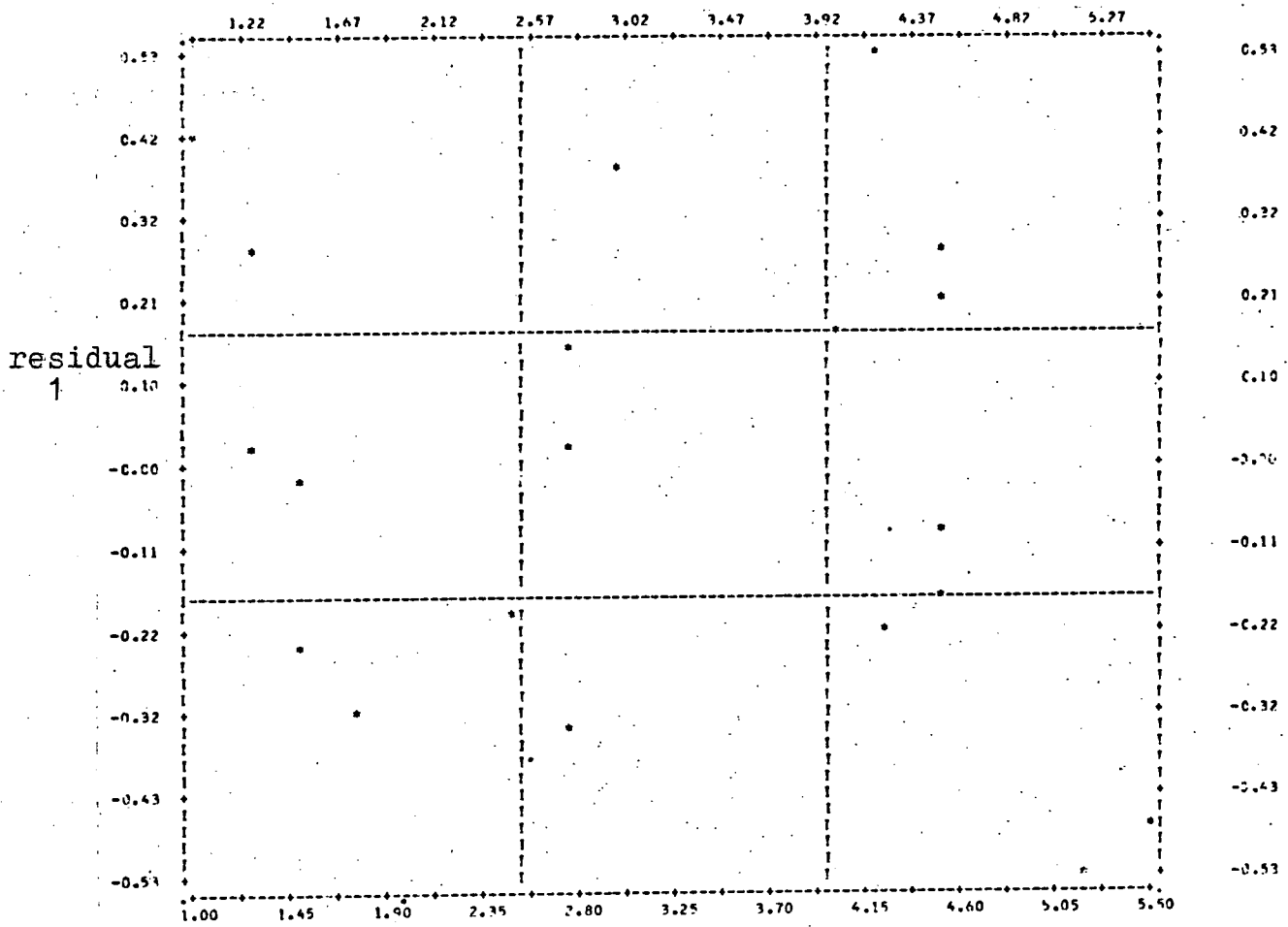


Fig. 13.19

Scattergram: Residual 1 and Penetration

variable is subsumed or masked by the residuals and bearing in mind the necessary assumptions and the possible problems discussed earlier, the final prediction equation can be considered optimum.

The model shows clearly the importance of winter moisture in predicting rates of creep while penetration was the resistance variable most highly negatively correlated with creep in the original first part of the analysis. These two account for the major share of the total variance. Thus the multiple regression reinforces the conclusion that creep rates vary positively with moisture conditions and negatively with resistance factors.

Thus although a large number of possible controls has been considered, the pattern finally emerging is relatively simple. The close interrelationships between a number of the variables constituting both the 'force' and the 'resistance' elements mean that while many factors are individually highly correlated with creep rates, it is still possible to produce a parsimonious statement of controls which has been confirmed both graphically and statistically. The importance of soil moisture established in this study agrees with the conclusions, empirical and theoretical, of Kirkby (1967, and oral communication). Other workers including Benedict (1970), Barr and Swanson, (1970) and Evans (1974) have also found that the soil moisture content can be related directly to the rate of creep.

In most cases this is viewed in the context of wetting and drying cycles. Conclusions have been drawn elsewhere about these (Chapters 5 and 6), and it must be stressed that, as a result of this study, soil moisture is seen as crucial to the process both absolutely and as a prerequisite for meteorological cycles. This therefore necessitated a re-consideration of the probable mechanism described (Chapter 1), and this appears in the next chapter. Finally, the importance of the resistance factors, particularly the measures of shear strength, in inhibiting soil creep should be mentioned, especially as there is little other evidence available on this aspect.

CHAPTER FOURTEEN

SUMMARY, MECHANISM AND PROSPECT

- 14.1 Summary
- 14.2 Mechanism
- 14.3 Prospect

14. SUMMARY, MECHANISM AND PROSPECT

14.1. Summary

Results from the supporting sites indicated that soil movement and soil moisture are directly related. Aspect is important with north-facing slopes recording creep rates approximately twice as large as those on south-facing slopes. Similarly immature soils were shown to be highly responsive, with soil movement twice as rapid as on neighbouring mature slopes. It was also shown that to provide the most realistic assessment of rates, measuring instruments should be inserted to a depth of 15cm.

The pilot study confirmed the findings on aspect and immature soils, but more crucial were the readings showing a relationship between creep rates and the assemblage of variables distinguished by the three main vegetation groups. In each case movement was found to be greatest under Juncus and least under Pteridium. The boundary pegs later indicated a possible separation of soil factors and vegetation factors. Other supplementary studies of velocity profiles showed that maximum rates of creep occur at approximately 2.5cm below the root mat.

The laboratory programme demonstrated a definite, if qualitative, relationship between soil movement and the two cycles, wetting and drying and freeze-thaw. It also showed that movement was twice as rapid in organic as in mineral soils. A further important conclusion was that daily movement, frequently as high as 0.5mm, was large compared with the rate of mean annual creep.

From daily readings obtained from the plot at Brandon, it could be concluded that the basic pattern of soil movement is regular, although the daily movement on bare soils is twice that on vegetated sites, which averages 0.5mm. The relationship between creep rates and meteorological controls was clearly demonstrated, being more obvious with wetting and drying than with freeze-thaw cycles. Finally, the time lag involved before meteorological changes produce an effect was established as ranging from approximately three hours to two days. In none of these studies was a relationship between rates of creep and slope angle or position on the slope demonstrated.

Annual linear rates of soil creep measured on the twenty main study plots within the Rookhope basin varied

from 0.3mm to 2.4mm, values which accord well with those published by other workers for similar environments. The lowest rates were on plots distinguished by Pteridium, while the highest occurred on Juncus plots. Furthermore the internal-plot differences recorded by the six different monitoring instruments were small. Bearing in mind the relative advantages of the devices, it can be concluded that to assess soil creep accurately, more than one instrument is required.

Using results from the Rookhope basin and the supporting studies, an assessment of the variables controlling creep rates could be made. Clearly there is a close relationship, demonstrated with both daily and seasonal readings, between wetting and drying cycles and creep. Wetting produces a tendency to downslope and drying to upslope movement. The effects of freeze-thaw are not so clear. High positive correlations were found between linear creep rate and soil moisture (winter), plasticity index, field capacity, linear shrinkage and percentage of organic matter. These may be considered 'force' factors. In contrast, high negative correlations were recorded with bulk density, penetration and angle of internal friction. These provide the resistance to movement. No relationship was found between linear creep rates and slope angle or distance from the watershed.

The importance of these major plot controls was further confirmed by principal components analysis. The first component, accounting for 79.6% of the total variance could, from the high positive loadings, be considered basically a 'moisture' component. A second such analysis, from which a number of variables closely related to moisture had been eliminated, confirmed the stability of this relationship.

Finally, by multiple regression analysis, a prediction equation was produced reinforcing the fact that creep rates vary positively with winter moisture and negatively with a major resistance factor, penetration. In this, winter moisture accounted for 74.2% of the total variance in the dependent variable, soil creep.

14.2. The Mechanism of Creep

Having drawn conclusions on the importance of the controlling variables, it is possible to speculate on the

mechanism of soil creep. As described earlier, the mechanism consists essentially of two parts: expansion and downslope movement. This distinction of convenience has been illustrated by the daily readings. Expansion clearly depends upon the moisture state of the soil and the importance of this factor has been confirmed by the correlations and the principal components analysis. This is in turn governed by a number of soil variables, notably the field capacity and the amount of organic matter present. As a result of changing moisture content, expansion and shrinkage occur. Opposing expansion is the bulk density of the soil, apparent cohesion and, to a degree, shear strength. This pattern accords with the analysis results except for the anomalous position of apparent cohesion, which has already been discussed.

However, as stressed by Kojan (1967), movement cannot occur only as a result of expansion, since there must also be shearing. Expansion from either meteorological cycle will lower shear strength by increasing the void ratio and thereby reducing cohesion (Embleton and King, 1968). If no actual shearing occurs, particles will return along the reciprocal path and may finish upslope of their original position. This retrograde movement, recognised in frost creep by French (1976) and Benedict (1976) has been demonstrated by the daily plot measurements at Brandon. Thus it can be concluded that rather than a sharp 'ratchet' like movement, the path of particles will be distended in a downslope direction during the period of maximum expansion. The movement must therefore appear more as an inverted 'U' than an inverted 'V' (Kojan, 1967). The positive relationship between creep and the incidence of meteorological cycles would be expected according to the probable mechanism described by Kirkby (1967). When the high positive correlation between the movement and soil moisture is also taken into account, the modified mechanism suggested by Kojan on theoretical grounds seems more appropriate.

Downslope movement under the influence of gravity is facilitated by the plasticity of the soil and its depth. The main resisting force is the strength of the soil, measured in a number of ways in the drainage basin.

14.3 Prospect

As, with minor boundary adjustments, rates of soil creep have been related to a complex of factors indicated by vegetation community, they can be rapidly mapped. It should be possible, for example, to map areas of varying slope mobility from aerial photographs of Upper Weardale. These results could then be related to measured rates of fluvial erosion to produce a dynamic picture of landscape wastage for a geomorphological unit (Caine, 1976). The current trend is to consider the interrelationship between slope form and process, but results from this study change the emphasis to that of the slope system as a whole with its component hydrological and ecological subsystems. However, as the creep rates measured in this study refer to one specific year of measurement they can only be regarded as accurate for comparative rather than absolute purposes. Therefore it would still be necessary to maintain a number of plots to check actual movement. This would allow a co-ordinated design for the area (Leopold, 1970) which could include monitoring fluvial and other processes.

As a result, the scale of investigation would be increased from that of a single local unit, such as a slope or stream reach, to that of a 'landscape'. A global integration (Thom, 1975) such as this, even for a comparatively small landscape such as that of Upper Weardale, would therefore facilitate more detailed and scientific description. It is certainly on this meso-scale that theoretical geomorphology is weakest (Chorley, oral communication).

The study could be further extended by measurements in areas of greater aridity and greater freeze-thaw activity. At the extremes, work on frost creep and measurements made in semi-arid environments have both been mentioned. It is the transition zones within the humid cool temperate region which have been largely neglected. If such results were available, the relative importance of the main meteorological cycles could be better assessed. Readings are also required for rates of soil creep on land which is dominated by the activities of man. For example, the

effects on land wastage through soil creep of treading, ploughing and cultivation together with changing land use in urban areas, are little known.

With regard to techniques, there would seem to be scope for further adaptation of soil mechanics procedures. As discussed earlier, for use in geomorphology, instruments should be ideally, portable while retaining an acceptable level of precision. It is important that rapid sampling in the field should be possible so that changes with environmental variations can be monitored. For example, a small triaxial shear tester for on-site investigations has been developed and is currently being tested in Cambridge University. This would increase the range of materials which could be investigated and would facilitate the study of related mass movement processes.

As a result of such developments, it should be possible to approach a more realistic assessment of the resistance of surface materials to erosional processes. However, the importance of relating field area, plot and laboratory results must still be stressed. It is necessary to examine resistance as a factor on the micro-scale (Kojan, 1967) and this is likely to be a laboratory-based programme. However it is realised that such a study would be very near the boundary of what is generally accepted as geomorphology.

Finally, the effects of time require further investigation. The time interval over which many of the environmental factors change is still largely conjectural. For example, with neighbouring areas exhibiting different rates of soil movement, soil depth must change, but the time required for such a response to occur is not known. Therefore it is necessary to establish a very long term programme of field measurements during which certain selected plots are monitored, possibly at intervals of years, but in detail. The ideal instrument for this would seem to be Anderson's Tube, which not only allows measurement at varying time intervals but also records bodily movement. This device has its own fixed base which could be used to measure total movement of a second instrument recording a depth profile.

Thus it can be seen that, in the broader spectrum of geomorphological theory, there are a number of ideas for future investigation suggested by this study, involving basically measurement, scale and time. A more realistic appraisal of 'resistance' would have general application in process studies, while an enlargement of scale over space and time would allow the development of more comprehensive and scientific theory.

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APPENDIX 1

SPECIFICATION OF THE ANDERSON INCLINOMETER

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SPECIFICATION OF THE ANDERSON INCLINOMETER

The vital measurements in the construction of the instruments are underlined, the remainder could be altered slightly without any loss of performance. The letters in the text following coincide with those on the diagram (Fig.3.1)

The Head

A. The upper limb is made of 1.9cm angle aluminium alloy and is 18.4cm long.

The parts of this limb are:

- (1) The spirit level tube mounted centrally over the pivot bolt on two 'Terry' clips.
- (2) The guard of 0.3cm perspex bent over to protect the spirit level.
- (3) A brass block of 1.2cm square cross section and length 2.9cm to receive the measuring thread. This block overlays the aluminium by 1.8cm.
- (4) The brass measuring thread of length 8.5cm and pitch 1mm. This thread fits through a threaded hole cut into the overlapping part of the block (3) and rests on the base of the lower limb (B).

NOTE The centre of the hole is exactly 10cm from the pivot bolt.

- (5) A 7cm diameter circular scale calibrated 1 to 100. The scale is mounted between two plates of 0.3cm perspex. The zero point for the scale is marked on the guard (2) above the centre line of the spirit level.
- (6) A knurled knob of diameter 2.5cm to turn the measuring thread.
- (7) The brass pivot block, 2.5cm square and 1.2cm thick. This thickness allows good clearance when the block is fitted into the lower limb.

- (8) The pivot bolt, drive fitted in the centre 1.9cm from the top of the pivot block (7). The ends of the bolt fit through holes drilled centrally 0.5cm from the top edge on either side of the lower limb (B). Washers are fitted on the bolt each side of the pivot block and nuts are tightened on either end of the bolt where it protrudes through the aluminium. This checks any lateral movement of the upper limb.

B. The lower limb is made of two pieces of 1.9cm angle aluminium alloy 21cm long and bolted together to form a trough. The parts of this limb are:

- (9) A retaining spring to maintain pressure on the measuring thread.

NOTE When the inclinometer is level there is 1.4cm clearance between the base of the upper limb and the top edge of the lower limb. The level position is indicated by lines etched on each side of the pivot block (8) which should coincide exactly with the upper edge of the lower limb.

- (10) The vertical indicator pin for accurately positioning the head above the direction card.
- (11) The upper part of the brass rotating joint which fits into the collar on the base. The joint is fitted centrally and is of diameter 3.8cm and length 3.1cm. The protruding part, made to be a running fit in the collar is of diameter 1.6cm and length 2.2cm.

The Base

C, The base plate is made of a piece of 3.8cm angle aluminium alloy 7.6cm long. The parts of this plate are:

- (12) The brass collar into which the joint (11) fits. It is the same diameter as the joint, 2.2cm long and machined to take the protruding part of the joint in a running fit.
- (13) A locking rod of diameter 7cm and length 9.1cm. The lower 1.5cm of the rod is threaded, fitting into a threaded hole in the brass collar (12) to lock the inclinometer head in a required direction.
- (14) The 17.1cm diameter direction card calibrated 0 to 360. The card is mounted between two plates of 0.3cm perspex.

D. The peg housing is fitted vertically under the base plate. The parts of the housing are:

- (15) The fixed section of the housing is made of two 3cm lengths of 1.3cm angle brass fitted round one end of a 7.5cm length of 1.3cm square wood. This end is bolted vertically under the centre of the base plate.
- (16) The adjustable section of the housing consists of two 10.5cm lengths of 1.3cm angle brass fixed by two bolts round the lower 4cm of the wood. The 6.5cm of angle brass extending below the wood forms a square for receiving the heads of the pegs.

NOTE The size of this square can be adjusted by slackening or tightening the two bolts.

APPENDIX 2

BRANDON PLOT: PEG MOVEMENTS

- Fig. A2.1 Earth Peg 1 Series 2
- Fig. A2.2 Earth Peg 1 Series 3
- Fig. A2.3 Earth Peg 2 Series 1
- Fig. A2.4 Earth Peg 2 Series 3
- Fig. A2.5 Grass Peg 1 Series 2
- Fig. A2.6 Grass Peg 1 Series 3
- Fig. A2.7 Grass Peg 2 Series 1
- Fig. A2.8 Grass Peg 2 Series 3
- Fig. A2.9 Control Peg Series 1
- Fig. A2.10 Control Peg Series 2

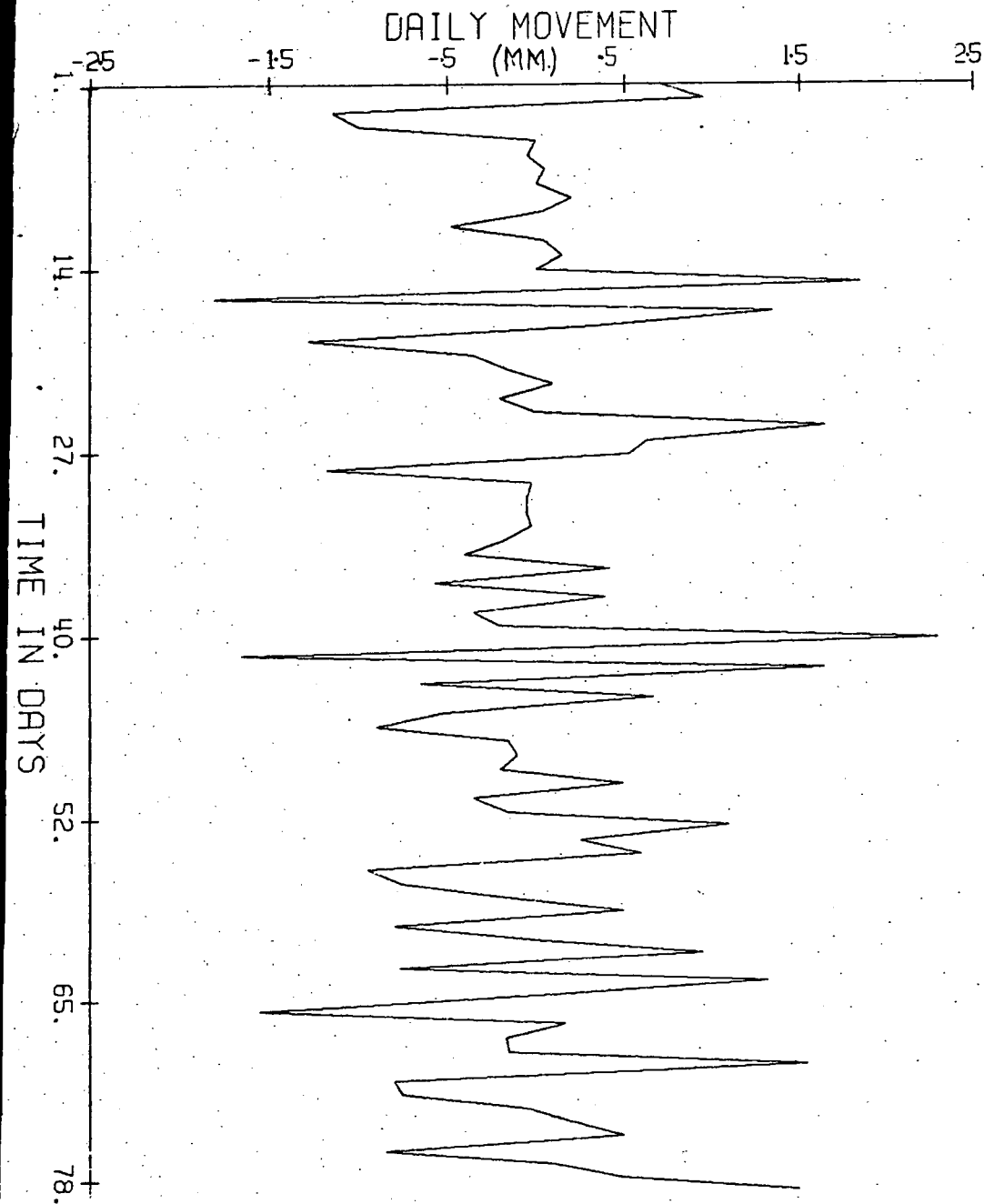


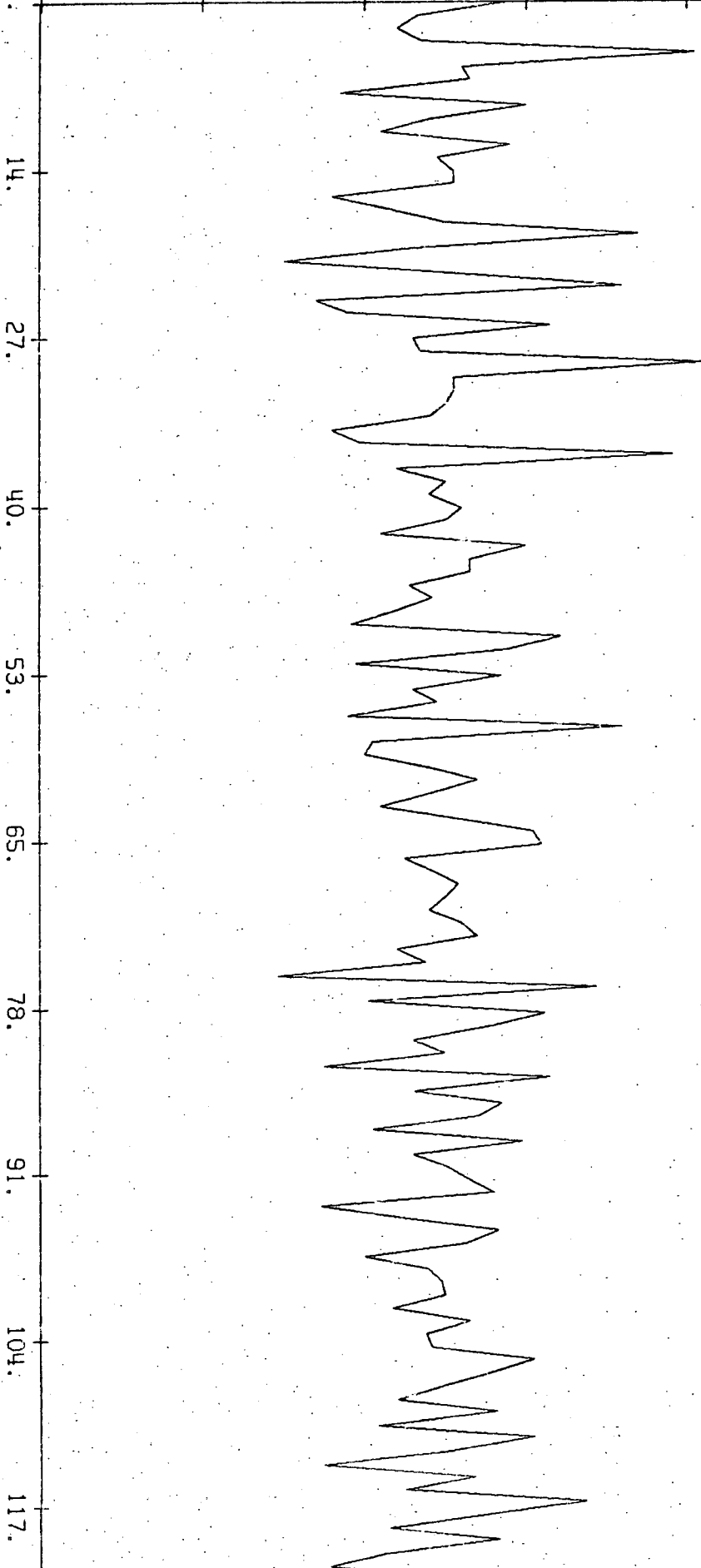
Fig.A2.1

Brandon Plot: Peg Movements
Earth Peg 1 Series 2

559

DAILY MOVEMENT
(MM.)

-25 -15 -5 5 15 25



TIME IN DAYS

Fig. A2.2 Brandon Plot; Peg Movements Earth Peg 1 Series 3

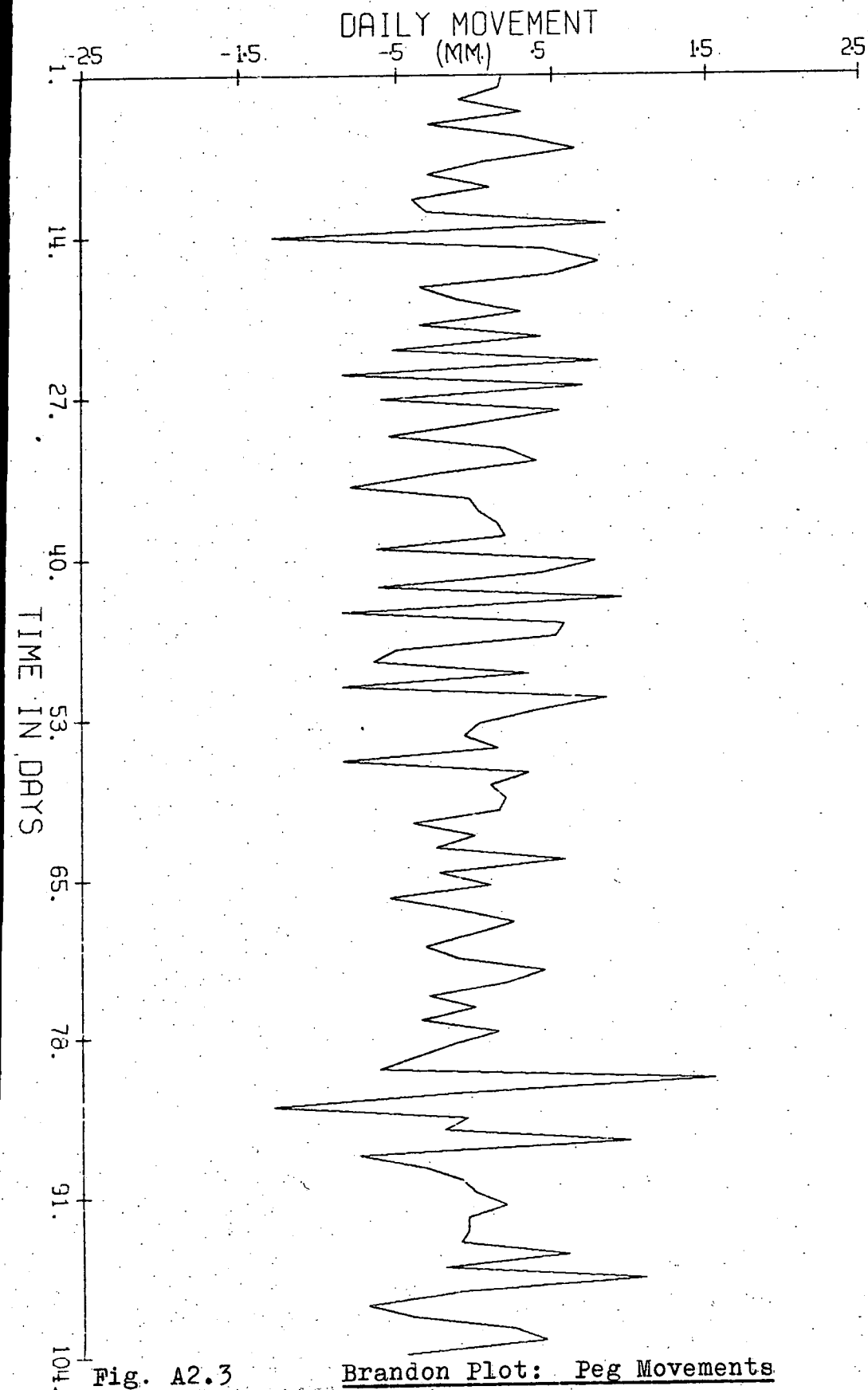


Fig. A2.3

Brandon Plot: Peg Movements
Earth Peg 2 Series 1

561

DAILY MOVEMENT
(MM.)

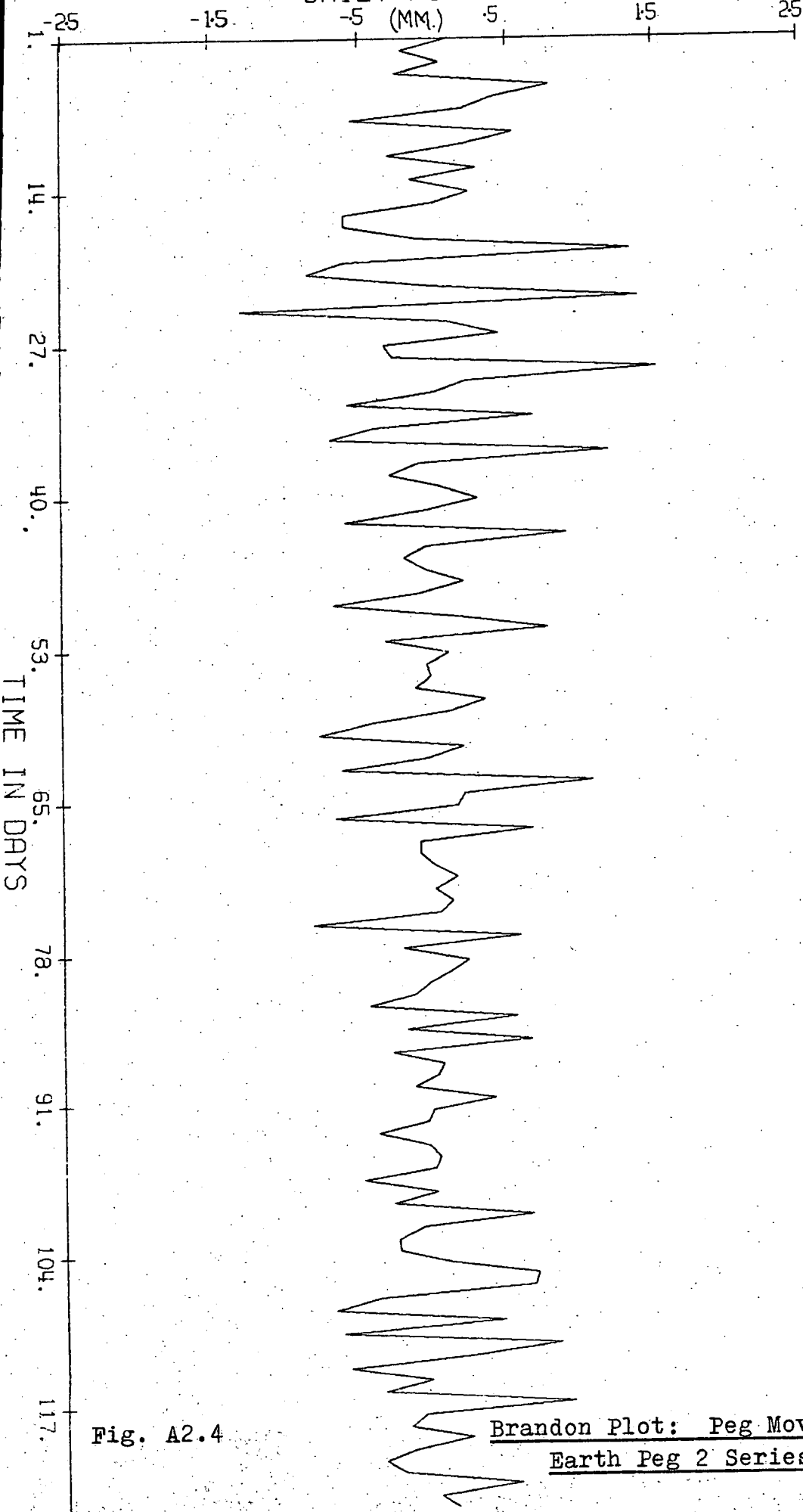


Fig. A2.4

Brandon Plot: Peg Movements
Earth Peg 2 Series 3

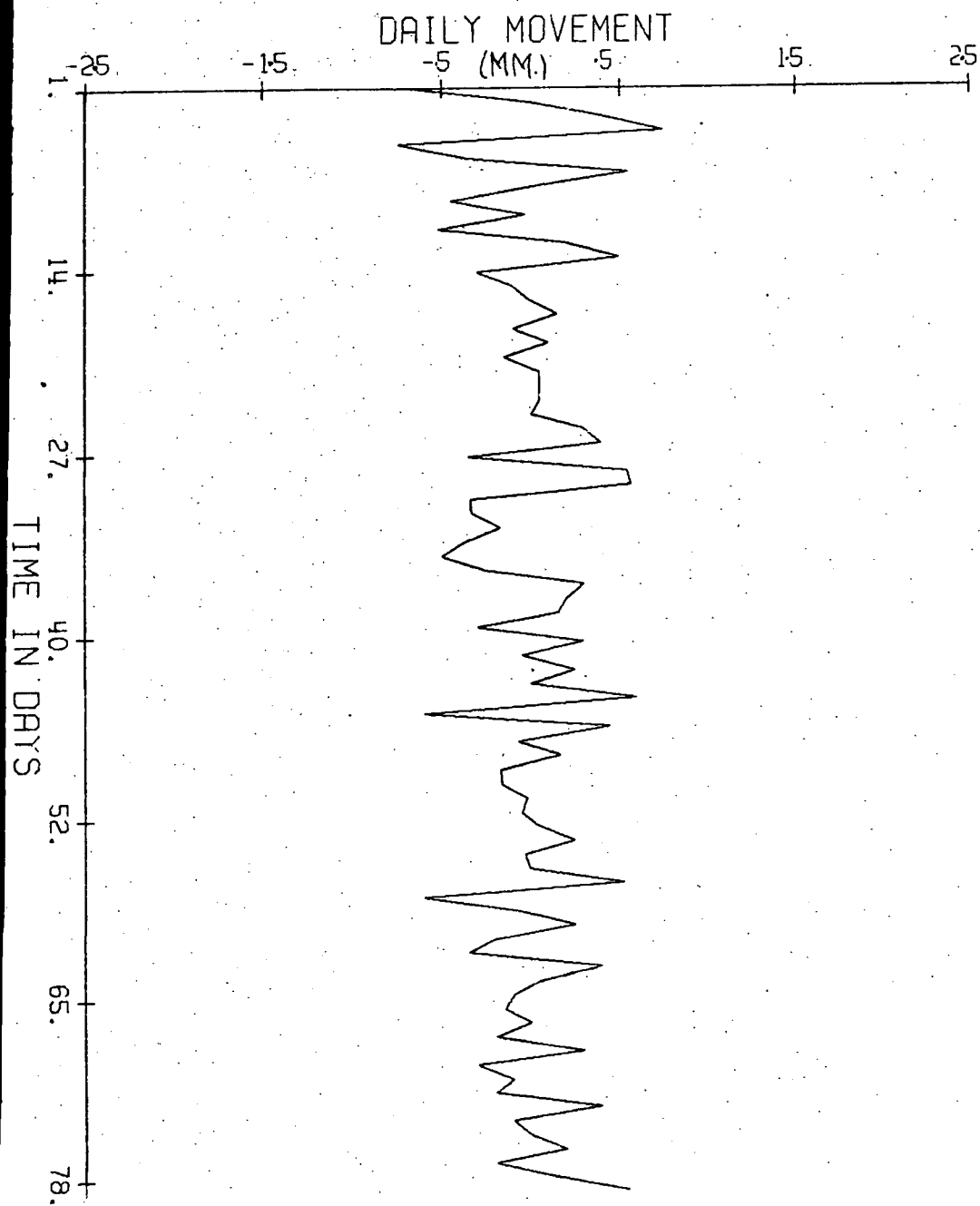


Fig. A2.5

Brandon Plot: Peg Movements
Grass Peg 1 Series 2

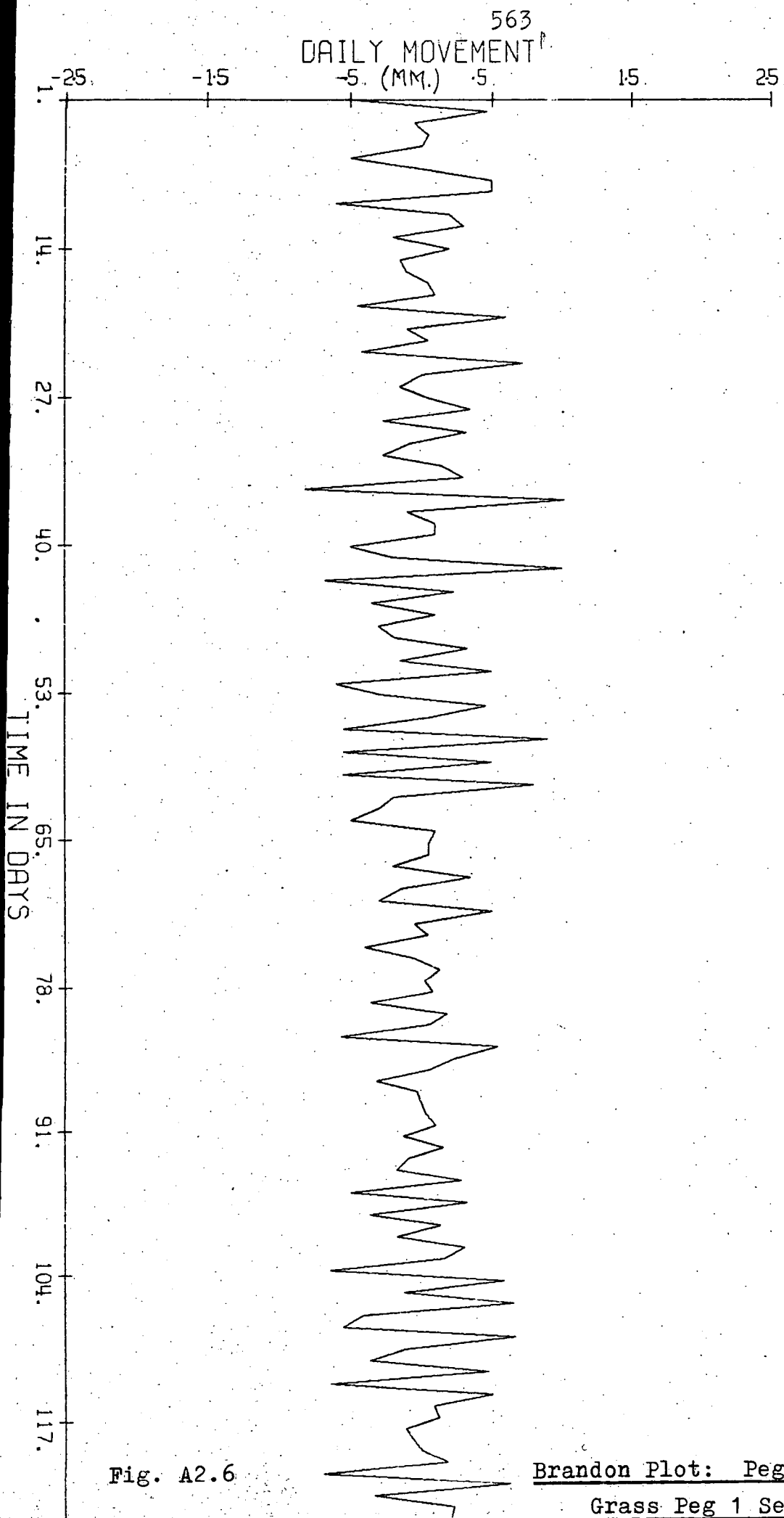
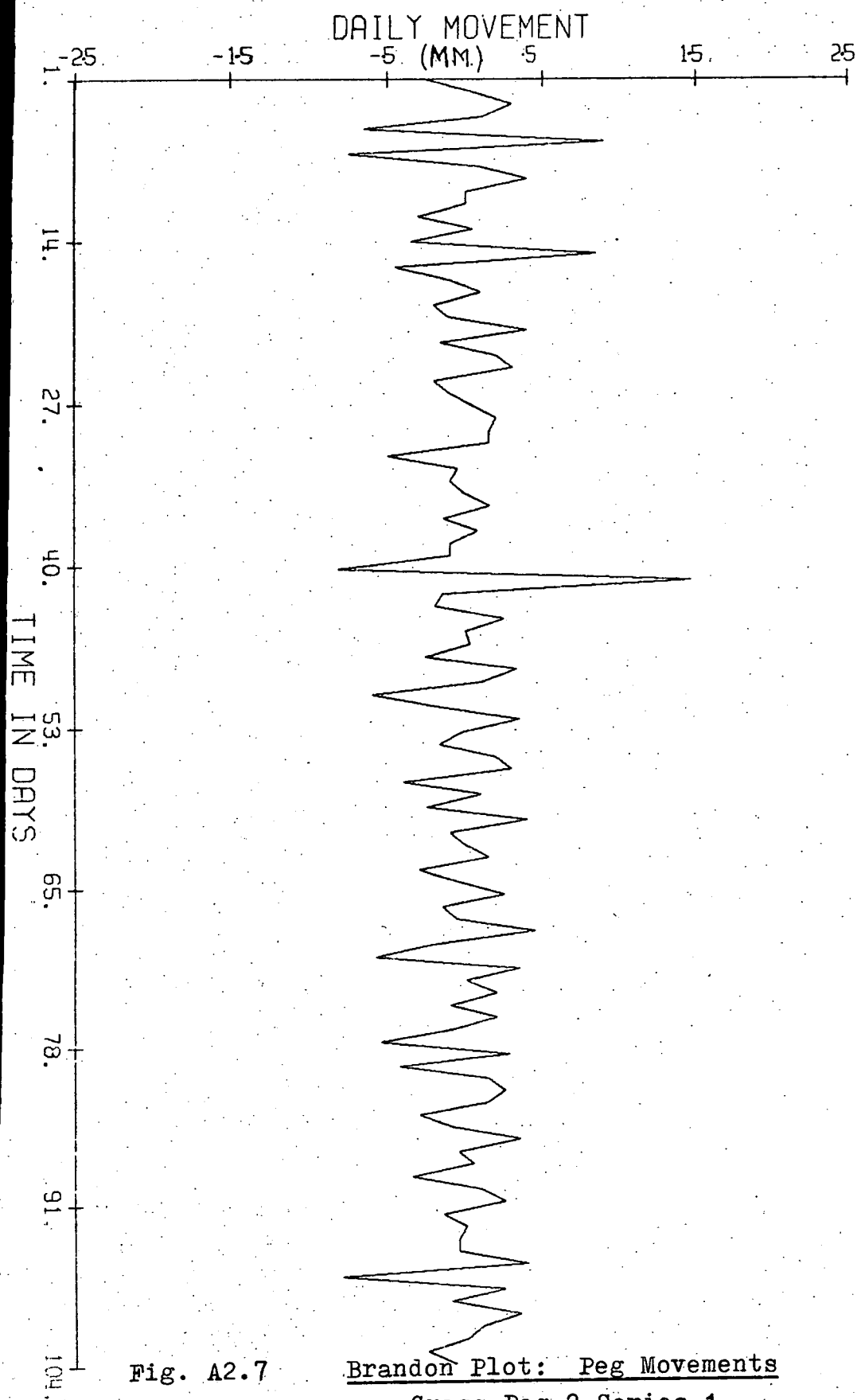
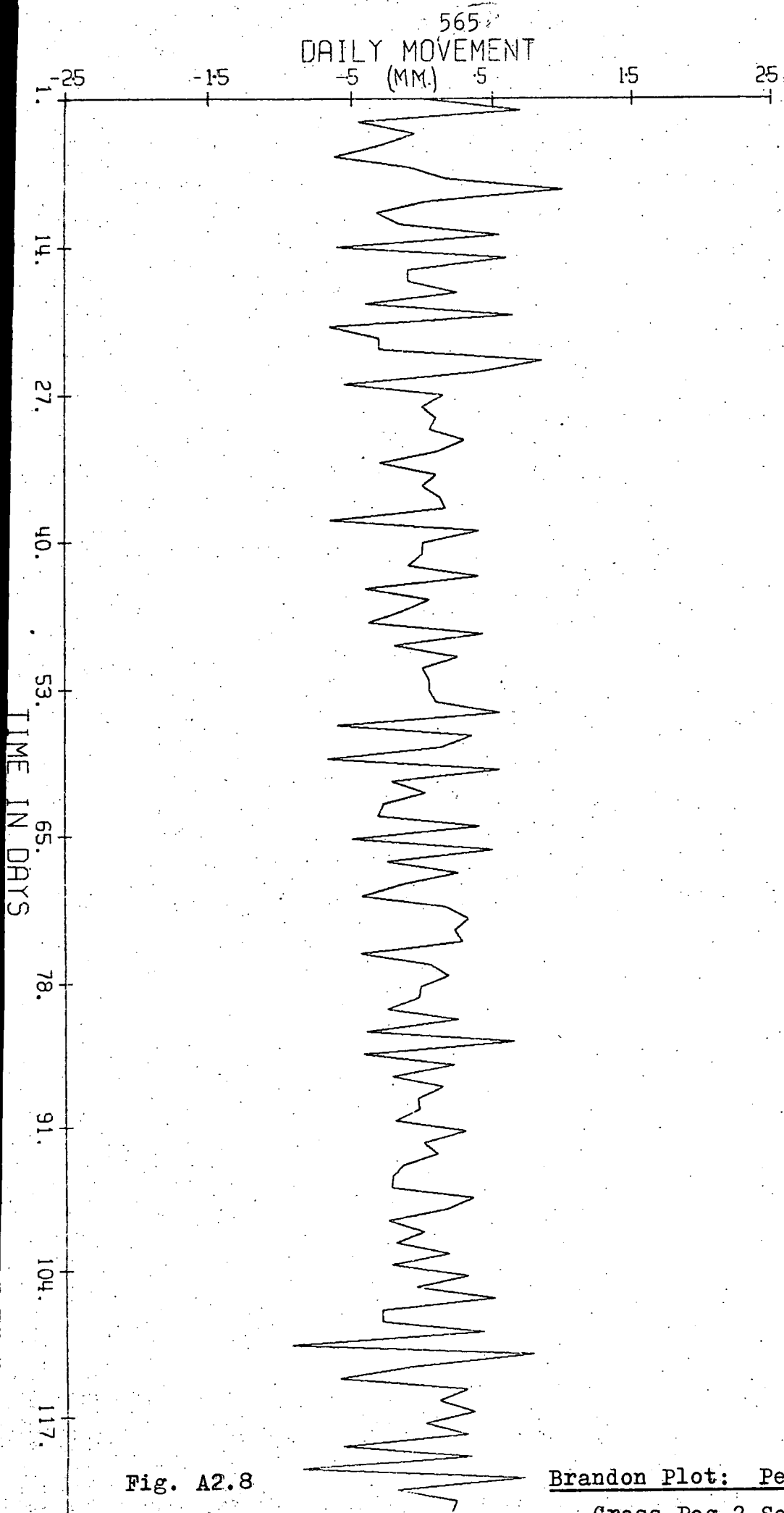


Fig. A2.6

Brandon Plot: Peg Movements
Grass Peg 1 Series 3





Brandon Plot: Peg Movements
Grass Peg 2 Series 3

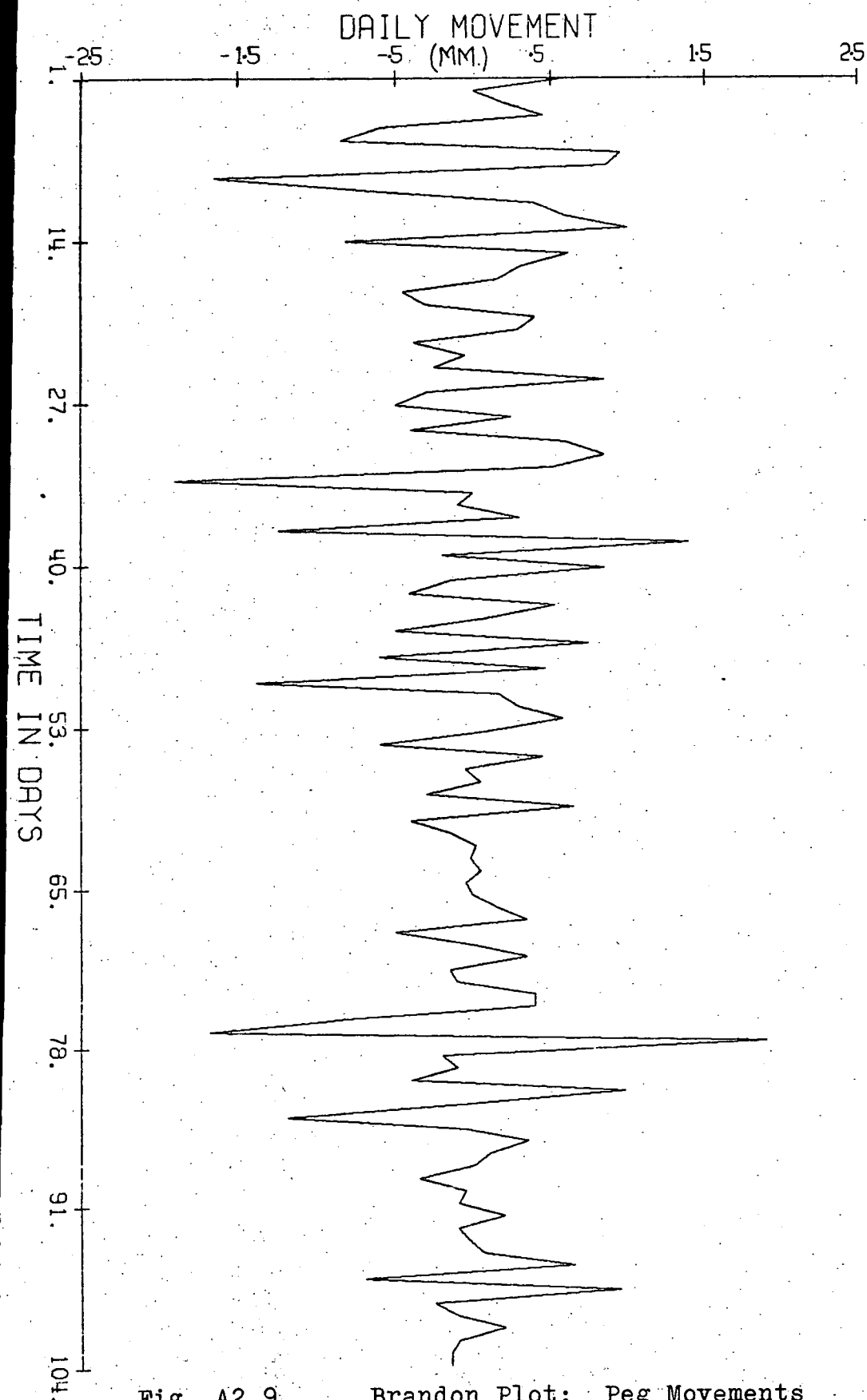


Fig. A2.9

Brandon Plot: Peg Movements
Control Peg Series 1

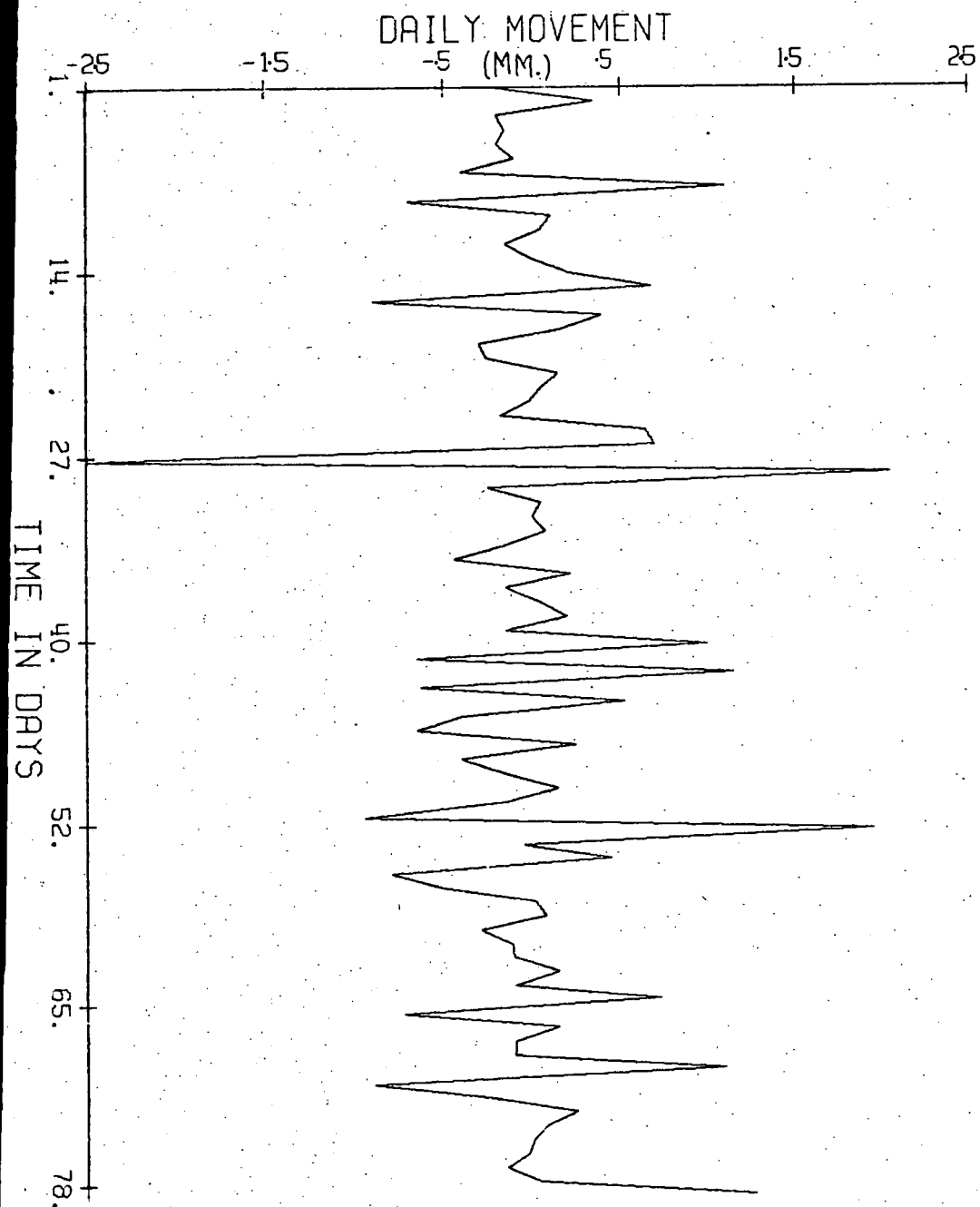


Fig. A2.10

Brandon Plot: Peg Movements
Control Peg Series 2

APPENDIX 3

ROOKHOPE PLOTS: PEG MOVEMENTS

- Fig. A3.1 Plot 4
- Fig. A3.2 Plot 5
- Fig. A3.3 Plot 6
- Fig. A3.4 Plot 7
- Fig. A3.5 Plot 8
- Fig. A3.6 Plot 9
- Fig. A3.7 Plot 10
- Fig. A3.8 Plot 11
- Fig. A3.9 Plot 12
- Fig. A3.10 Plot 13
- Fig. A3.11 Plot 14
- Fig. A3.12 Plot 15
- Fig. A3.13 Plot 16
- Fig. A3.14 Plot 17
- Fig. A3.15 Plot 18
- Fig. A3.16 Plot 19
- Fig. A3.17 Plot 20

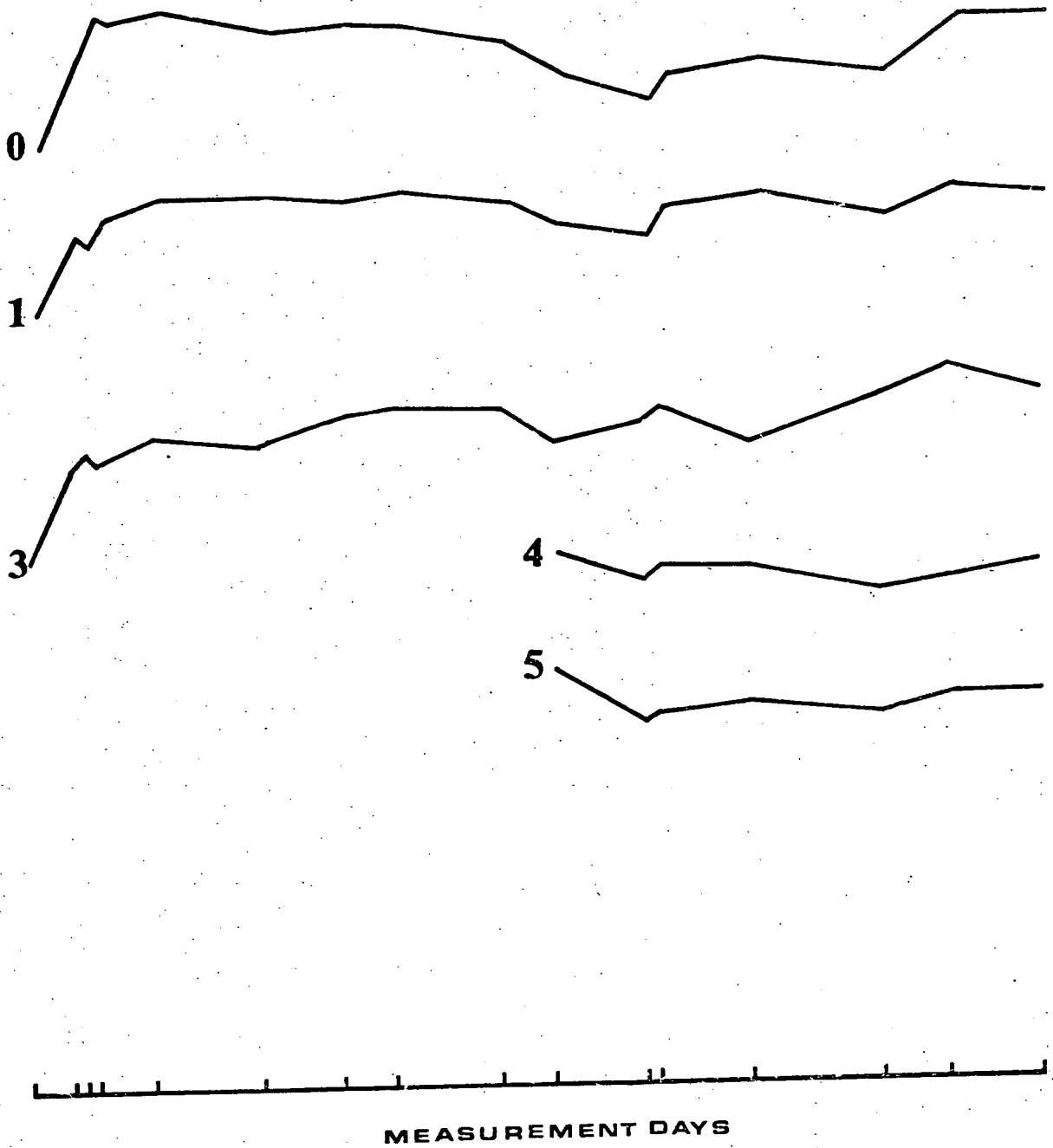
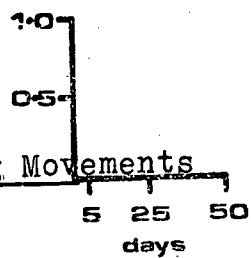


Fig. A3.1

Rookhope Plots: Peg Movements
Plot 4



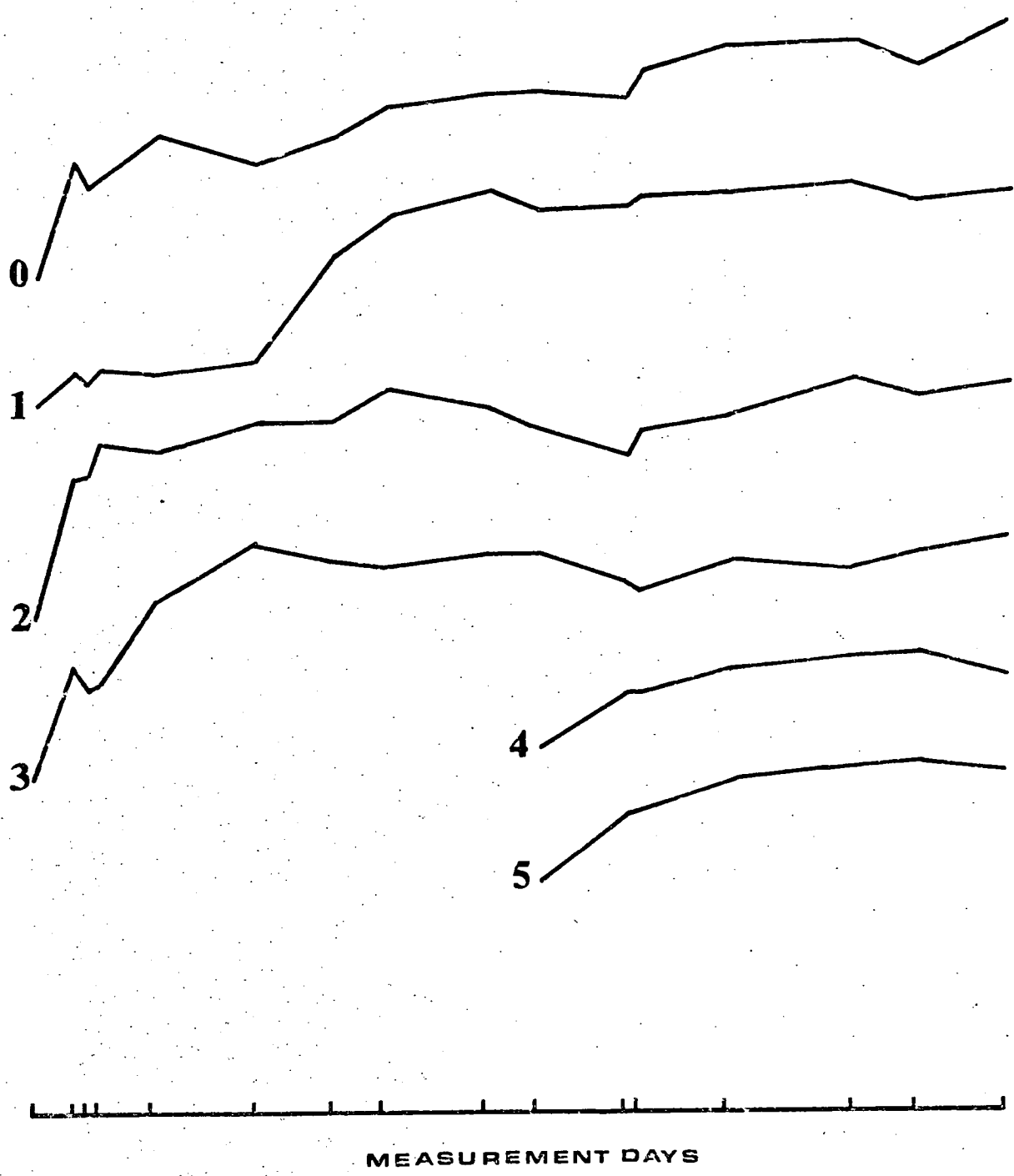


Fig. A3.2 Rookhope Plots: Peg Movements
Plot 5

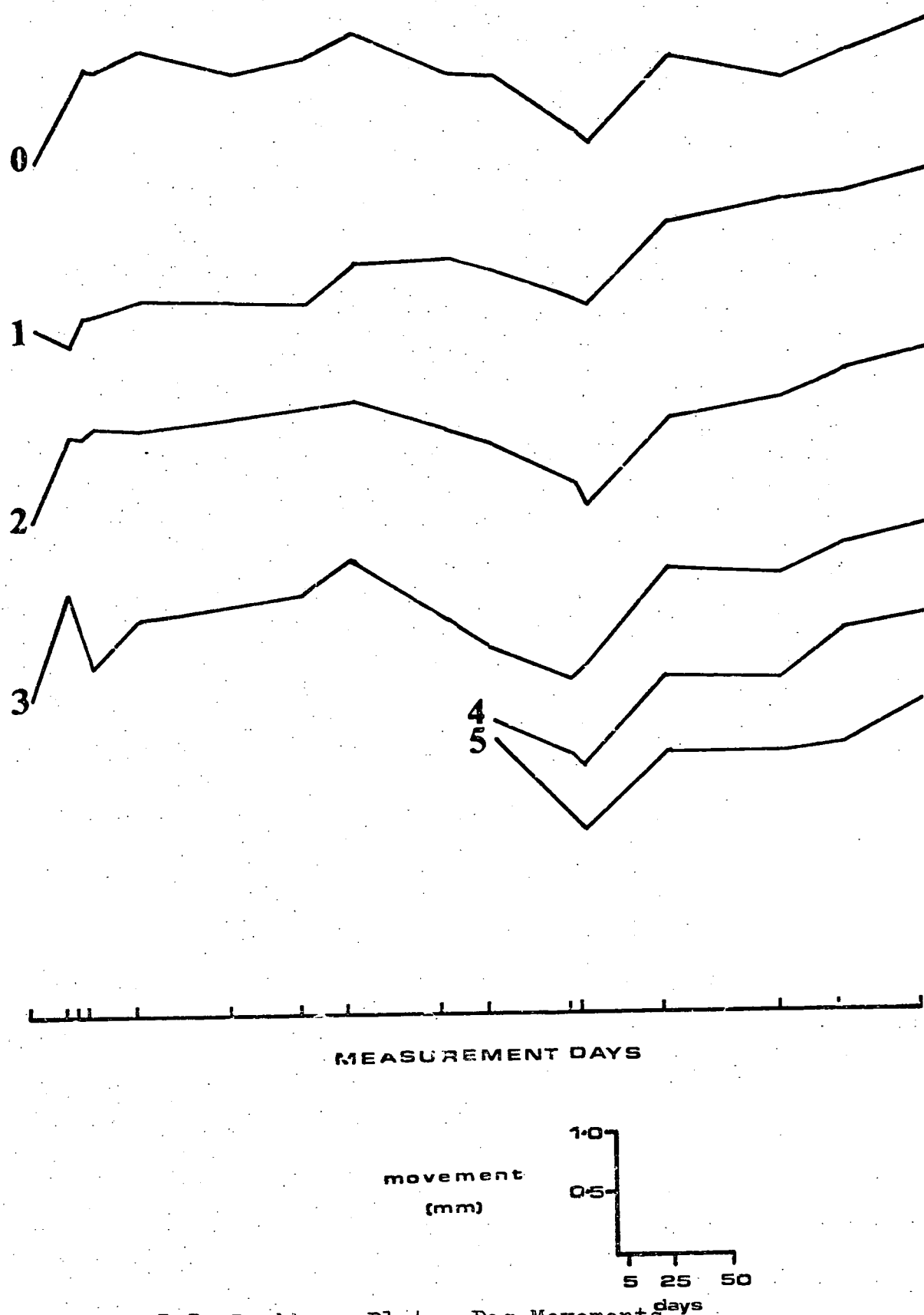


Fig. A3.3 Rookhope Plots: Peg Movements
Plot 6

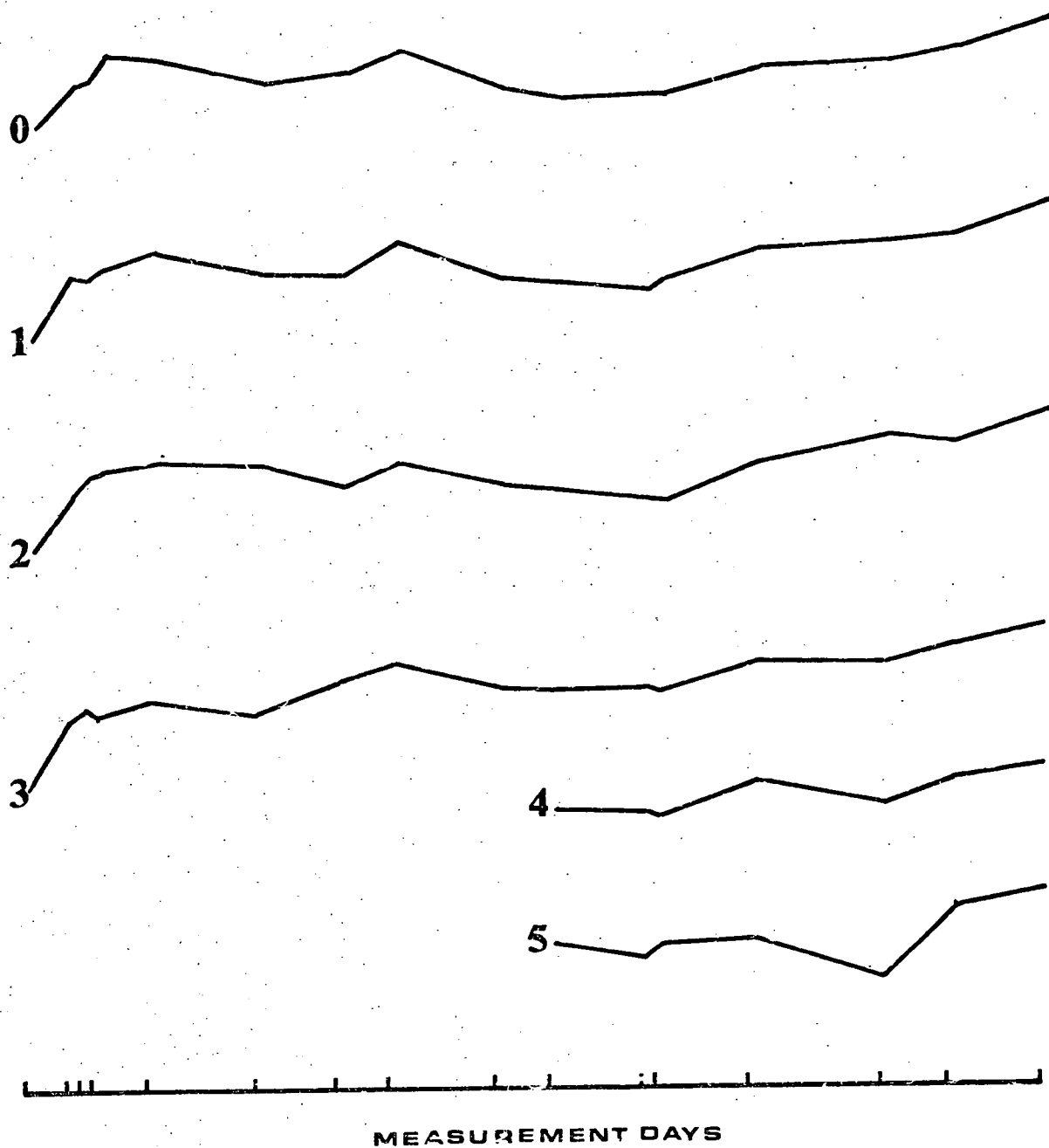


Fig. A3.4 Rookhope Plots: Peg Movements
Plot 7

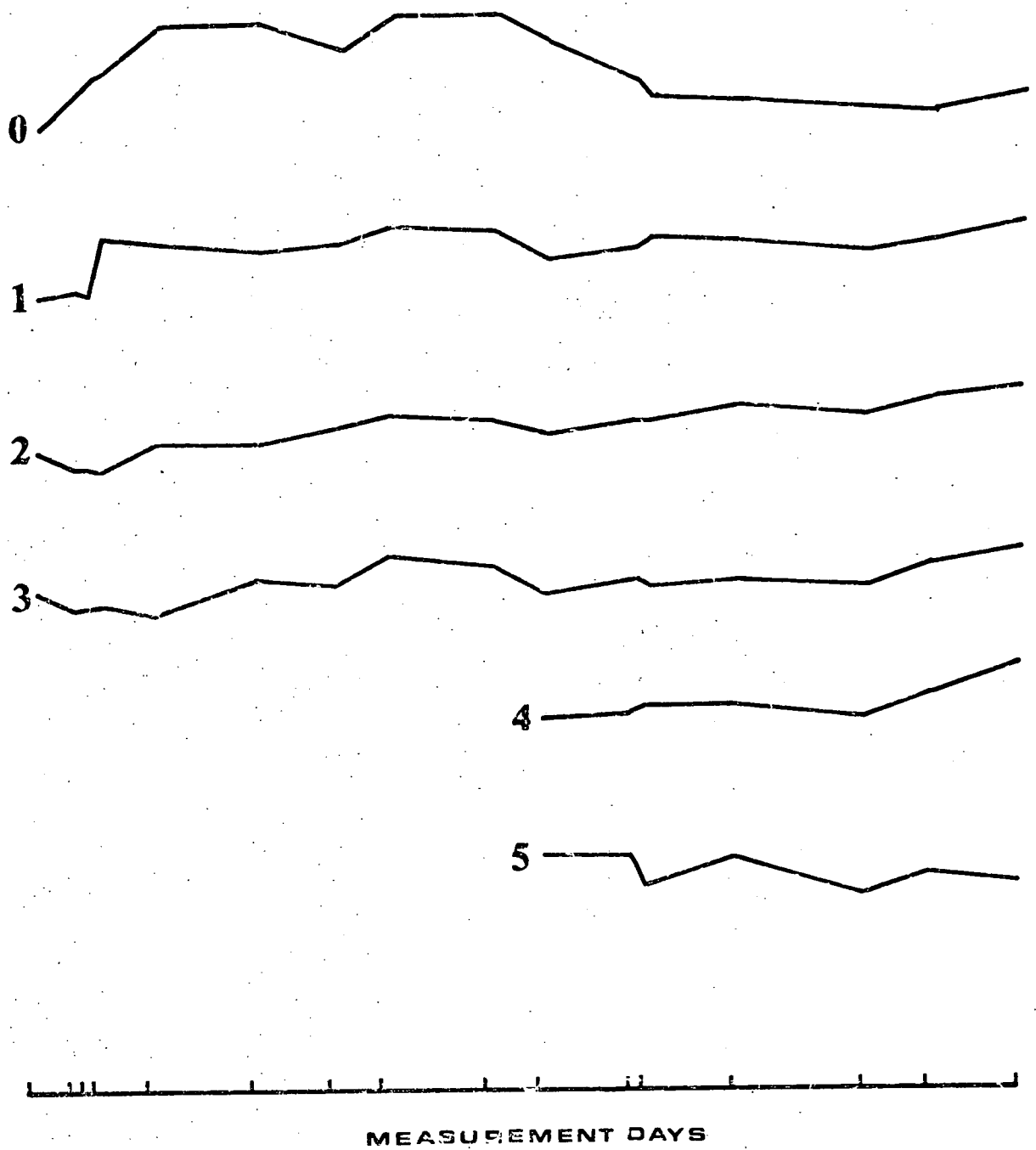


Fig. A3.5 Rookhope Plots: Peg Movements
Plot 8

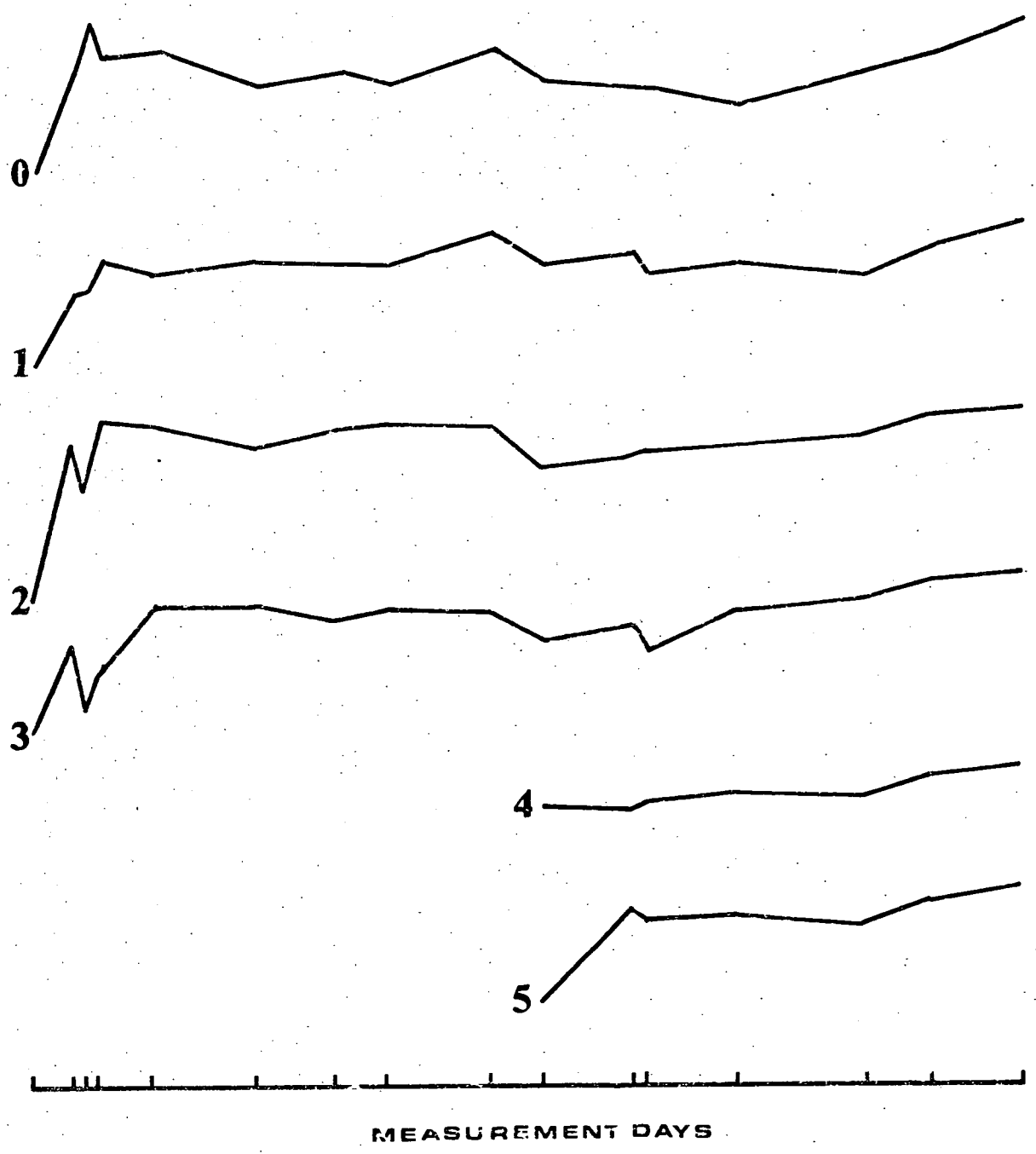


Fig. A3.6 Rookhope Plots: Peg Movements
Plot 9

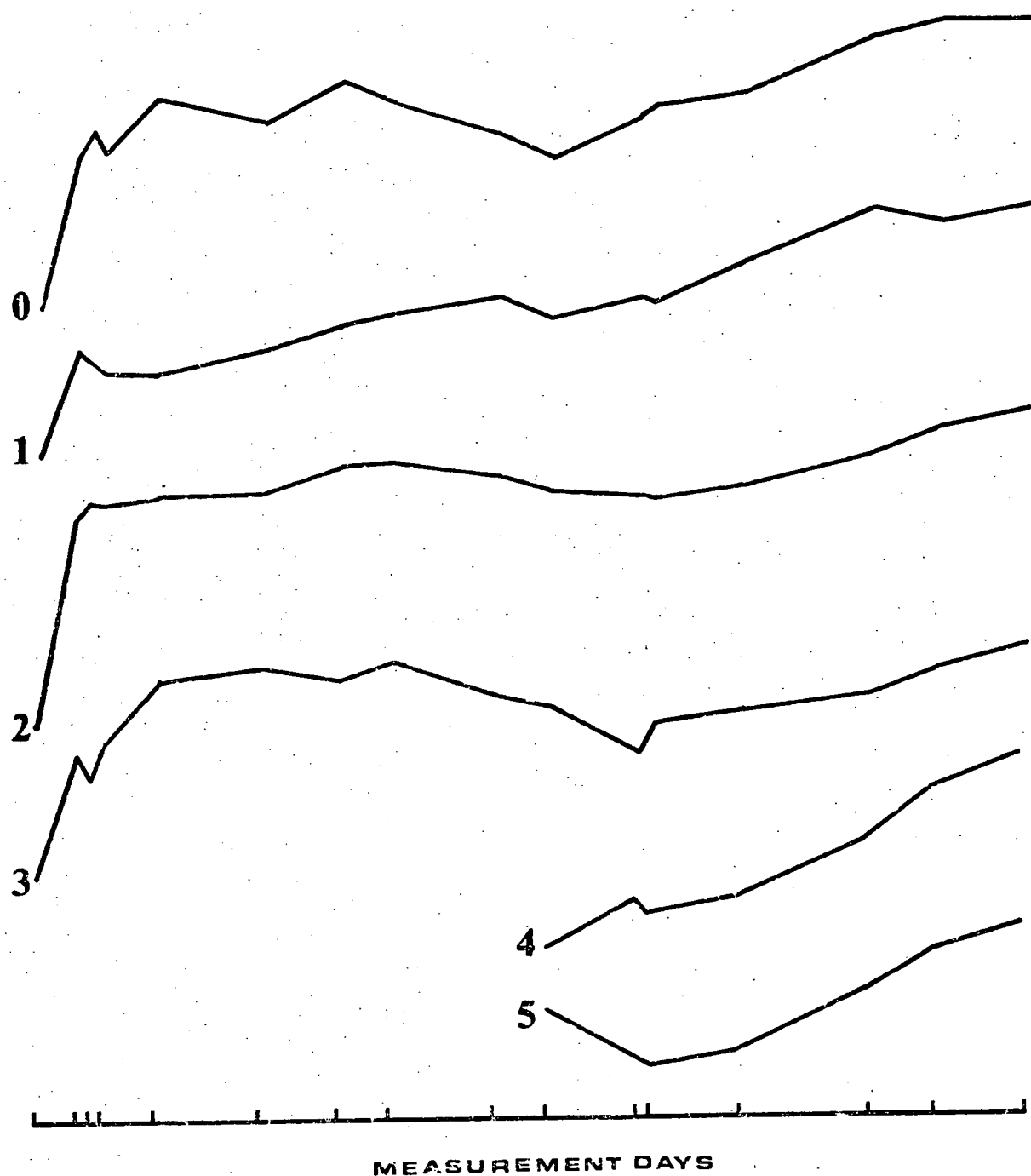


Fig. A3.7 Rookhope Plots: Peg Movements
Plot 10

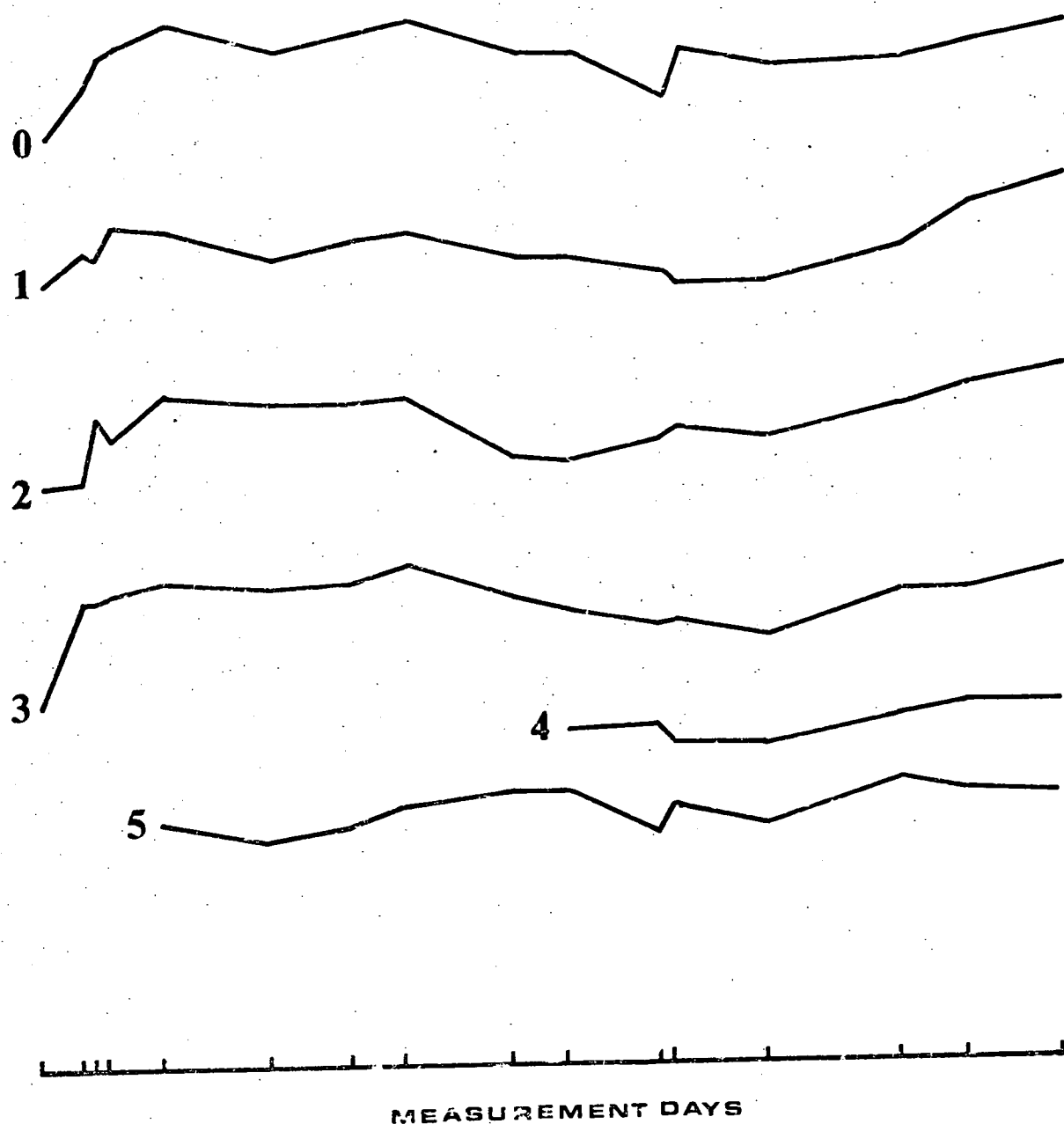


Fig. A3.8 Rookhope Plots: Peg Movements
Plot 11

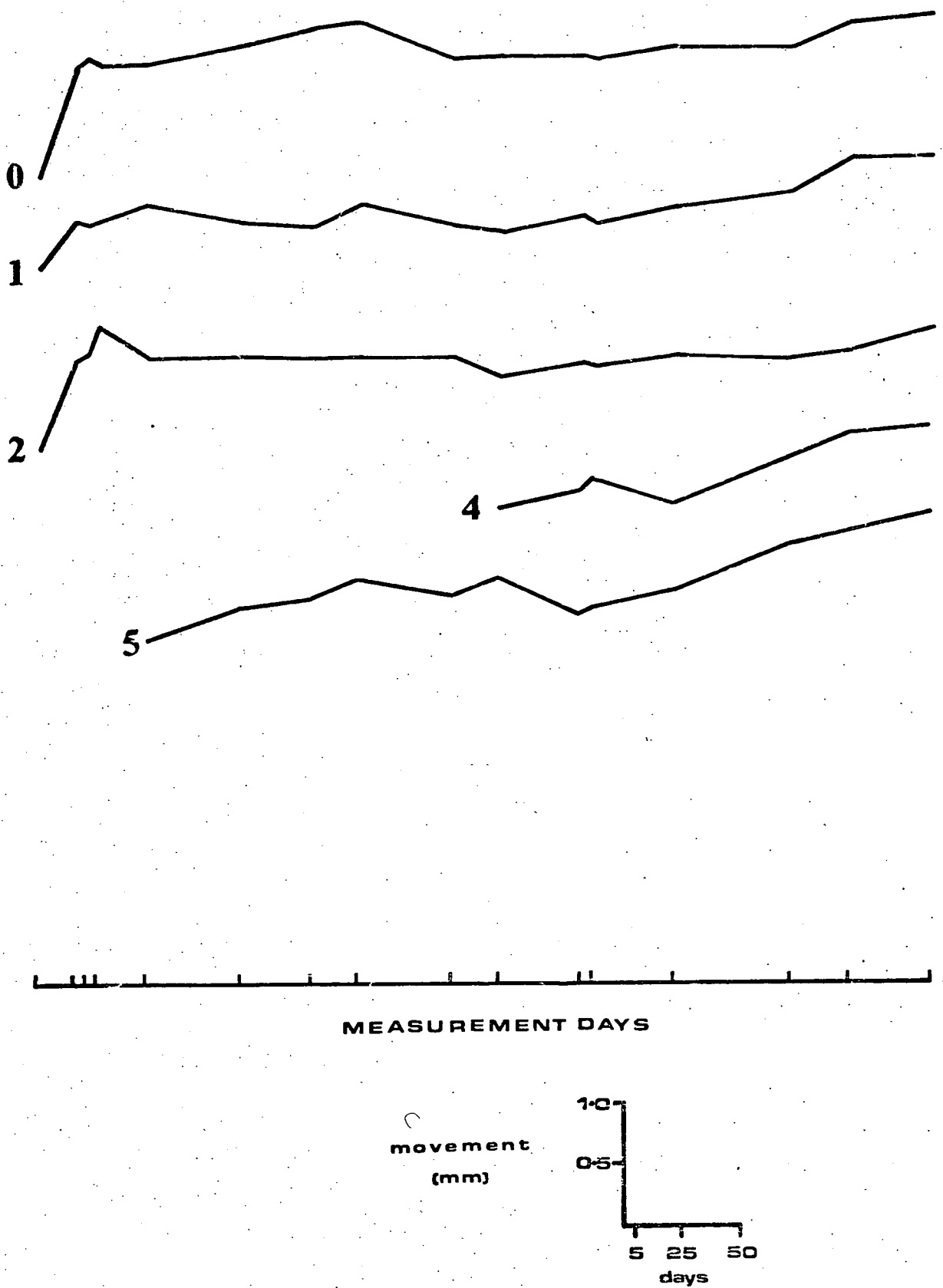
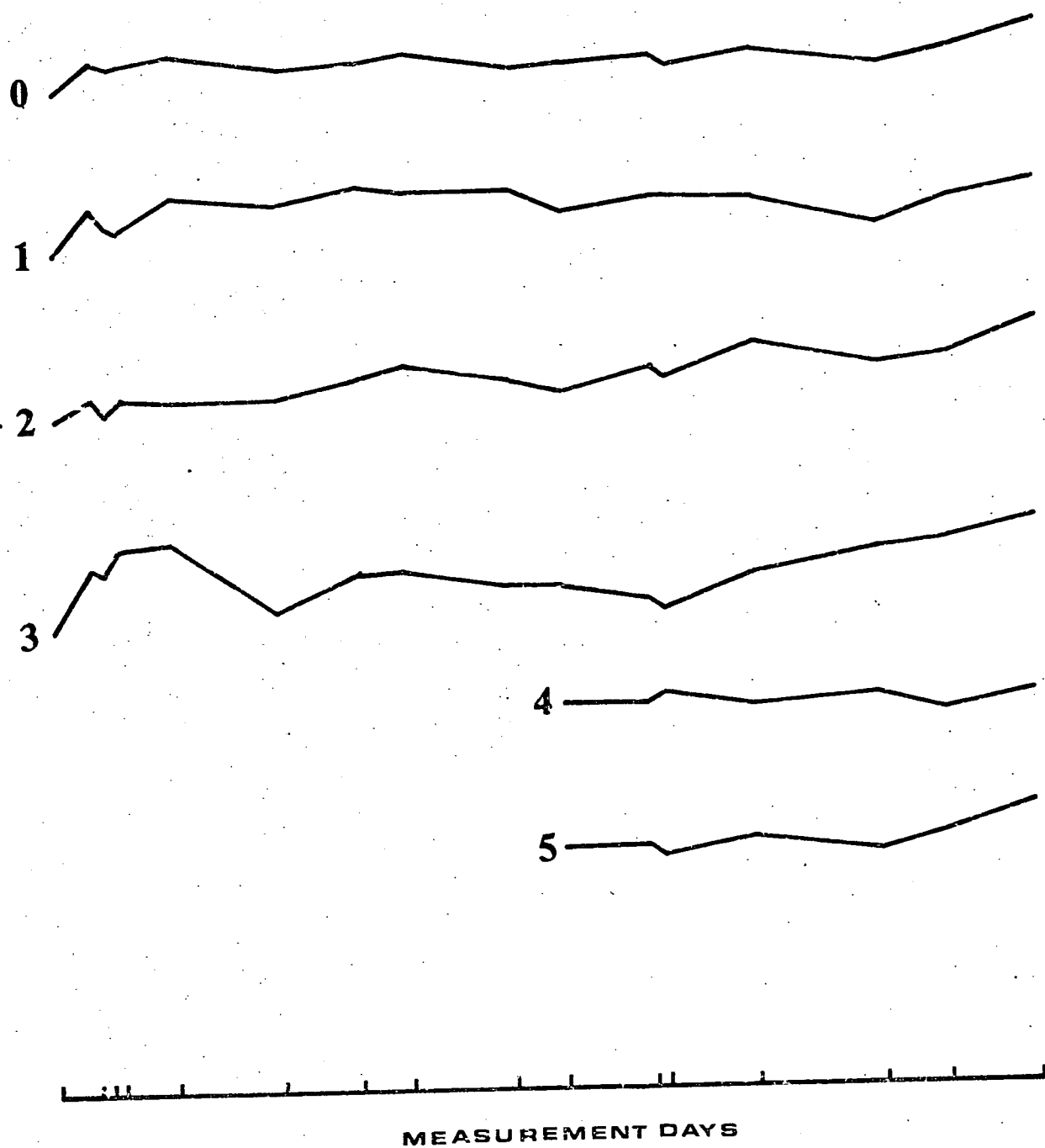


Fig. A3.9 Rookhope Plots: Peg Movements
Plot 12



movement
(mm)

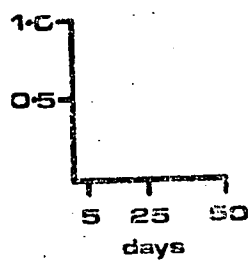


Fig. A3.10 Rookhope Plots: Peg Movements
Plot 13

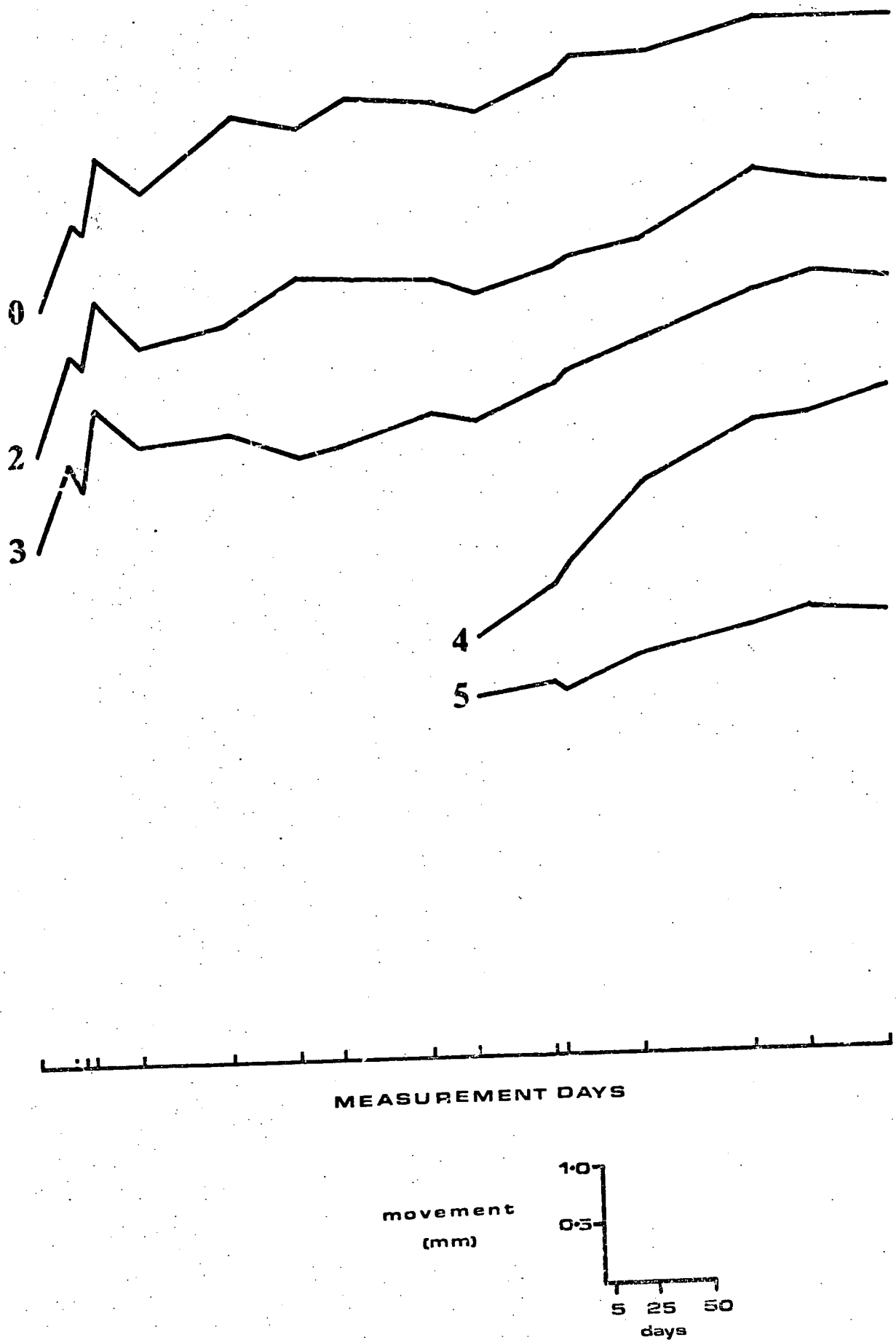
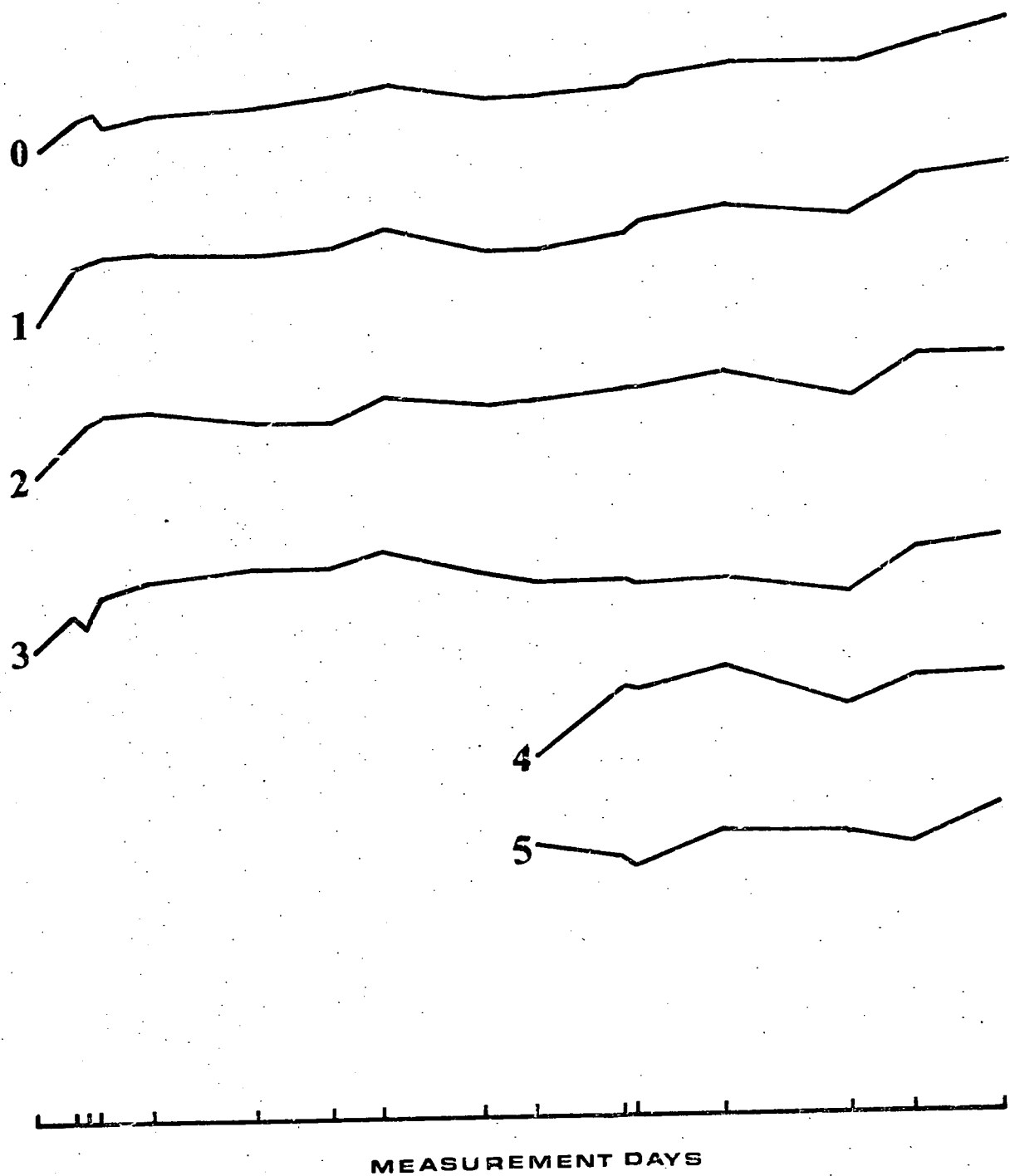


Fig. A3.11 Rookhope Plots: Peg Movements
Plot 14



movement
(mm)

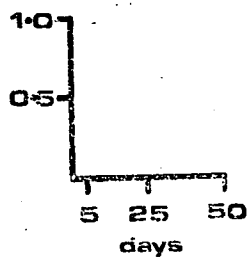


Fig. A3.12 Rookhope Plots: Peg Movements

Plot 15

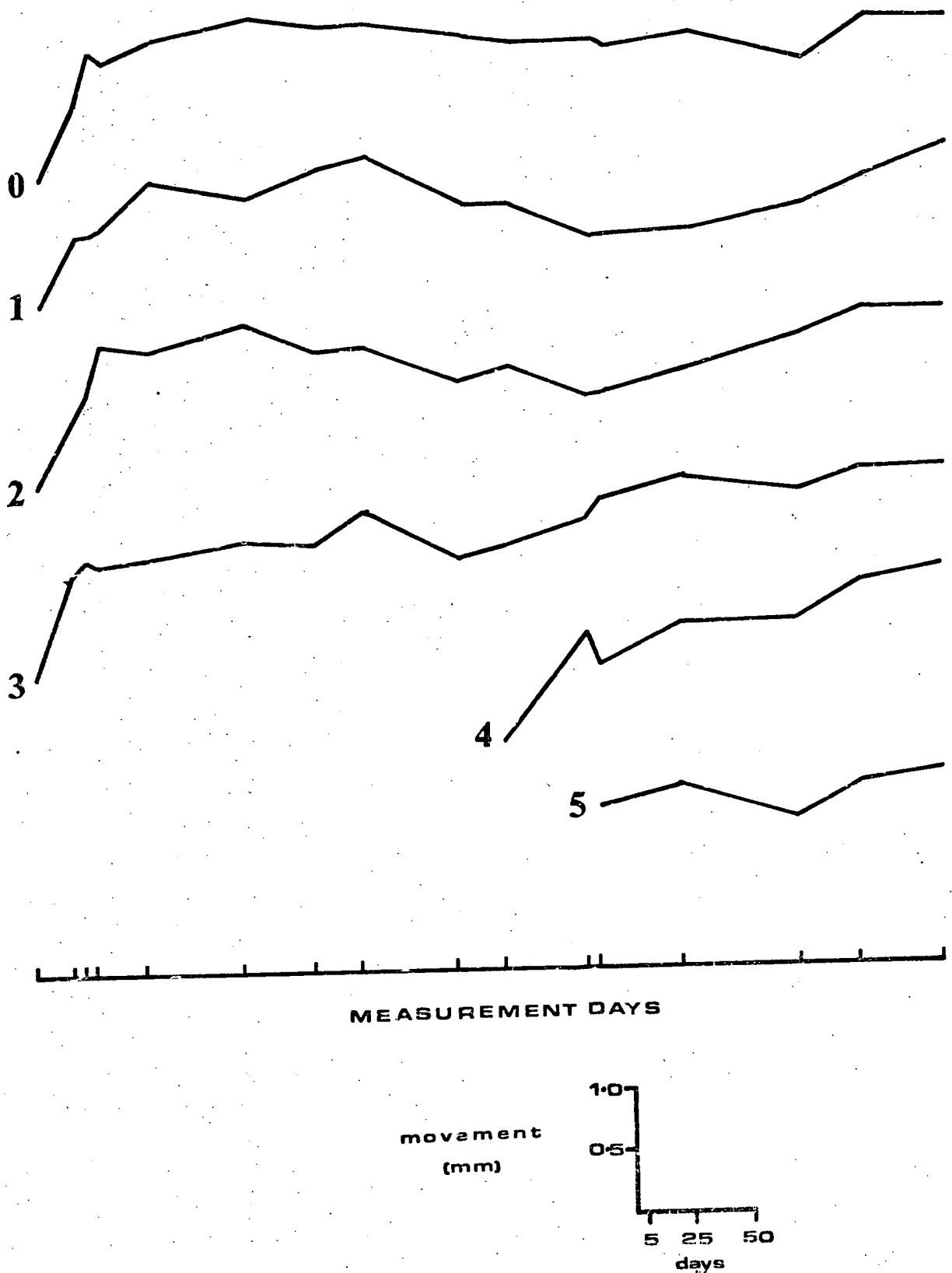


Fig. A3.13 Rookhope Plots: Peg Movements
Plot 16

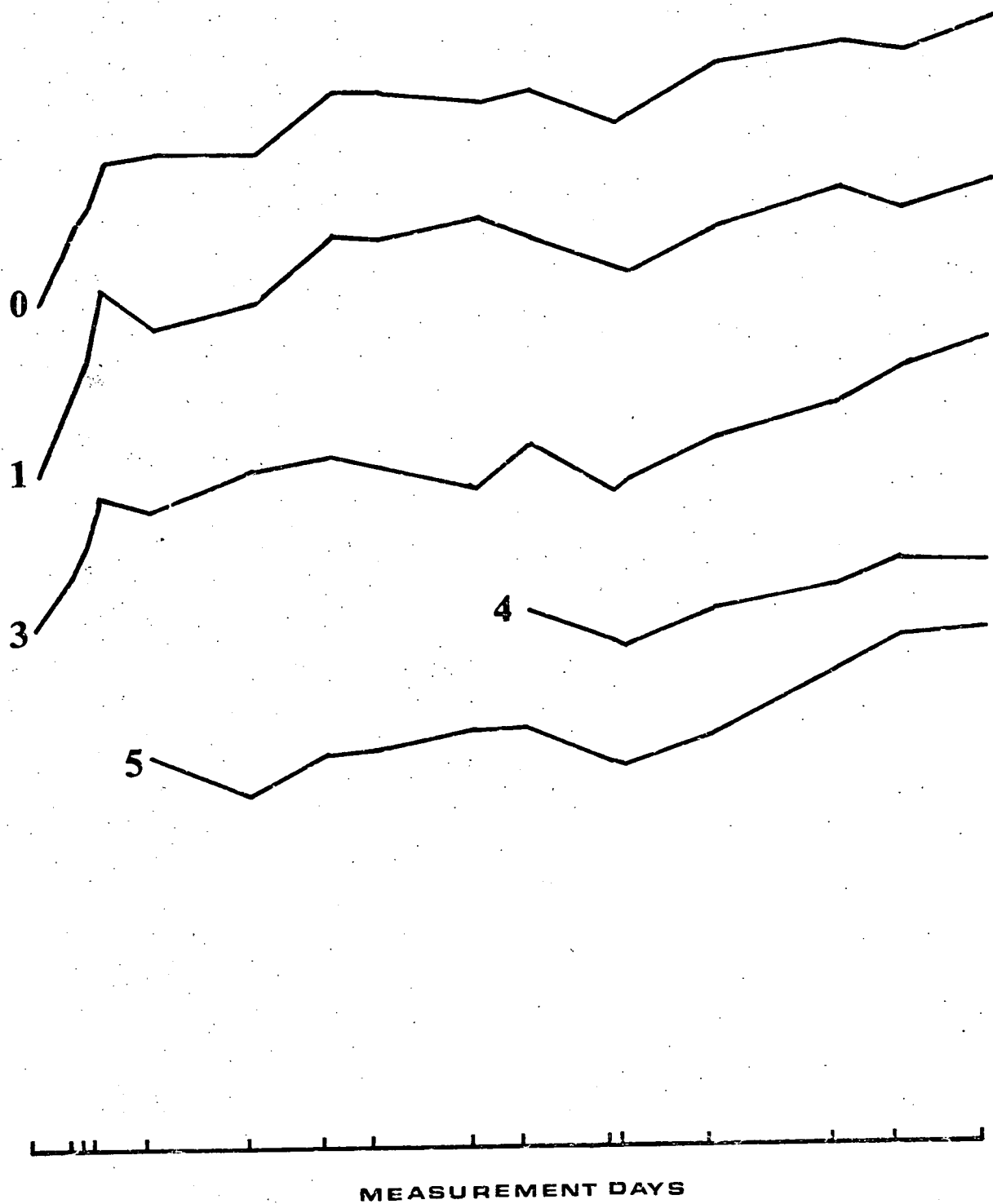
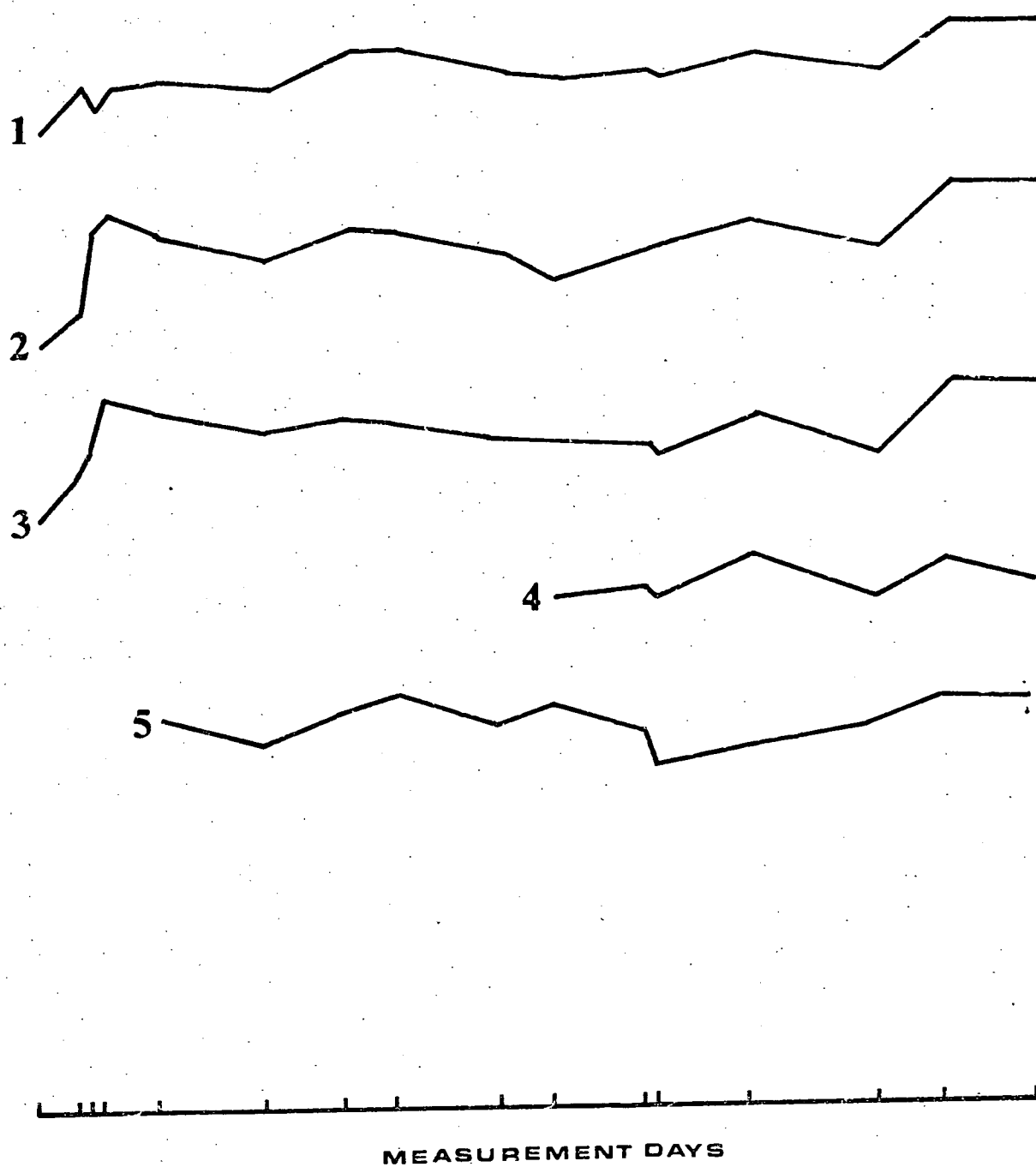


Fig. A3.14 Rookhope Plots: Peg Movements
Plot 17



movement
(mm)

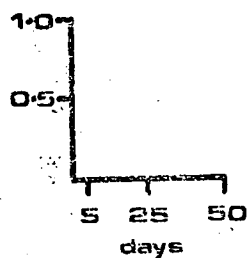


Fig. A3.15 Rookhope Plots: Peg Movements
Plot 18

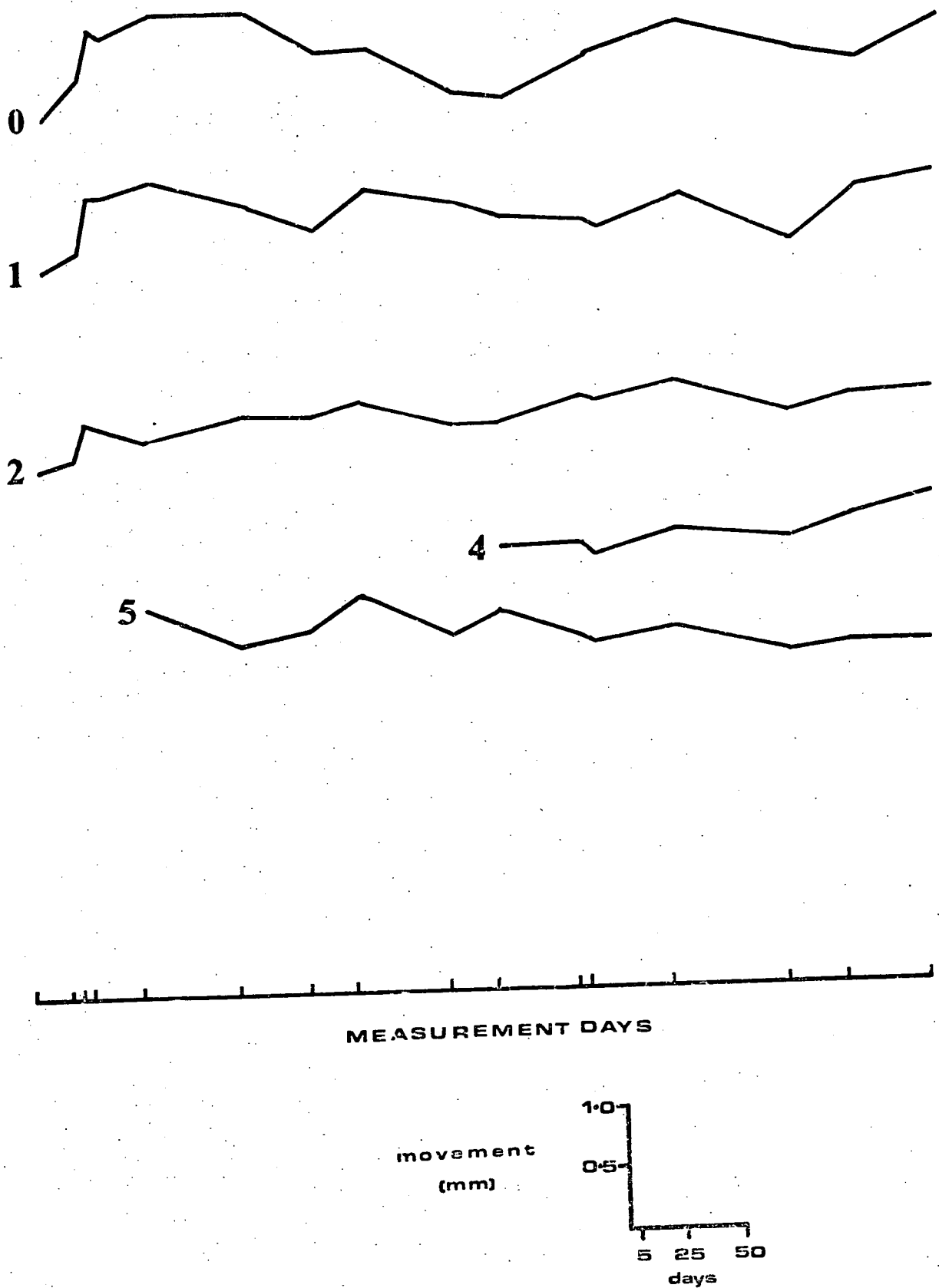
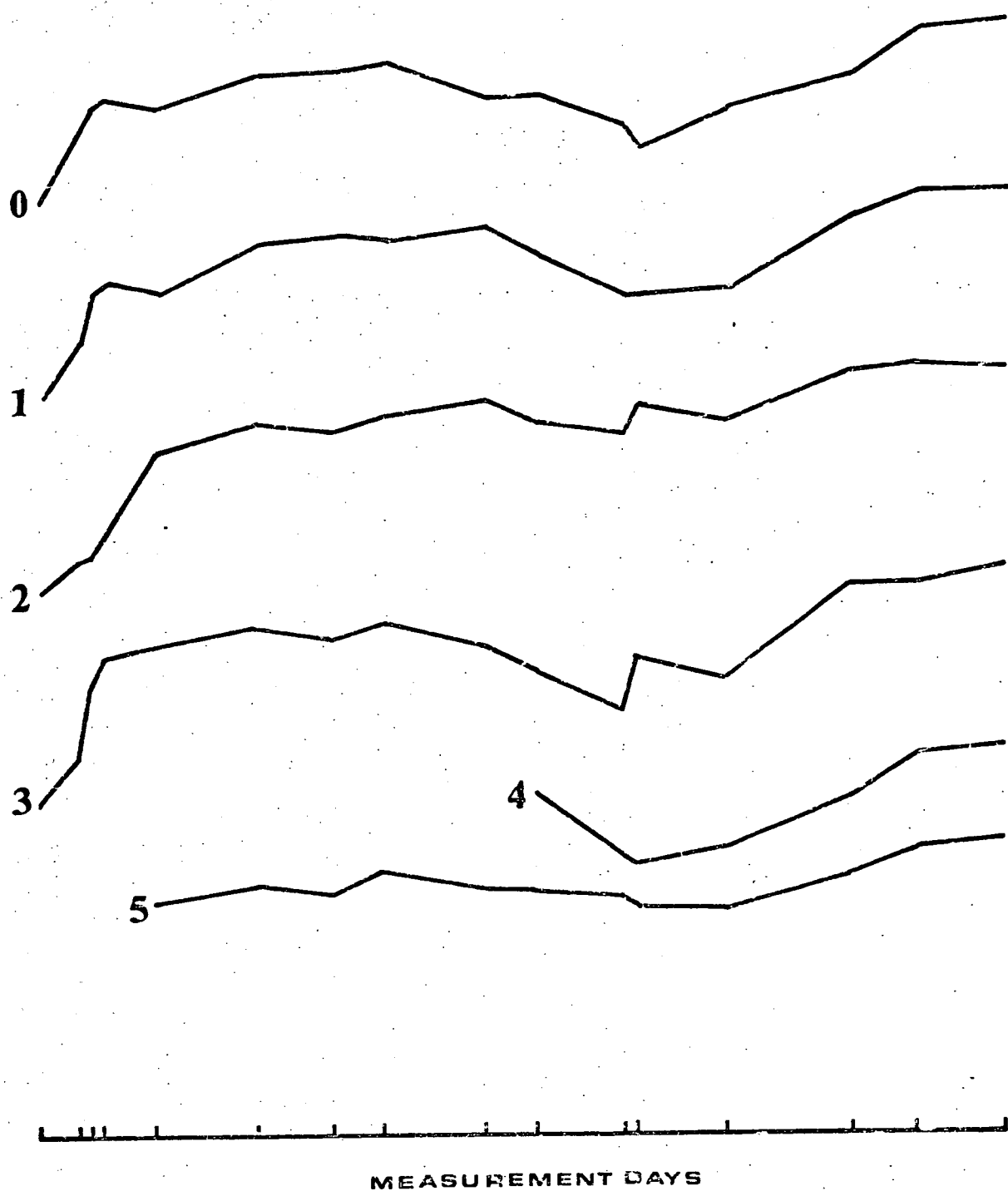


Fig. A3.16 Rookhope Plots: Peg Movements
Plot 19



movement
(mm)

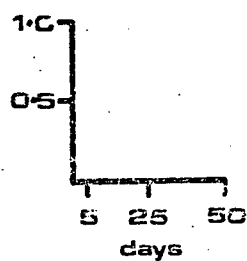


Fig. A3.17 Rookhope Plots: Peg Movements
Plot 20