Analysis of historic rammed earth construction

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Appendix A

Historic rammed earth distribution

A.1 Introduction

Rammed earth is a construction technique where soil is taken from the ground and compacted to form structures. Removable formwork is installed, and the soil compacted within it. The technique is widespread but the distribution of rammed earth across the world and its development over time has not previously been fully documented. Many sources quote the same examples of the Potala Palace in Lhasa, parts of the Great Wall of China, and the Alhambra in Granada. The distribution of rammed earth is however more complex than usually portrayed, appearing to spread over the world in a number of temporal waves, each precipitated by a different set of needs.

In this appendix, a strict definition of the rammed earth technique is first presented, identifying it by name in different languages. It will be argued that the rammed earth technique appears to have developed independently in China and around the Mediterranean. The technique then spread with the movement of peoples to different parts of the world. Rammed earth has continually been reinvented as a building material. At times it has been used as a quick technique for the building of fortifications, a cheap way a man can build his own home, and a sustainable construction technique using only what is available on site.

The paper concentrates on monumental rather than vernacular architecture, as monumental architecture is better documented and preserved. It is assumed that rammed earth was used as a vernacular technique where it is found as monumental buildings. The examples given are taken from a wide literature review and from field visits by the authors to Spain and India. The two identified nuclei of rammed earth are dealt with separately, beginning with China. It is shown that similar techniques to those in China are found in central Asia and India. Rammed earth around the Mediterranean is then discussed, its spread into Europe, and use during the Muslim caliphates. European migration to the Americas and to Australasia spread rammed earth to regions where it did not previously exist, but now flourishes. The differences between these two schools of historic rammed earth architecture are shown. Because the technique is not found in Pre-Columbian America or Australasia prior to European settlement, a spread through the movement of peoples from these centres may explain the current geographical distribution of rammed earth.

In a study of this nature it is likely that some rammed earth architecture is missing and there may be rammed earth sites which should be added. The nature of earthen architecture means that sites are extremely vulnerable to decay, and thus historic sites may no longer exist in a useful form to be studied. Further investigation is clearly required, but it is hoped that this paper is able to broadly outline the distribution and development of what we term "historic" rammed earth.

A.2 Defining "rammed earth"

The term rammed earth has been used to describe a large number of different processes involving the dynamic compaction of soil to form a solid mass. This has led to confusion and misdiagnosis amongst practitioners, and the following three distinct processes are therefore outlined.

1. Compaction of a large area to make level. This is known as a rammed earth floor and its use is again becoming popular in modern architecture.

2. Raising of mounds or platforms by the repeated addition and compaction of soil. Soil would be taken from the surroundings, placed and compacted to increase the height of an area. This method is seen as the production of defensive ramparts.

3. Compaction of soil between formwork boards, which are later removed. This is the process by which rammed earth walls are formed. This differs from 2 in that vertical faces of soil are formed, and remain exposed above ground. This is the definition which is used throughout the rest of this paper. This technique is known as *pise* in French, *tapial* in Spanish and *taipa* in Portuguese.

Difficulty arises when describing similar techniques in various languages. In Spanish *tapial* is used to define rammed earth, but is broadly used for placement of material between removable formwork. Many *tapial* structures in Aragon, Spain are constructed using gravel cemented with lime, but cannot be considered as rammed earth. In Central America, the word *tapial* is used to describe a technique which is actually a hybrid of rammed earth and wattle and daub (Easton 1996). The term *hangtu* is used by Chinese archaeologists to describe both rammed earth mounds and earth rammed between formwork. In Farsi *chineh* and in Uzbek *pakhsa* are the terms used for earth walls built up without formwork, known in English as *cob*. *A* variation on *pakhsa* described by Schroeder, Schwarz et al. (2005) involves the throwing of moist clay into formwork, which is then removed and the resulting bricks stacked to form a wall. The *layered technique* (Walls 2003) is similar to *hangtu* and *cob*, but a layer of lime is spread over a compacted layer prior to construction of the next.

A.3 China (Figure A.15)

Warren (1993) observes that the simplest form of construction on the alluvial plains of northern China is rammed earth. Nomadic peoples in China began to form permanent settlements during the Lung-shan era (c. 2310-1810BC). These settlements became ringed with defensive walls, initially no more than mounds and ditches, but as the size of the settlements grew, so did the size and complexity of the encircling walls. Walls were initially constructed by heaping soil to form a rhomboid section wall, with the base width increasing in proportion to the height. Yunxiang (2003) describes how these initially rhomboid walls may have been cut to present a vertical exterior face. Later soil may have been heaped against a single vertical timber wall acting as formwork, which was then removed. The technique may then have developed by the placing of two parallel vertical timber walls, with soil heaped against each one, and finally the rammed earth technique defined above was developed.

The Lung-shan sites of Lianyungang, Jiangsu and Taosi, in Shanxi Province (see Figure A.15 for locations) are encircled with large rammed earth mound walls. Taosi is also the site of what is considered to be the world's oldest observatory, which has a rammed earth wall of 60m diameter (Da 2003). The first definite use of formwork boards for the production of rammed earth walls comes from the walled Lung-shan settlement of Pingliangtai in Henan Province in the middle Yellow River area, where traces of small wooden boards used for formwork and ramming tools have been found (Yunxiang 2003). Pingliangtai has walls 13m wide at the base and the walls are still 3m high over 4000 years after construction. The walls here form a square around the village of side length 185m (Owen 2006). Due to the great thickness of these walls, it is thought that the walls were constructed by heaping soil against two removable timber walls.

The foundations of rammed earth walls have been found at palace complexes in Erlitou and Longwan, Hubei dated to 1900BC-1500BC (Hong 2005). Rammed earth mound walls were likely to have been used at the city of Cheng tzu-yai, Shantung where walls 9m wide and 6m high have been found (Wenke 1999. Excavations at the Shang dynasty (1600-1000BC) capital in Anyang city, Henan carried out in 1933 revealed a rammed earth wall 70m long and 2-4m wide (Houben and Guillaud 1994), and the cities of Linzi and Xiadu, built during the Warring States period (475-221BC), were encircled with massive rammed mound walls, up to 30m thick at the base (Shen 1994). The Qin dynasty (221BC-206BC) were the first to construct a wall along the northern frontier of China, using stone in the mountain ranges, and rammed earth in the plains. However it is in the Great Wall where the use of rammed earth is most recorded. The Han (206BC-202AD) and Jin (265-420) dynasties repaired or rebuilt the walls, but few sections remain, and thus it is impossible to tell the nature of their construction (Jiyao and Weitung 1990).

Houben and Guillaud (1994) argue that a 'true' rammed earth technique was first developed during the Three Kingdoms Period (221AD to 581AD), where formwork was held in place by long poles driven into the ground. This type of construction was used by the Hakka people, who originated in the Henan and Shanxi provinces. The Sui dynasty (581-618) reunited northern and southern China, and was followed by the Tang dynasty (618-907) which came under attack from Turkic tribes to the north of China. The Tang dynasty built cities (for example Jiahoe, Gaochang and Xian) along the Silk Route, each encircled with large rammed earth walls (Jiyao and Weitung 1990). The Tang fort of Baishui, at the western end of the Silk Route is constructed wholly in rammed earth (Xinhua 2007). Upheaval at the end of the Tang dynasty led to the southward migration of the Hakka, who moved to Guangdong, Jiangxi and Fujian provinces. The influx of the Hakka into these regions drove them into conflict with their new neighbours and they constructed the fortified farms known as *Tu lou* (meaning earthen structures). The *Tu lou* are large round or square rammed earth structures, which take many years to build and often house the whole family. There is only one entrance and no windows at ground level, making the structure easily defensible. The *Tu lou* are usually over 4 storeys high, with walls over 1m thick, and can be between 60 and 90m in diameter. The highest concentration of *Tu lou* is in Nanjing County, Fujian, where within a radius of 25km, there are over 2000 such buildings (Aaberg-Jørgensen 2000).

The Ming dynasty (1368–1644) arose from the defeat of the Jin empire by the Mongols, and saw a period of Chinese expansionism. Constant trouble from the Mongols on the northern borders led to the to the upgrade and repair of the Great Wall at this time. Sections of the

Ming wall were stronger than previous walls, being built in fired brick and stone, such as the famous section north of Beijing, but sections in the far west of China continued to be constructed in rammed earth. The walls of Xi'an, the Ming capital city, were initially constructed in rammed earth, and are 18m wide at the base and 12m high. In 1558 they were faced with brick, and so the rammed earth is now invisible (Jiyao and Weitung 1990). The town of Cockcrow, north of Beijing was established in 1420 and has a massive masonry fronted rammed earth wall now under the protection of the World Monument Fund (Evarts 2006). The greatest lengths of rammed earth in the Ming Great Wall occur in Ningxia province (Evarts 2006; Smith 2006, Figure A.1), where sections of wall originally 9m high are constructed in layers of 15 to 30cm high, to form a rhomboid shaped wall. A number of forts are constructed along the wall at for example Jiayuguan and Hexibao. Jiayuguan Fort was begun in 1372 and the bottom 6m of walls are rammed earth, but were raised using adobe bricks to their current height of 9m (Fletcher and Nicholas 2007). The use of rammed earth as a monumental building material in China appears to decline following the construction of the Ming wall. Rammed earth may have been extensively used in Tibet, and is certainly found at the Potala Palace in the capital Lhasa (Hurd 2006b), and may thus have spread south to the Himalayas.

Figure A.1 Great Wall in Ningxia. Photograph Smith (2006)

Figure A.2 Hakka formwork (Aaberg-Jørgensen 2000)

Figure A.3 Jiayuguan fort (Fletcher and Nicholas 2007)

Figure A.4 Hakka roundhouse (Aaberg-Jørgensen 2000)

A.4 Himalayas (Figure A.15)

Rammed earth is found extensively in the Himalayan kingdoms of Ladakh, Mustang (part of Nepal) and Bhutan. These kingdoms trace much of their history from Tibet and China to north, rather than India to the south. It is possible that the same rammed earth techniques used in China and Central Asia were also used in the Himalayas. Rammed earth is considered to be the oldest construction technique in Ladakh, its use preceding that of sun dried mud brick (Jest, Chayet et al. 1990). Evidence of the historic use of rammed earth in the Himalaya is provided by a rammed earth fortress at Basgo, Ladakh which was constructed before 1357 (Howard 1995). Lo Manthang the capital of Mustang in Nepal is surrounded by a rammed earth wall which was built in 1380 (UNITAR 2006). Much of the monumental and vernacular architecture in western Bhutan is rammed earth (Nock 1995). Rammed earth was a successful construction technique used for Muslim fortifications in north Africa and Spain from the 8th century. Although the initial Muslim expansion (in 712AD) did not reach the Himalayas, there were repeated incursions into Ladakh during the 15th century. These incursions destroyed much of the monumental architecture, making it impossible to know if rammed earth was present prior to this period (Rizvi 1996). An Indo-Muslim manuscript written in Urdu (date unknown), details rammed earth construction (Acedo 2006). Following the Muslim incursions into Ladakh, rammed earth was used for fortress construction at the towns of Shey and Leh. The technique is still used today where corrugated steel sheeting is seen to have been used as formwork, producing corrugated rammed earth walls.

Figure A.5 Rammed earth in Mustang, Nepal

Figure A.6 Rammed earth Urdu manuscript (Acedo 2006)

A.5 Middle East and Central Asia (Figure A.15)

Evidence of rammed earth in the Middle East is very scarce. Ochsenschlager 1998) is convinced that the rammed earth used by modern Iraqi Marsh Arabs was used in antiquity, but a lack of archaeological investigation of the region means that identification of historic rammed earth is currently unlikely. Walls (2003, 2004) identifies the *layered technique* used in Oman and Iran, but this technique is more similar to cob. At Bam in Iran, a highly studied site following the 2003 earthquake, the majority of construction is in adobe or *Chineh* with only a few examples of rammed earth (Langenbach 2004). In Uzbekistan *pakhsa* walls are found (Schroeder, Schwarz et al. 2005) which involve no formwork, but *pakhsa* walls observed by Cooke (2005b) appear to have been constructed using formwork, in a manner which would be described as rammed earth. Construction in rammed earth in these regions is hampered by the lack of available timber for formwork (Schroeder, Schwarz et al. 2005), and as such any earth construction would take the form of cob, adobe or similar which do not require large timber formwork. Locations of these sites are shown in Figure 1.

Jest, Chayet *et al.* (1990) argue that remnants of rammed earth walls and houses have been found at Qinghai, Tsaidam between Tibet and Central Asia, which are thought to date from the Muomhong period (2000-500BC). Marshak (1990) and Turkekulova (2005) cite the mud brick city of Penjikent (Tajikistan) as the highlight of pre-Islamic culture on the Silk Route. The city, established in the 5th century AD, is surrounded by earthen walls, and the ground floors of many buildings are constructed in rammed earth. The city was razed by the Muslim expansion in 722 and is now a working archaeological site, but many of the uncovered earth buildings quickly disintegrate once exposed. The Muslim expansion brought the destruction of many earthen sites in Central Asia, and further archaeological investigation is required to establish the building techniques used (Stevens and Talon-Noppe 1983). City walls and buildings constructed in rammed earth at Khar Balgas city in Mongolia , capital of the Uyghur empire (745 - 840) were uncovered by Russian archaeologists in 1949 but only a small amount of investigation has taken place. The site was declared a World Heritage site in 2004 (ICOMOS 2002; UNESCO 2003). Many Silk Route sites which survived the Muslim expansion were later razed by Genghis Khan in his campaigns in the 13th century. The fragile nature of earthen construction means that little remains of many central Asian historic sites (Turkekulova 2005).

A.6 Mediterranean (Figure A.12)

Rammed earth appears to first have been used in Phoenician settlements around the Mediterranean. The Phoenicians spread from modern Lebanon, founding numerous cities along the Mediterranean including the Carthage in 814BC. Excavations of Phoenician settlements suggest the use of rammed earth both in north Africa (Carthage, Kerouane and Utique (Houben and Guillaud 1994)) and in Spain (Morro de Mequitilla (Chazelles 1993)). Michon 1990) argues that the art of rammed earth building was practised by in north African by oasis dwellers. Pliny the Elder describes rammed earth towers constructed by the Carthagean general Hannibal (invader of Iberia in 218BC):

> 'Moreover, are there not in Africa and Spain walls made of earth that are called framed walls, because they are made by packing a frame enclosed between two boards, one on each side, and so are stuffed rather than built, and do they not last for ages, undamaged by rain, wind and fire, and stronger than quarry stone? Spain still sees the watchtowers of Hannibal and turrets of earth placed on mountain ridges' (Pliny and Healy, 1991).

The Romans admired rammed earth from a distance, using pozzolanic based concrete in preference to rammed earth, but Vitruvius' *De architectura,* a systematic compilation of the construction techniques known to the Romans and written between 27 and 23 BC, reports rammed earth used in the city of Marseilles. Recent excavations at 3rd century AD sites of La Lagaste, Entremont, Martigues, Marignane, Mouries, Ruscino and Lyon in southern France have all uncovered sections of rammed earth walls (Houben and Guillaud 1994). The Latin verb *pinsere* is coined for the action of ramming earth and has passed into French as *pise.*

A.7 Muslim expansion (Figure A.12 and Figure A.15)

While it is obvious that rammed earth was used as a construction technique before and during Roman times, the use of rammed earth may have increased through the expansion of Islam. Following the death of Muhammad in 632, Muslim armies spread quickly from the Arabian Peninsula, controlling Persia by 656. The Armenian city of Yerevan was taken in 658, and is now surrounded by a historic rammed earth wall (Hurd 2006b). By 705 modern Afghanistan was Muslim, and the Indus river, the most easterly point of the empire, was reached in 712.

The Iberian peninsula was invaded in 711, and the maximum extent of the occupation occurred around 756. There has been a continued presence of Islam in Persia, the Arabian Peninsula and north Africa since the initial expansion, and in Iberia a Muslim presence lasted until 1492.

The use of rammed earth may have increased with the growth of the Muslim Almoravid and Almohade Berber dynasties which originated from the Sahara and ruled north Africa and Iberia. The famous Berber Kasbahs in the Draa and Dades valleys of Aït Ben Haddou and Tamnougalt are now World Heritage sites but the date of their construction is unknown. In Marrakesh the city walls and the El Badi Palace, constructed in 1578 are constructed mainly in rammed earth. Much of the vernacular architecture in Morocco is still rammed earth.

Azuar Ruiz (1995) argues that a lack of evidence means that it is not possible to trace the use of rammed earth prior to the 9th century in Iberia. The first rammed earth may have been the castle of Badajoz, built in 874, of which nothing now remains. However town fortifications in Calatayud and Pla d'Almata dated to 884 have been uncovered. Graciani García and Tabales Rodríguez (2003) argue that the oldest walls in the *Alcazar* of Seville (circa 914) constructed as dressed stone with a compacted mortar fill, are rammed earth, but this is considered to be the Roman technique of *opus quadratum* rather than rammed earth.

Internal political strife in Iberia at the end of the 10th century led to the construction of castles (for example Baños de la Encina, Figure 6) which were built using rammed earth as a speedy construction method which producing durable fortifications. During this period separate kingdoms (Taifas) ruled small parts of the peninsula, constructing many fortifications (for example the *Alcazar* in Granada). Following repeated Christian incursions, the Almohade ruler from north Africa was invited to defend the Iberian Muslims, and the majority of rammed earth castle sites in southern Spain are associated with the Almohade era (for example Castle of la Atalaya, Villena). Dating the initial construction of these sites is extremely difficult. The technique was widespread during the 11th and 12th centuries, and Moses Maimonides, a Jewish writer and philosopher, born in Cordoba in 1135, but residing in Morocco, Egypt and Israel wrote of rammed earth:

> The builders take two boards, about six cubits long and two cubits high and place them parallel to each other on their edges, as far apart

> as the thickness of the wall they wish to build; they steady these boards with pieces of wood fastened with cords. The space between the boards is then filled with earth, which is beaten down firmly with hammers or stampers; this is continued until the wall reaches the requisite height and the boards are withdrawn. (Moses Maimonides, cited Cooke 2005a).

Figure A.7 Rammed earth wall at Yerevan, Armenia (Hurd 2006b)

A.8 Late Medieval Europe (Figure A.12)

The Muslim rule in Spain waned, and the last Muslim king of Granada was removed in 1492. The Christian rulers of Spain initially employed the Muslim population as craftsmen and artisans, and the rammed earth technique is found throughout Christian Spain. Fired brick began to be mixed with rammed earth (Gerrard 2003), and the introduction of artillery led to the cladding of rammed earth walls in masonry. Some strategic military structures were strengthened and enlarged in stone by the Christians, but rammed earth continued to be used for both strategic and vernacular architecture (Jaquin, Augarde *et al.* 2007a). In Spain rammed earth was used for military architecture and vernacular architecture until the 19^{th} century (Font and Hidalgo 1991; Gerrard 2003).

Vernacular rammed earth in southern France may have been prevalent in Christian medieval France, because rammed earth was introduced into Switzerland from the Lyon region of France around 1660 where the alluvial soils proved ideal for rammed earth construction. The oldest Swiss rammed earth constructions are Gonzenbach castle outbuildings near Geneva (Kleespies 2000).

A.9 Expansion to the Americas (Figure A.13)

Rammed earth was not found in the Americas prior to 1492. In 1549 Manuel da Nobrega, a Jesuit missionary sent a request to Europe to send 'artisans able to handle loam, and carpenters, for the construction of a rammed earth wall'. Jose de Anchieta, a Spanish Jesuit arrived, and supervised the construction of Colegio da Companhia de Jesus in Piratininga, Sao Paulo, Brazil (Puccioni 1993). Tibbets (1989) and Easton (1996) argue that the first rammed earth in North America used a soil and sea shell mix, compacted in heavy formwork, found in St Augustine, Florida and built in 1556.

Rammed earth was used in the Goiás and Minas Geras areas of Brazil (Oliver 1997; Pisani 2004), In São Paulo the cathedral of Taubaté was constructed from rammed earth in 1645 (Alvarenga 1993; Pereira 1993; Vinuales 1993) and the Church of Our Lady of the Rosary in 1720 (Pecoraro 1993). In São João del Rei the Basilica of Our Lady of Pillar was built sometime in the early 18th century (Lima and Puccioni 1990). In Goias, the House of the Chamber constructed in 1776 is of very similar architecture to that found in Portugal in the late 18th century (McHenry 1984). In São Paulo and the surrounding area rammed earth use was widespread in the 18th and early 19th century. However in 1850 following flooding in the city a public campaign against the use of rammed earth led to a reduction in the use and demolition of much of the rammed earth architecture in São Paulo (Pecoraro 1993; Pereira 1993; Pisani 2004). A small number of examples of rammed earth architecture still exist, such as the Chapel of Morumbi which was built in 1850 on farmland outside of São Paulo and is now a national monument.

Figure A.8 Rammed earth formwork South America

Figure A.9 Capello Morumbi

A.10 18th century Europe (Figure A.12)

The prevailing political climate in Europe at the end of the 18th century was of revolution and for a rise in status of the common worker. Rammed earth began to be championed as a low cost owner-builder construction technique. In France G C Goiffon published *Art du macon piseur* in Le Jai, an obscure Paris journal in 1772 and in 1786 François Boulard published an article on rammed earth in Cours Complet d'Architecture (Cody 1990). Neither article was as successful as the series of pamphlets published by Francois Cointeraux in 1791. Cointeraux lived in Lyon and "rediscovered" the rammed earth legacy left by the Phoenicians almost 2000 years earlier. Cointeraux conducted a number of experiments on rammed earth, detailed in four documents (Cointeraux 1791; Figure 12) which were distributed around Europe. Gilly (1798) translated the works into German and Guiseppe del Rosso, an architect in Toscana, Italy published a rammed earth construction manual probably inspired by the work of Cointeraux (Bertagnin 1993). English translations of Cointeraux's work were published in 1798 in England by Holland and Salmon (1798) and in the United States by Johnson (1806).

A large number of barns and agricultural buildings were constructed to Cointeraux's specifications in rammed earth and can be found in the Lyon area of France (CRATerre 2006). In the rest of Europe, known surviving large buildings include a three storey hotel in Marcon, France, constructed in 1790 (McHenry 1984). In Germany a fire resistant house was constructed in 1795 by the head of the local fire service in Meldof, Schleswig-Holstein, who wanted an alternative to timber construction. Haus Rath in Weilburg an der Lahn, was constructed in 1828 which climbs to five storeys (Guntzel 1990; Steingass 2005).

In the early 18th century a group of craftsmen travelled through Norway and Sweden building in rammed earth using fixed formwork filled with lime mortar and slag of pebbles and stone. The increase in popularity of rammed earth was brought about by the perceived ecological crisis engulfing Europe at the time, which was seeking alternatives to timber construction to prevent deforestation in Europe (Palmgreen 2005). A Swedish mining engineer built houses in Hartz (1735) and Falun (1739). Lime production led to the construction of rammed lime buildings in the middle of the 19th century. In Sweden outbuildings of the Karlsborg Fortress in Stockholm were built from rammed earth in 1842 and parts of the summer residence of the Queen of Norway was constructed in rammed earth at Kongsvinger in 1890. However following the introduction of locally produced Portland cement in Scandinavia at the turn of the 20th century, rammed earth fell into decline (Palmgreen 2005).

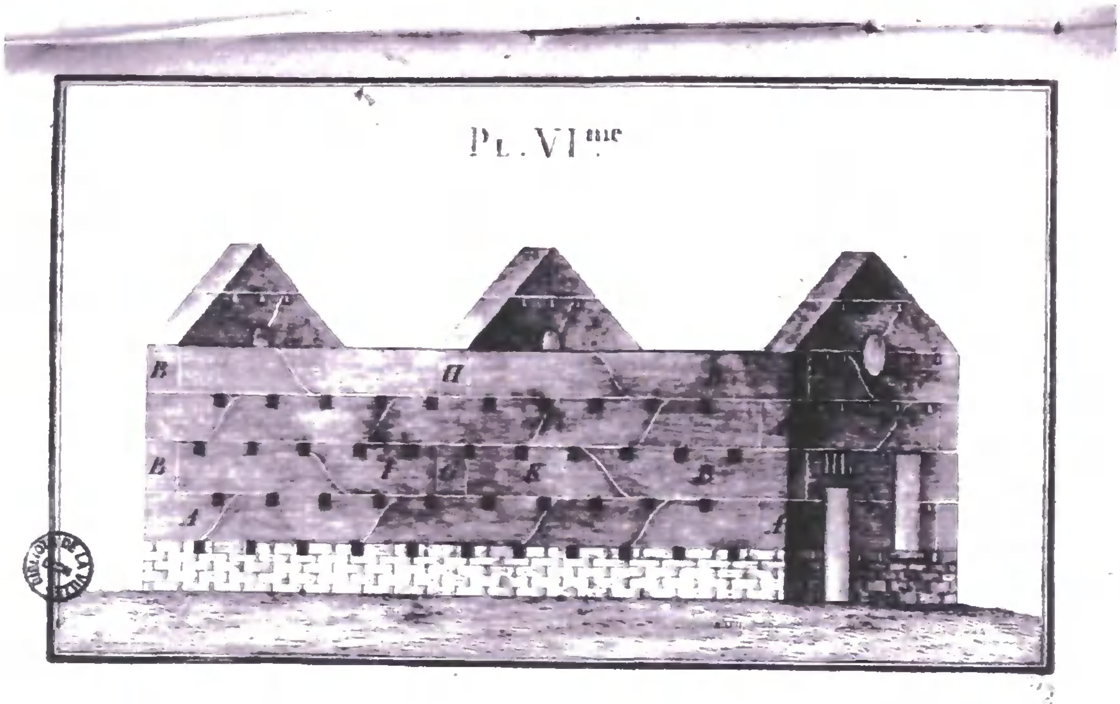


Figure A.10 Example of a rammed earth home, from Cointeraux 1791

A.11 18th and 19th century migration

The late 18th and 19th centuries saw the first truly mass migrations of peoples. Movement of peoples to North America, Australia and New Zealand brought previously unknown skills and customs to these lands. Rammed earth spread from rural to urban China, and from China and Europe to America. European settlers to Australia and New Zealand experimented in rammed earth. Rammed earth did not succeed everywhere, but there are many examples of historic rammed earth structures built by these immigrants.

Hoi Pa Village, Hong Kong, grew up in the 18th and 19th centuries built by Hakka peoples who had migrated south. The Fan Sin Kung temple in Hong Kong was constructed in 1790 and Holmes (2000) states that it was common in this period for buildings in Hong Kong to have at least one wall (usually the rear) constructed in rammed earth. A good example of traditional southern Chinese village architecture is the Old House, built in 1904 and now preserved as an Environmental Resource Centre (AMO 2004).

A depression in China, and the lure of gold mining, led to large migration to California in the mid 19th century. In Fiddletown, California Chinese immigrants constructed a small rammed earth herb shop (The Chew Kee Store) around 1850, which was recently repaired to become a museum (Easton 1993; Easton 2007). In Palo Alto, a business woman named Juana Briones built a rammed earth type house around the same time (Camarillo 2005).

On the east coast of the United States a rammed earth construction manual was published in New Jersey (Johnson 1806) which drew heavily on the work of Holland and Cointeraux. Johnson built a house near Trenton, New Jersey, hoping to provide a model to newly arrived Americans looking to settle new farm land. Tibbets (1989) argues that German immigrants built in rammed earth in New York and Pennsylvania, and that Thomas Jefferson built his home (Monticello, Virginia) in rammed earth. Another well documented structure, Hilltop House, was constructed in 1773 in Washington DC. Bushrod Washington (nephew of George Washington) built rammed earth lodges on his estate at Mount Vernon in 1812 (Pogue 2007). In 1819 John Stuart Skinner, editor of *The American Farmer* published a translation of Holland's work, and later several other articles on rammed earth construction experiments taking place in North America, notably John Hartwell Cocke's slave quarters at his plantation in Bremo, New Canton, Virginia (Johnston, Cocke et al. 1969). Dr. William W. Anderson of Stateborough, South Carolina, recounted his experimentation with rammed earth construction, which had begun with the construction of a small dairy in April 1821. Pleased with the results, Anderson constructed rammed earth servants quarters in July 1823. Gilman (1839) published a treatise extolling the virtues of rammed earth, and John Stephen Wright, editor of *Prairie Farmer* published 40 references to rammed earth in this periodical between 1843 and 1855 (Cody 1990). In 1842 St Thomas Church in Shanty Bay Ontario was built and in 1850 Dr Anderson began the *Episcopal Church of the Holy Cross* in Sumter County, South Carolina (Easton 1996).

European settlers in Australasia in the mid 19th century experimented with a wide range of building techniques (see Figure 4 for site locations) . The first reference to rammed earth may be a notice by the Agricultural Society in May 1823 on the front page of the Hobart Town Gazette, Tasmania.

> 'Resolved that the mode of building in pise, or rammed earth, appearing to this Society to be both economical and expeditious, the

Society earnestly recommend its adoption in Van Diemen's Land' (Moor and Heathcote 2002).

The *Southern Australian* reported in 1839 that '*nearly thirty houses have been erected, they are mostly built of pise'*. In Rushworth, a gold rush town in Victoria, rammed earth was used as a speedy construction technique and in Harden, Australian Capital Territories, a rammed earth barn and stables are now a heritage monument (ACT 2004). Much of the original settler architecture in Oberon (Gemmell-Smith 2004), and Penrith (NSWCR 1991) New South Wales was constructed in rammed earth, and though much has been demolished, a small number of historic examples remain. On the west coast, the village of Moora contains a large number of rammed earth structures, constructed between 1847 and 1869 (Laurie 1995). Earth building in New Zealand began with the first European settlers in 1840, but all forms of masonry construction fell out of favour following earthquakes in 1846 and 1855 (Walker and Morris 1997). The best known example of historic rammed earth in New Zealand is Pompallier House in Russell which was completed in 1842 and has recently undergone conservation work (Bowman 2000).

Figure A.11 Chew Kee Store

A.12 20th century

The two World Wars in the 20th century both saw rammed earth suggested as a solution to the housing and labour shortages which followed each war. In the UK following the First World War, Welsh architect Clough William-Ellis 'discovered' earth buildings hidden beneath plaster veneers of historic cottages. His father-in-law St. Loe Strachey, an ideologue aristocrat and media mogul, ran a campaign in *The Spectator* magazine, both for information and to promote rammed earth as a building material in the UK. Following the campaign, William-Ellis published a book (William Ellis 1919) explaining earth building techniques for use in the UK, and the Board of Agriculture constructed a series of prototype cottages at Amesbury, Wiltshire, some in rammed earth, others in brick and others in rammed chalk. The rammed earth cottages, while initially popular, did succeed due to the differential costs of labour and materials following the collapse of the post war boom (Easton 1996; Swenarton 2003; Walker, Keable et al. 2005).

In the United States Karl Ellington published a book (Ellington 1924) with a preface by William-Ellis, and in 1926 Thomas Miller of the US Department of Agriculture was sent to investigate the *Church of the Holy Cross* in South Carolina, and as a result published *Farmers Bulletin No 1500*, which detailed rammed earth construction methods. Harry Baker Humphrey, a senior member of the Department of Agriculture, was impressed with the technique and built his rammed earth home in 1926. Many others followed suit, using the *Farmers Bulletin* to construct their own homes in rammed earth. Academic research was carried out by Ralph Patty and Henry Delong of South Dakota State College, with many publications produced (for example Patty 1936). As part of President Roosevelt's New Deal programme, a number of intentionally labour intensive homestead projects were initiated. In 1932 Thomas Hibben built seven experimental rammed earth houses at Gardendale, Alabama, all of which stand today. Elbert Hubbell, continuing the work of Patty, built a many rammed earth structures on an Indian reservation in North Dakota, and together with Miller and Hibben, Hubbell conducted tests on a number of earth building systems. They published the Building Materials and Structures report (BMS78) which concluded that all of the earth building methods tested were suitable for the construction of single or two storey structures (Tibbets 1989; Easton 1996). A single reference (Kornouchow 1933) suggests that rammed earth may also have been investigated in the Soviet Union as a solution to social housing during this period.

Following the Second World War, rammed earth was used in East Germany as a cheap and widely available construction material for immediate postwar reconstruction (Steingass 2005) and Building Standards documents covering rammed earth construction were published between 1947 and 1956 (Houben and Guillaud 1994). A similar revival was seen in Scandinavia at the same time with two books on rammed earth being published and a number of constructions (Palmgreen 2005). In Australia an English trained architect, G F Middleton was employed by the Commonwealth Experimental Building Station in Sydney and conducted a large number of tests on rammed earth and other earth building techniques. His initial reports (Middleton 1952) and his *Build Your House of Earth* book (Middleton 1953) were until recently the accepted standard reference in Australian earth building (Moor and Heathcote 2002).

In the mid 1970s, a number of different groups began reinvestigating rammed earth, and established themselves as builders or academics to spread the rammed earth message. In the United States, David Easton and Tom Schmidt began to build in rammed earth, in Australia Giles Hohnen and Stephen Dobson founded companies offering rammed earth homes. Architecture graduates Hugo Houben and Patrice Doat founded CRATerre at the University of Grenoble, for the study of earth building materials. Following those pioneers, the use of rammed earth has grown and shrunk in different parts of the world, but is now enjoying a growth, and reinvention as a sustainable and environmentally friendly building technique. Rammed earth is now a well established construction technique in Western Australia and the south west United States, with increasing interest in Europe and other parts of the world as a sustainable construction material.

A.13 Summary

The discussion above has detailed the development of rammed earth (as defined at the start of this Appendix) across time and over specified regions. This is summarised in a timeline in Table A.1 supplemented by Figure A.16 which indicates the most significant movements of rammed earth methods over time. A development of the technique in China was explained, and it is possible that rammed earth developed from the heaping of soil against vertical formwork in many parts of the world. Two independent schools can be observed, around the Mediterranean and centred on China.

Rammed earth in China developed as a necessary construction technique where few building materials were available. Yunxiang (2003) shows that heaping of soil may have developed into compacting between formwork as a method of producing a vertical face. The technique was successfully used for long sections of defensive walls built by successive empires, eventually becoming known as the Great Wall of China. The technique is certainly used by the Hakka people originally from central China, and may have been used in Tibet. Rammed earth is currently found in southern China as a result of Hakka migration, and in the Himalayan kingdoms of Ladakh, Mustang and Bhutan.

Rammed earth around the Mediterranean appears to be present in Phoenician and later Carthaginian settlements, such as those of Hannibal described by Pliny and Healy (1991). This appears to be independent from the rammed earth technique practiced by the 'oasis dwellers' of north Africa' described by Michon (1990). The explosion of Islam in the 8th century led to the second introduction of rammed earth into Europe, this time from north Africa, and many rammed earth fortifications in southern Spain are a result of this spread. Evidence in Central Asia is scarce, rammed earth is found in Penjikent in Tajikistan, dated to the 5th century, and rammed earth walls at Yerevan in Armenia exist, but the date of their construction is unknown. Muslim technology and architecture spread east with the armies, but it is probable that rammed earth already existed in central Asia prior to this.

There is no evidence of rammed earth in the Americas or Australasia prior to European settlement, even though rammed earth is now flourishing in those parts of the world. 16th century migration took the technique from Spain and Portugal to South America. 18th and 19th century migrants to North America and Australasia tried rammed earth amongst a wide range of building techniques, and a small number of historic examples have been highlighted. Chinese migration to the west coast of north America may have been responsible for the Chew Kee store in California (Easton 1996).

Rammed earth use in Europe was revitalised by the publications of Cointeraux, and translations of his work helped to spread the message far. In the 20th century rammed earth was again revived as a solution to the housing and labour shortages following each World War. Recently rammed earth has once again seen a revival in interest, this time as a sustainable building material.

Rammed earth is not a ubiquitous construction technique, instead finding niches in different parts of the world. Rammed earth is found only where certain criteria are fulfilled. The building material, namely soil, must be suitable, and the wide range of different suitable soils is testament to different mixtures which can be used. If a soil is predominantly clay, then it is more likely that moulded sun dried clay bricks will be made. If the soil is too sandy, then any attempt to make rammed earth will ultimately fail. The availability of timber is paramount. If timber is freely available, then it will be used for construction, but formwork cannot be produced if it is wholly absent. The climate in which rammed earth will survive is the source of much debate. Rammed earth is found in regions with a Mediterranean climate, which includes western Australia and the south west United States.

Differences in rammed earth construction techniques have been proposed by Jaquin, Augarde et al. (2007). Two main differences can be seen between the Muslim and Chinese types of rammed earth, in that most Muslim rammed earth is constructed using crawling formwork (Acedo 2006), and so displays characteristic putlog holes in wall. Chinese walls appear without these putlog holes (Lovell 2007), but do in some cases seem stepped, indicating perhaps that the formwork was stood on a layer below. In Spain rammed earth architecture developed over time, with the addition of fired brick to the face of a wall, or between each rammed earth lift. This Spanish rammed earth was then taken to South America where further refinements were added. It may be possible to identify rammed earth constructed following the publications of Francois Cointeraux. These suggest a number of techniques, including sloped joints between rammed earth blocks, and specific formwork sizes. Many modern builders are ignorant of the history of rammed earth and the study of historic building is able to inform modern rammed earth construction. Modern rammed earth makes use of either concrete or proprietary formwork. The historic use of crawling formwork shows that this may be used in modern construction. The survival for many centuries of unstabilised rammed earth structures shows that in some cases it is not necessary to add cement to a rammed earth mix, and that historic hand compaction may be just as effective as modern pneumatic methods. Iconic rammed earth structures, such as the Alhambra in Granada may be held up as an example of monumental architecture, allowing larger rammed earth ventures to be proposed.

This paper has provided a chronological account of rammed earth in different locations around the world. Monumental architecture has been used as references, and it is assumed that vernacular rammed earth existed where monumental rammed earth is found. It may be likely that rammed earth may be discovered at sites not yet investigated, but the fragile nature of rammed earth means that many sites may no longer exist.

Rammed earth has been used for the quick construction of fortifications, and is used where few other building materials are available. Rammed earth flourishes where labour is comparatively cheap, and has repeatedly been proposed as a solution for owner-builder construction. Most recently rammed earth has been suggested as a sustainable building technique, and it is hoped that the rich heritage of historic sites are able to inform modern construction.

Time period	Europe and North Africa	Middle East Central Asia	China	Americas	Australasia
2300-1810 BC			Lung-Shan begin building rammed mound walls around their settlements		
1900-1500 BC			Erlitou culture settlements		
1600-1000 BC			Shang era sites of Anyang		
800BC	Phoenician settlements in western Europe	Muomhong period			
200 BC	Phoenician sites in North Africa, southern France. Hannibal invades Spain, builds rammed earth watchtowers.		Qin dynasty Great wall		
200 AD			Three Kingdoms period		
500		Panjikent silk route site			
600	Muslim expansion from Arabian Peninsula to Indus river		Tang dynasty, silk route cities		
700	Muslim expansion from North Africa to Spain	Khar Balgas, Mongol site			

900	Muslim rule in parts of Spain and North Africa		End of Tang dynasty, southward movement of Hakka peoples		
1100	Almohade rule in Spain and north Africa				
1200		Genghis Khan razes many silk route sites			
1300		Muslim Buddhist building in Ladakh, Mustang and Bhutan	Ming dynasty Great Wall		
1500	Christian Spain, vernacular buildings throughout Europe. El Badi Palace constructed in Marrakesh			Spanish expansion to North and South America	
1600	Introduction of rammed earth to Switzerland	Construction of the Potala Palace			
1800	Construction following the publications of Cointeraux		Chinese migration to Americas		European migration to Australia and New Zealand
1900	WWI low cost housing in England WWII low cost housing in Germany, Scandinavia.			New Deal housing in USA	G F Middleton testing
1970	CRATerre founded			David Easton	Stephen Dobson and Giles Hohnen

Table A.1 Timeline of rammed earth around the world

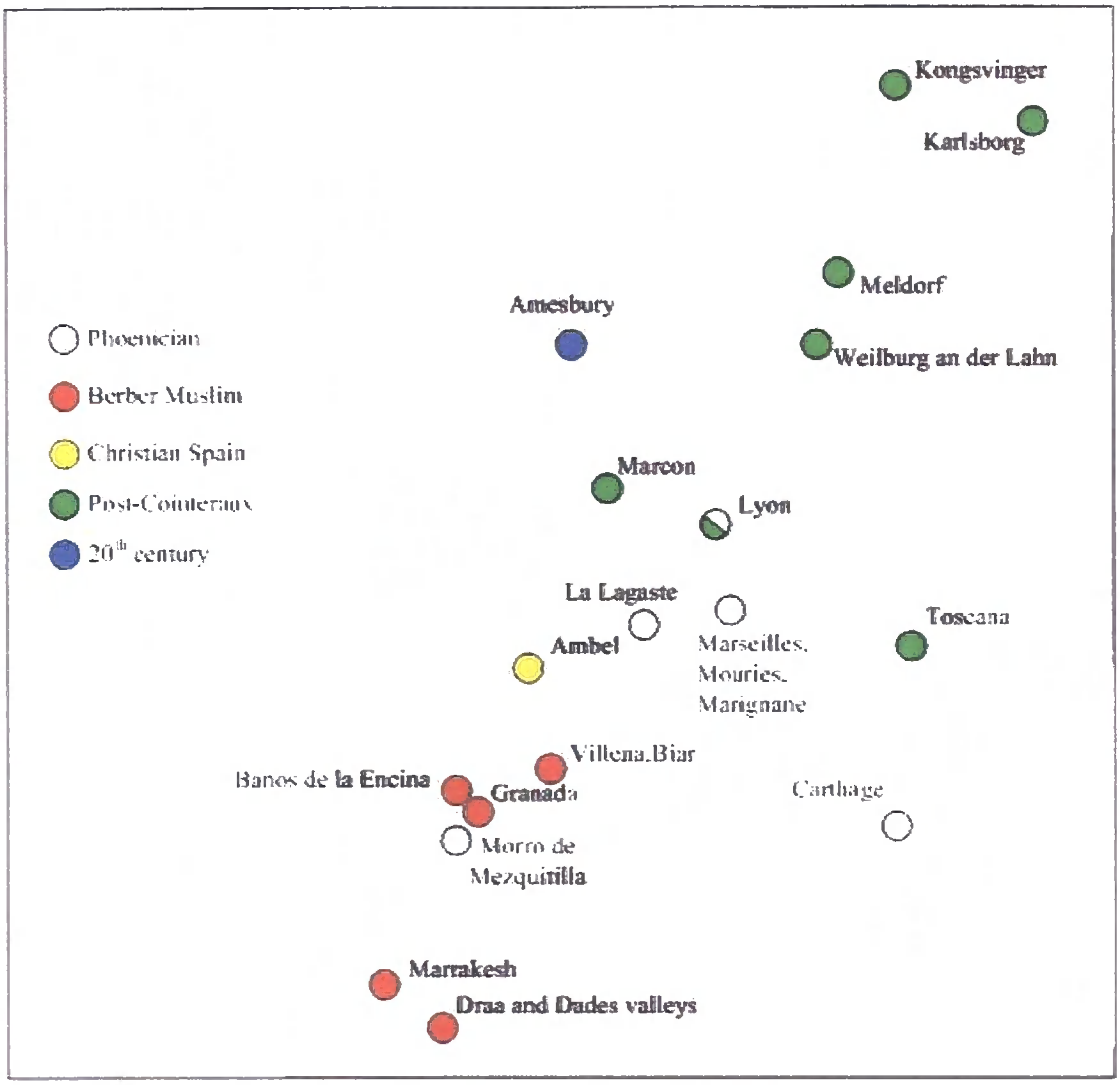


Figure A.12 Selected rammed earth sites in Europe

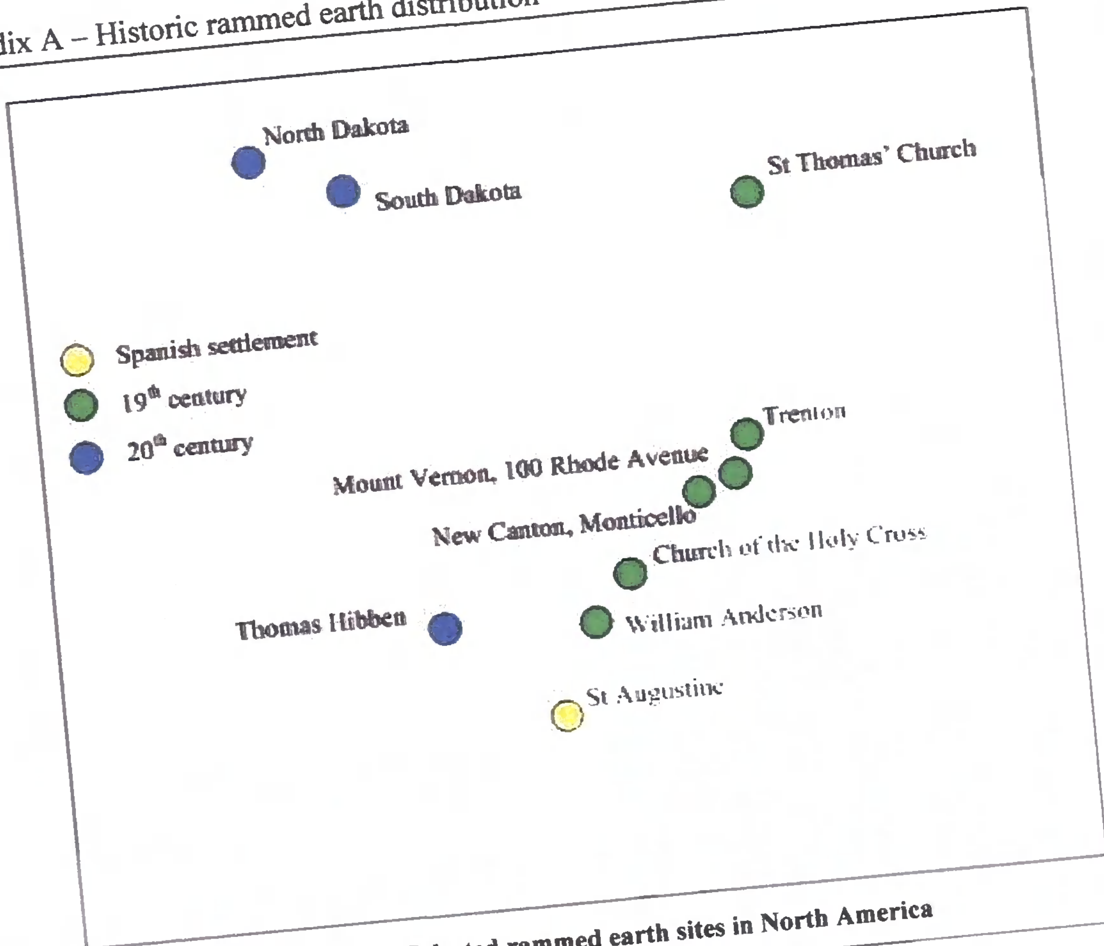


Figure A.13 Selected rammed earth sites in North America

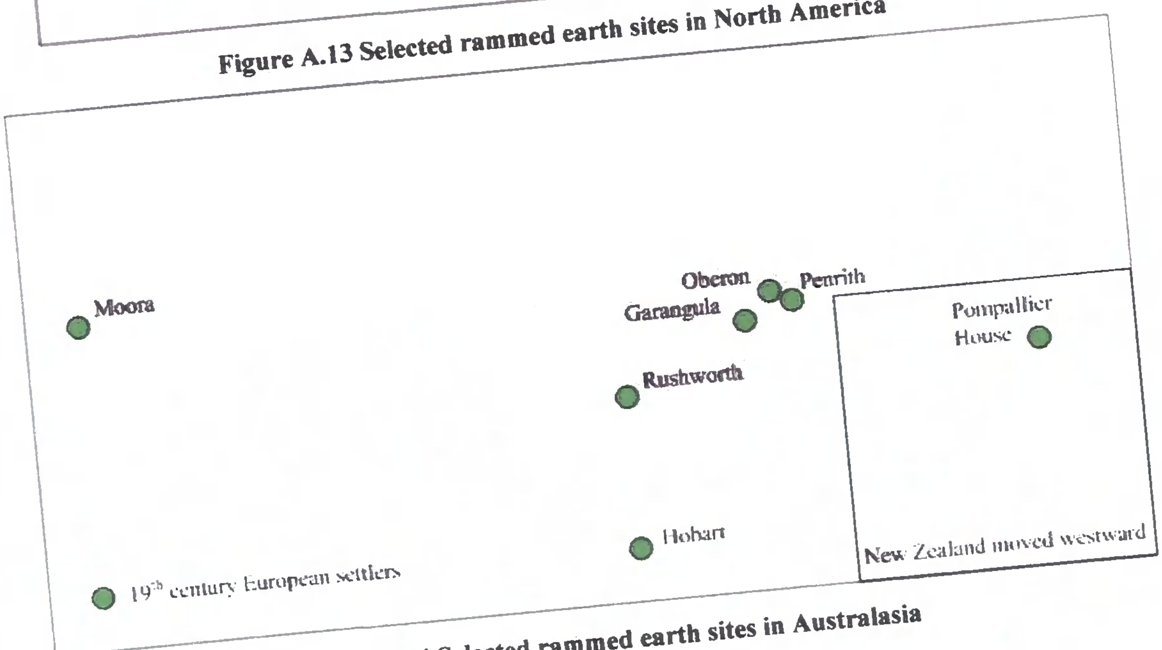


Figure A.14 Selected rammed earth sites in Australasia

Figure A.15 Selected rammed earth sites in China and Central Asia

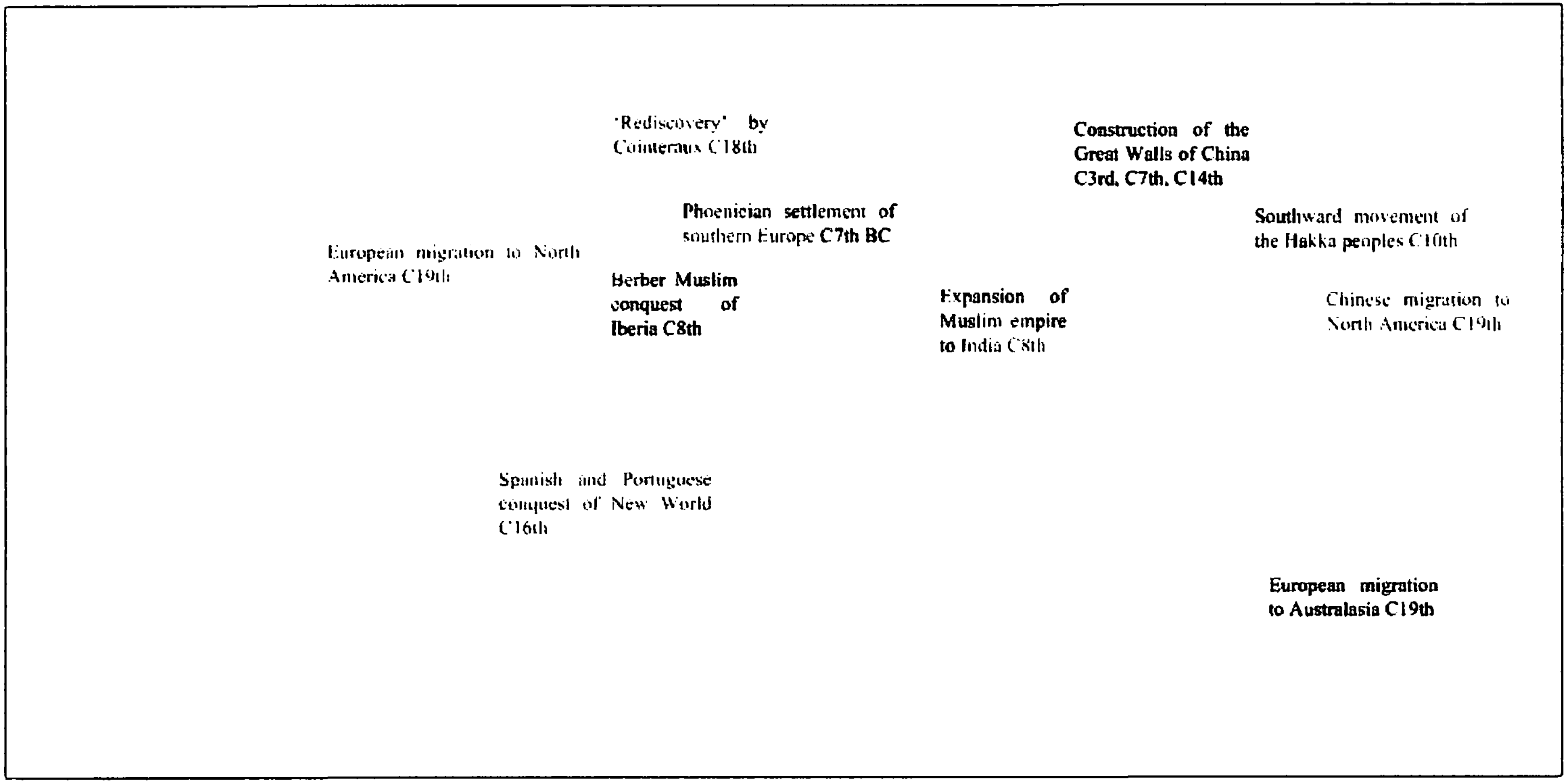


Figure A.16 Major movements of the rammed earth technique

Appendix B

North Spain

B.1 Introduction

A field visit to northern Spain was carried out in October 2007, with assistance from the Institution of Structural Engineers Rowen Travel Award. Dr Charles Augarde and Dr Chris Gerrard were present for the first three days, and for the following week I was accompanied on a number of days by Mr Nick Watson. A large number of sites were visited, not all of which were found to be rammed earth, and the four sites described in this appendix relate to those mentioned in the body of thesis. Those sites which appear briefly in the text are also shown on the map below (Figure B.1) but are not described in detail in this appendix.

Site	**ID**
Ambel north east tower	Am1
Buretta	Bu1
Daroca Torre Jaques	Da1
Daroca Great hall	Da2
Daroca 1837 castle walls	Da3
Daroca medieval city walls	Da4
Maggallon farm	Ma1
Tarazona tower	Tz1
Talamantes tower	Tl1
Villafeliche barn	Vi1
Villafeliche church	Vi2

Table B.1 Site IDs north Spain

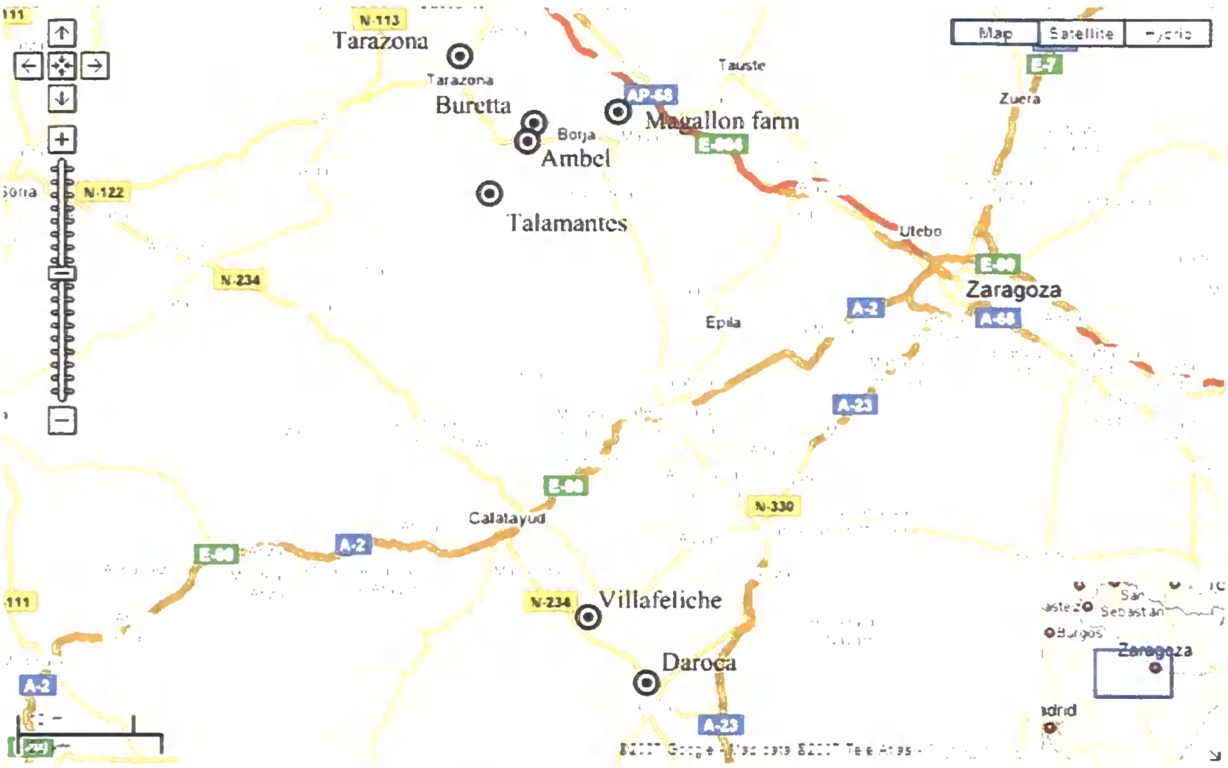


Figure B.1 Map of sites visited in northern Spain

Figure B.2 Map of Villafeliche sites

B.2 History of Spain

Spain and Portugal are unique in Europe as the only countries which have spent any period of time under Muslim rule. A development of rammed earth use in Spain is given in Appendix A. The history of the Iberian peninsula is one of competing small kingdoms, each acting relatively autonomously. The current Basque and Catalan separatist movements are a recent example of the independence of the individual regions.

Spain was settled by the seafaring Phoenicians, and remains of rammed earth sites have been found in southern Spain (Appendix A). Later Greeks and Carthaginians also settled the coastlines. Roman texts tell of rammed earth watchtowers constructed by Hannibal, the Carthaginian General, who passed through Spain to invade Rome in 218BC. The defeat of Hannibal allowed the Romans to take control of Carthaginian trading posts throughout the Mediterranean, and Roman influence was exerted over the Peninsula, leading to a Romanisation of the indigenous Celt-Iberian population. As the Roman empire decayed in the 5^{th} century AD, Germanic tribes crossed the Pyrenees, and a Visigoth kingdom was established over most of the Iberia.

In 711 a Muslim force invaded from north Africa, spreading north to occupy the majority of the Peninsula. They crossed the Pyrenees, but were defeated at the battle of Poitiers in 732. This battle stopped the advance of Muslim armies, but around 750AD the empire centred on Damascus stretched from Spain in the west to Afghanistan in the East. Internal political strife in the large empire allowed an exiled prince *Abd-ar-Rahman I* to establish himself as independent Emir of Cordoba in 750AD, wresting control of Spain and north Africa from Damascus. The power of the Cordoban rulers increased, and period from 912 to 1009AD was a golden age of Islamic science and culture. Cordoba overtook Constantinople as the most prosperous city in Europe.

Civil war in the Cordoba Caliphate in 1009 led to the break up of the kingdom, and its dissolution in many smaller kingdom known as *Taifas*. Christians to the north took advantage of the Taifa infighting, and began to spread south again, a period known as the *reconquesta*. As the Christian reconquesta spread, the Muslims of Spain were forced to appeal to the *Almoravid* Muslims of north Africa. In 1086 the *Almoravid* king crossed into Spain and forced the Christians as far north as Zaragoza. In north Africa the *Almoravids* were succeeded by the *Almohad* dynasty in 1130, and the Almohad dynasty transferred its capital to Seville in 1170. The battle of Las Navas de Tolosa in 1212 proved a turning point for the Christians, after which they spread further south, taking the strongholds of Cordoba in 1236 and Seville in 1248, eventually controlling all of the Peninsula save the Emirate of Granada. This was a time of relative religious freedom in Spain, with both Jews and Muslims living peacefully under Christian rule. The Muslims were employed as artisans, and were probably responsible for much of the actual rammed earth construction in Christian times. The people, the culture and the architecture were known variously as *Mudejar, Morisco* or *Mozarab.*

The Christian kingdoms of Aragon, Castille, León, Navarre, and Portugal operated as independent entities, but in 1469 Aragon and Castille were united by the marriage of under Isabel and Ferdinand known as the Catholic Monarchs. Together they ushered in a golden age for Spain, capturing Granada in 1492, a year which saw Christopher Columbus set sail under the patronage of Isabel. The height of Spanish power came during the Spanish Habsburg empire, under Charles I (1516 - 1556) and Phillip II (1556 - 1598). The 17^{th} century saw war throughout much of Europe, and the independence of Portugal from Spain. The War of the Spanish Succession (1701-1714) cost Spain its position as a leading player in Europe. Spain went to war with France in 1793, following the execution of the Spanish Bourbon king Louis XVI, but made peace in 1795, with Joseph Bonaparte installed as king. The French were removed from Spain following the Peninsular War, but this left Spain a shadow of it former self. A final chapter in Spain's history is the Spanish Civil War (1936-39), followed by the rule of General Franco until 1975. Spain is now a constitutional monarchy and active member of the European Union.

B.3 Ambel

The preceptory at Ambel has been extensively studied by Dr Christopher Gerrard (Gerrard 1999; Gerrard 2003) and was the building which provided the impetus for this PhD. Dr Gerrard approached the School of Engineering around 2003, looking for advice on arresting the cracking observed in the building. This led to a small investigation and MEng project (Jaquin 2004, Jaquin 2005) and a further MSc investigation (McChlery 2004). The lack of available quality advice on the conservation and repair of rammed earth structures, identified during the course of these projects led directly to the instigation of this PhD.

The chronology of the site is extremely complex, but well researched and documented (Gerrard 2003). This thesis details only part of one structure – a granary at the north east corner of the site (Figure B.3). This building has significant structural problems and is in need of both investigation and remediation. The basement appears to be a part-stone, part-brick building, with evidence of possible Roman stones used for the construction and involving the reuse of the original precinct wall. An archway in the east wall exists, which stands over a drainage channel, both of which have been blocked (Figure B.9). The archway may have originally been an entrance to the basement, and a stream which originally ran through the archway is probably that now seenon the north side of the northern precinct wall.

The earliest building on the site (Figure B.3) is a probably 11th century Islamic tower to the south of the north east tower, which is constructed from large rammed earth blocks on a mortared rubble foundation. Later rammed earth accommodation (1) and (2) were constructed between the northeast tower and the early tower. By 1380 towers (3 – 6) had been added to these living quarters, and at the same time a church was built at the south of the site, abutting the Islamic tower on its south east side.

In the mid 16th century the complex expanded, and earlier buildings at the north east of the present complex were partially rebuilt, creating wine cellars and granaries which form the core of the current structure. In 1569 further granaries were built in the north west corner of the complex (7), creating a courtyard in the centre. Some time after this the southern end of the floor of the first floor is thought to have collapsed, shown by changing tile patterns on the floor at first floor level, and new columns and repaired beams at the ground floor.

By 1797 the building had fallen into disrepair, and at this time the two 14th century towers (3 and 4) were removed and the roof of the north east tower was replaced. There is evidence for a multitude of repairs to the north wall of the structure, with timber tie beams being inserted in the walls at the top and first floor levels. The ceiling jack arches and beams also show evidence of 19th century repairs.

In the 1960s two families were occupying the site, the building passed to its current owners in the 1980s when crack monitoring was initiated in the north east tower. The crack data is reproduced in Figure B.12 and the location of the monitoring points is shown in Figure B.16. This monitoring showed continued movement of the north wall, and in 2000 tie bars were placed at ceiling level at the ground, first and roof levels, fixed internally by being bolted to the ceiling beams and externally to H bars at the face.

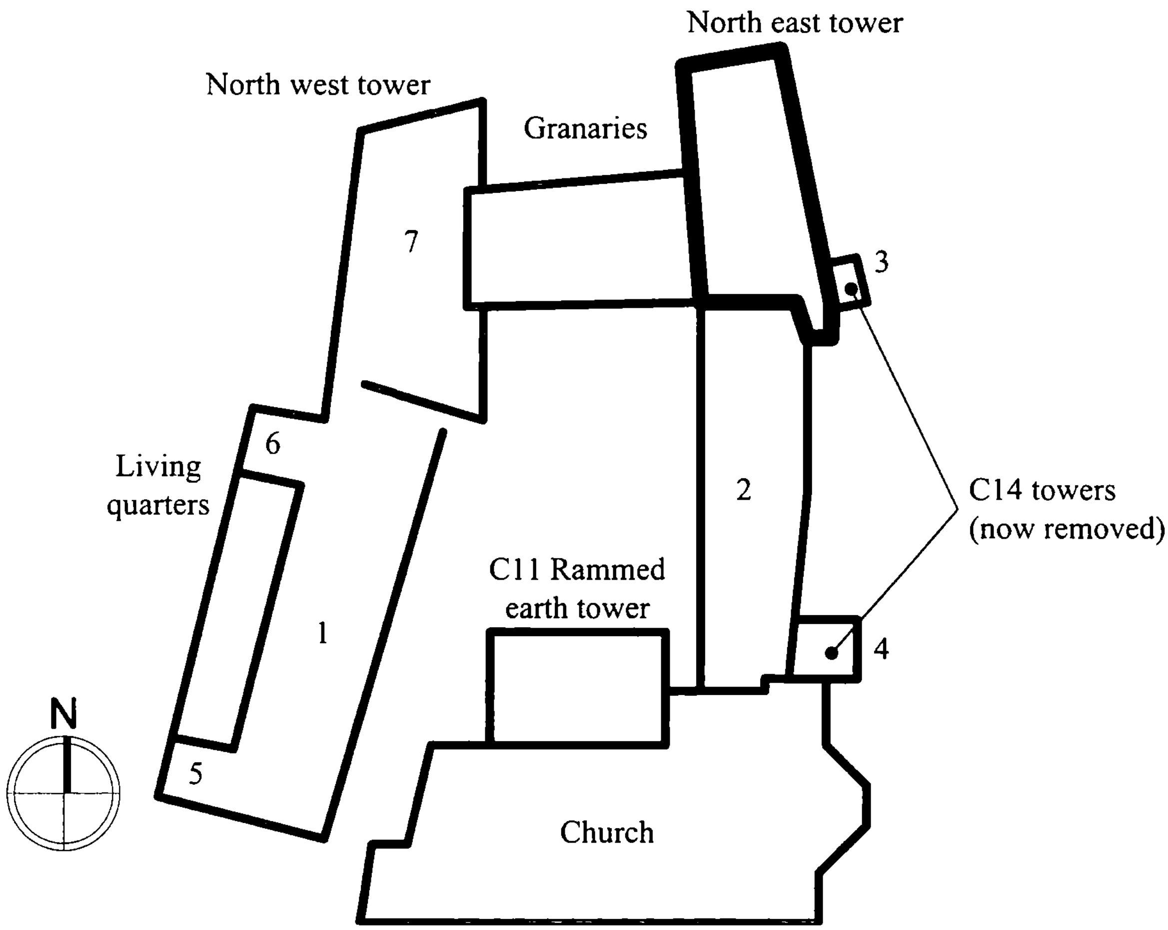


Figure B.3 Ambel site plan

B.3.1 The north east tower

The north east tower (bolded in Figure B.3) is the main subject of investigation in this thesis. The structure was also the subject of investigation by Jaquin (2004) and McChlery (2004). The building was extensively surveyed in October 2006 and plans and elevations are shown in Figure B.4 to Figure B.8. Monitoring of the cracks has taken place since 1997, and the results of this monitoring are shown in Figure B.16. A tentative chronology, based on Gerrard (2003) is shown in Figure B.18 to Figure B.20.

The structure is built on bedrock, high to the south of the site, and sloping to the north. There is evidence of a water course beneath the present structure, which has now been diverted to run across the north side of the current building within a concrete culvert. The stream (an irrigation canal) runs parallel to a road, which is adjacent to a field. The level of the field is around 2m below that of the road, with a retaining wall separating the road and the field (Figure B.10).

In Chapter 5 it is argued that the north east corner of the structure is settling with respect to the rest, as evidenced by the cracking pattern on the north east tower (described in Chapter 5, and the cracking pattern on the central section of the building (Figure B.11).

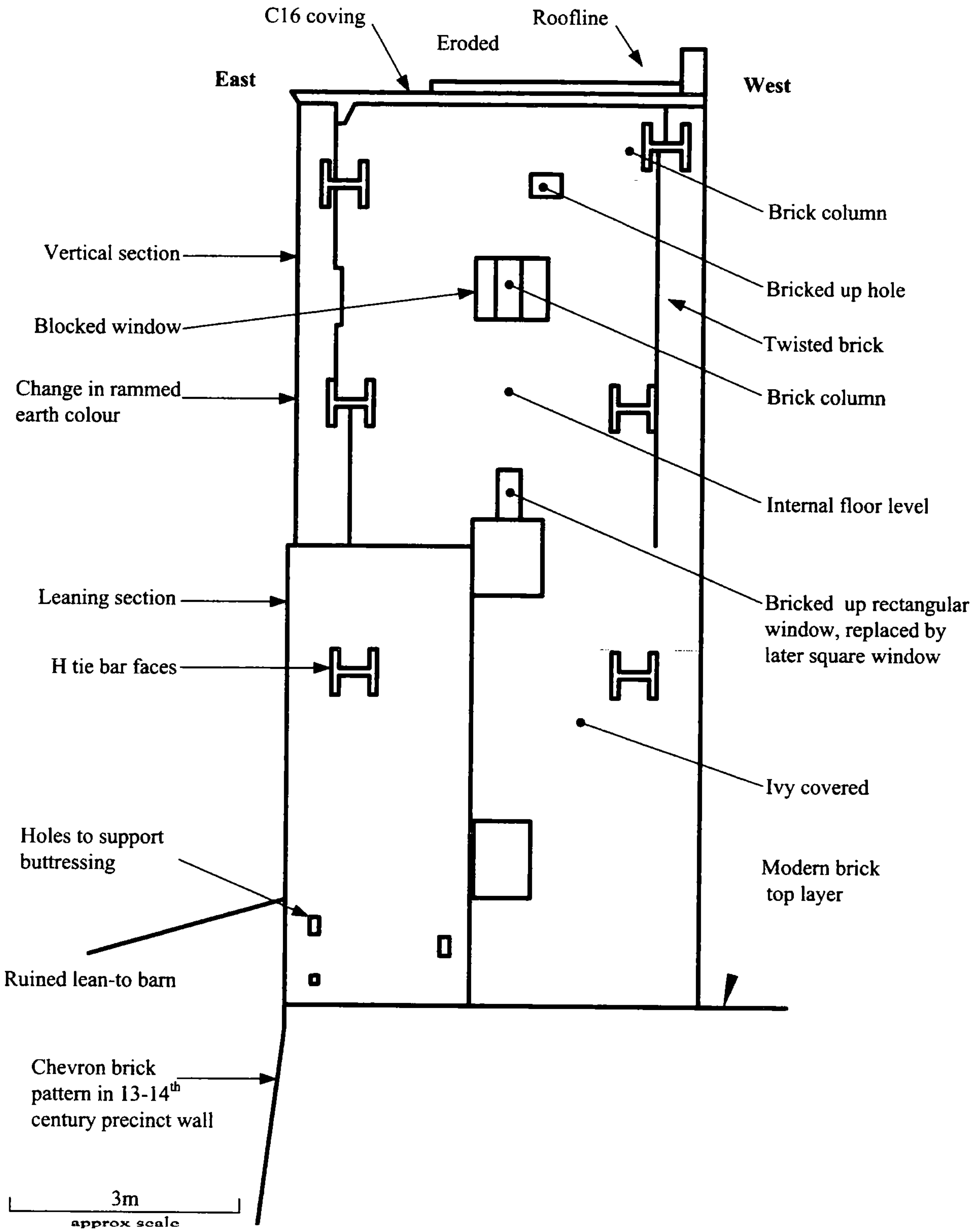


Figure B.4 Am1 Ambel north east tower north face external elevation

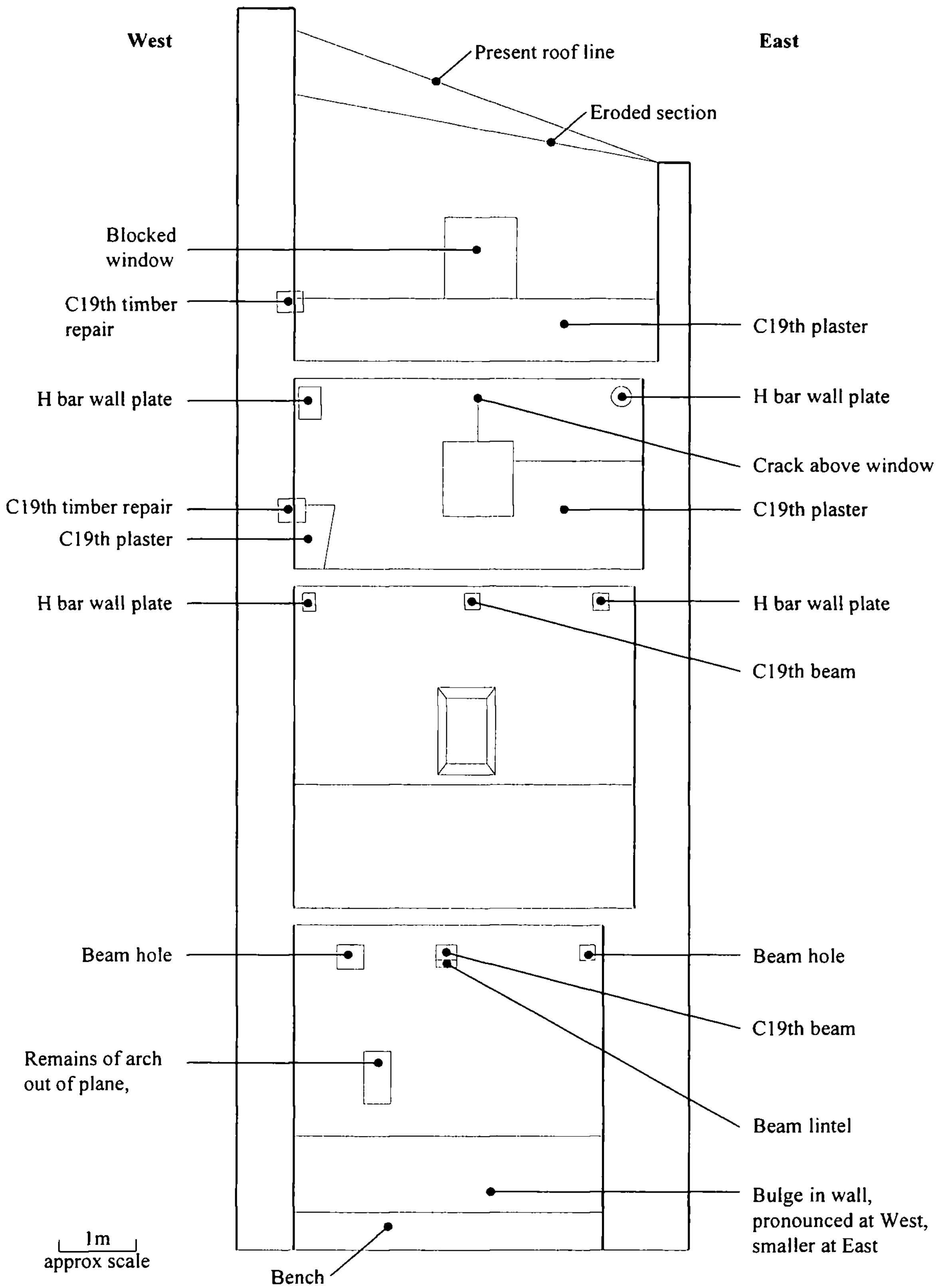


Figure B.5 Am1 Ambel north east tower north face internal elevation

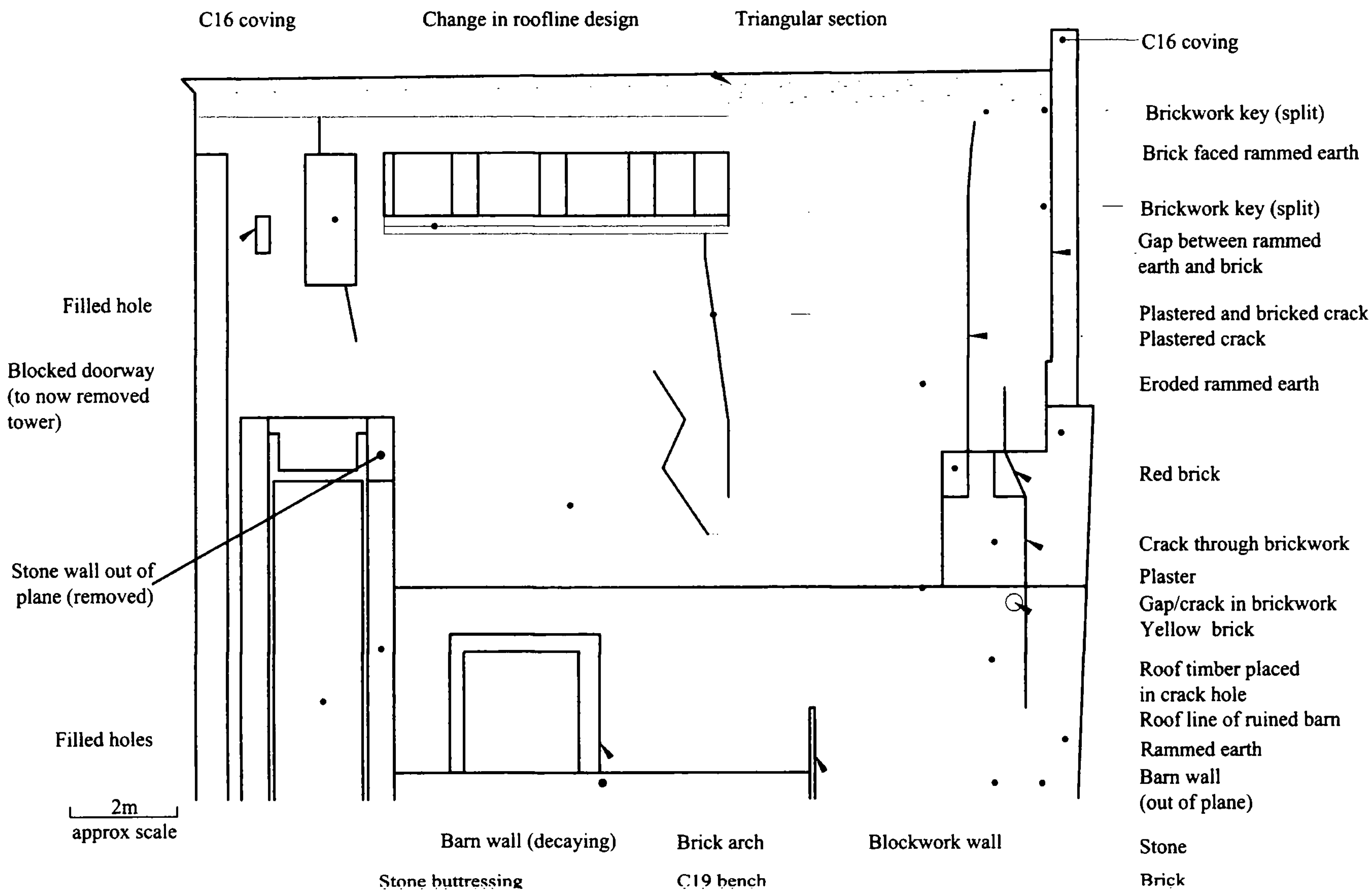


Figure B.6 Am1 Ambel north east tower, east face external elevation

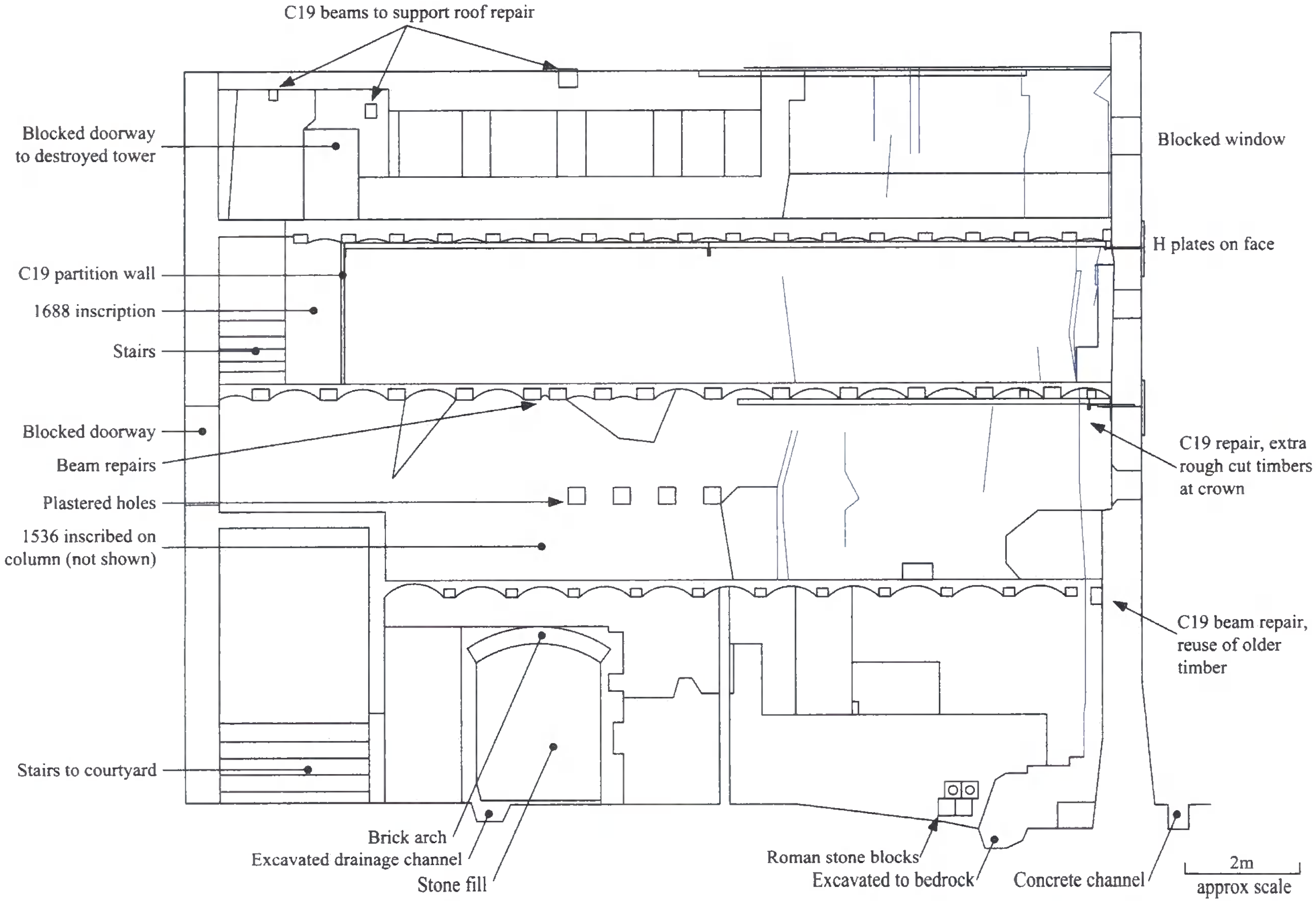


Figure B.7 Am1 Ambel north east tower east face elevation internal of the east wall, here inverted to match the external elevation. Cracks shown in blue

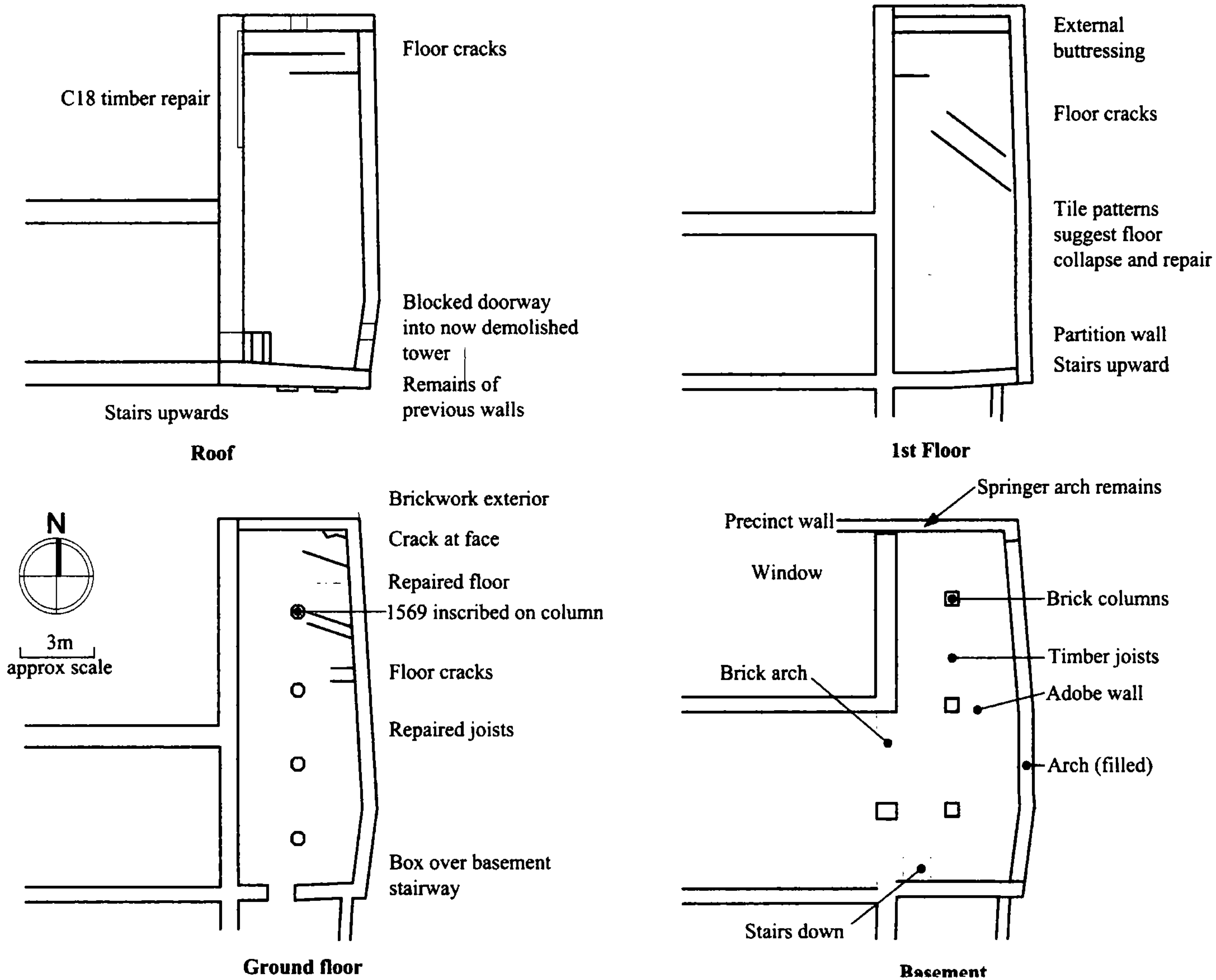


Figure B.8 Am1 Ambel north east tower plan

Figure B.9 Am1 Ambel north east tower, east face elevation

Figure B.10 Am1 Ambel north east elevation

Figure B.11 Central section of Ambel preceptory. Cracks suggest settlement of north east tower (left)

Figure B.12 Am1 Ambel north east tower north face external photograph

Figure B.13 Cracks 1 to 4. East wall internal. Roof level of north east tower

Figure B.14 Cracks 5 to 7 and timber repair. West wall internal. Roof level of north east tower

Figure B.15 Cracks 9 (left) and 10 (right), and gap between floor and wall. First floor. East wall of north east tower

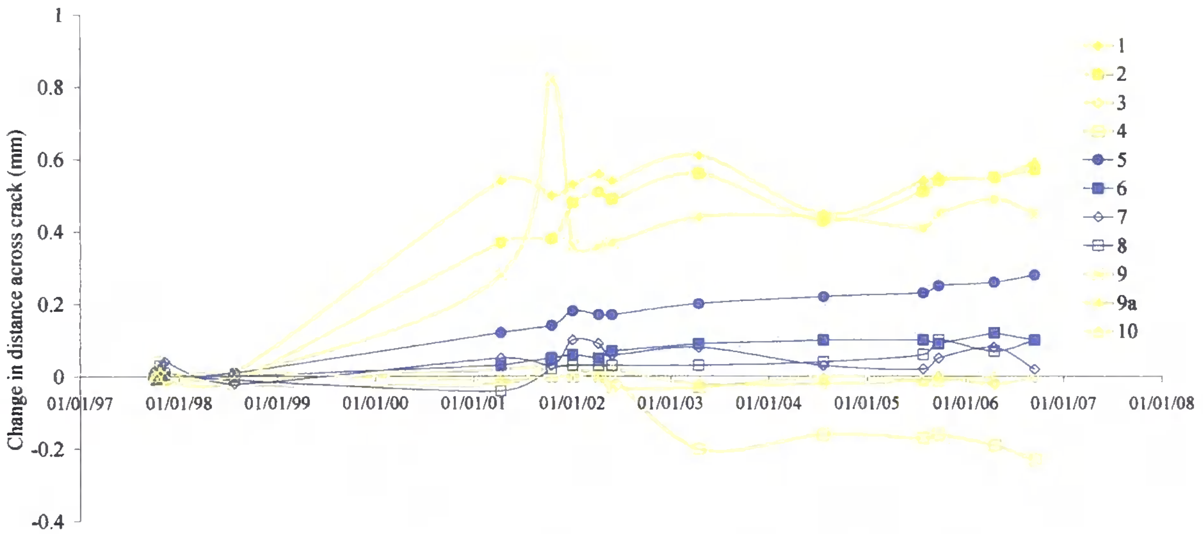


Figure B.16 Crack monitoring data in Ambel north east tower

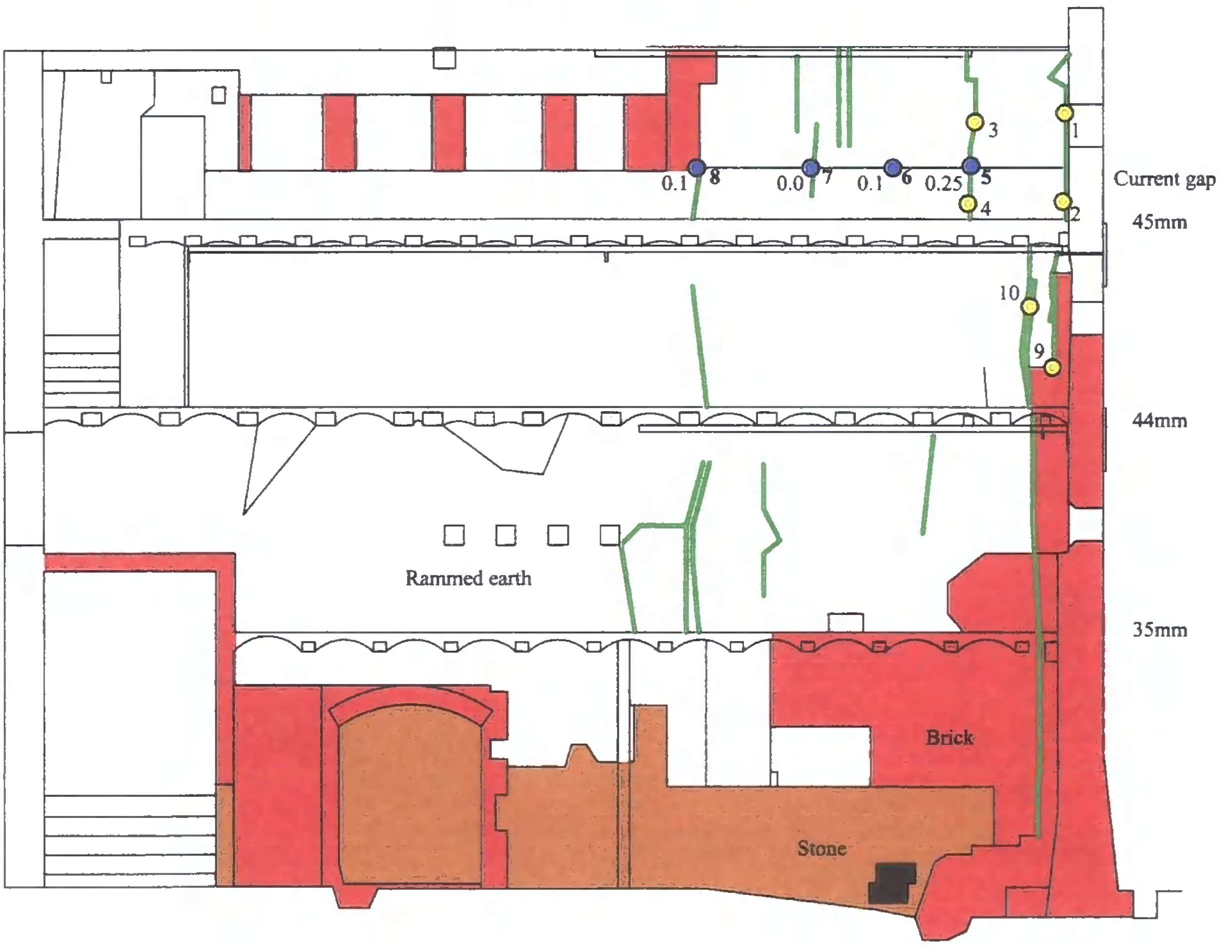
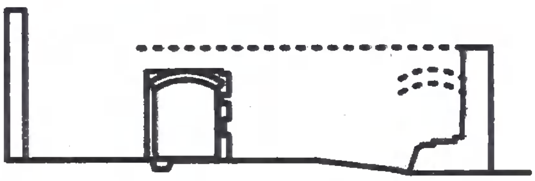


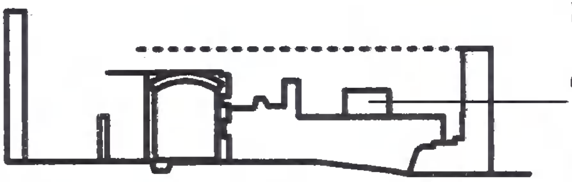
Figure B.17 Crack monitoring points and construction materials. Ambel north east tower internal elevation of the west face of the east wall. Inverted to match external elevation.

Rammed earth building to south of site
Stream running north of this building



Brick structure one the site of the current building. Arch acts as entrance to current courtyard.

Remains of further arch at the north of site, at base of current gable end.

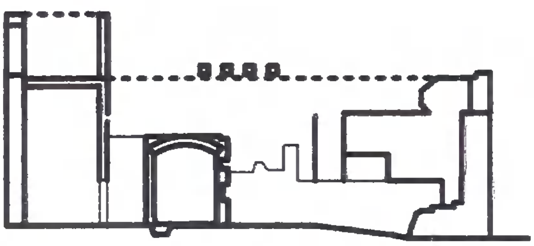


Stone building constructing above foundations of previous stone building. Stone possibly used as base for rammed earth structure.

Building extends to current stairs to south

Brick arch filled.

Only remaining rammed earth block



13th century

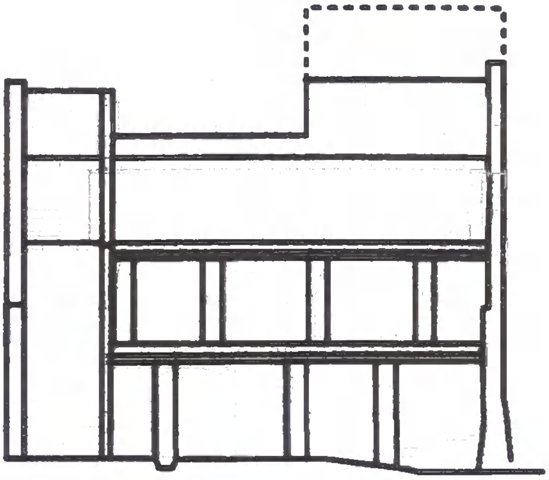
Previous stone/rammed earth building collapses/ removed

Build new rammed earth and brick building. Large rammed earth formwork used.

Possible roofline still visible within formwork.

Tower constructed at south of site, access at ground floor level

Figure B.18 Chronology of Ambel North East Tower - 1



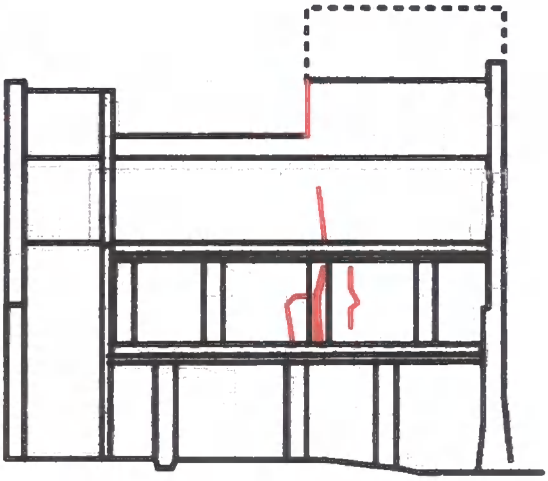
Before 1536

Construction of major face. Similar to the rest of the north west.

Gable end constructed vertically above outward leaning base

North section may have been higher

Date inscribed on column at ground floor

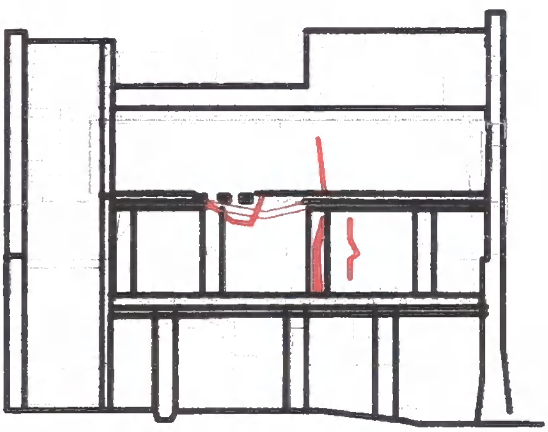


After 1536

Cracking in centre of wall, likely caused by differential settlement of north section of wall.

Continual rebuilding of north section of this wall indicates settlement problems.

Diversion of watercourse may have led to change in groundwater distribution



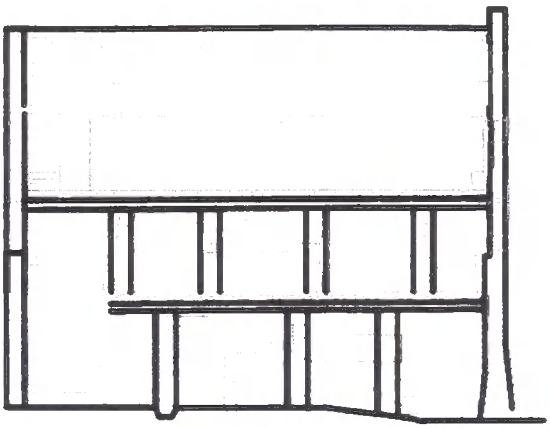
Before 1796

1st floor collapse, likely due to overloading of floor when used as a granary.

May exacerbate central cracking, causes 1st floor to fail.

Removal of north section of tower (change in roofline)

Figure B.19 Chronology of Ambel North East Tower - 2



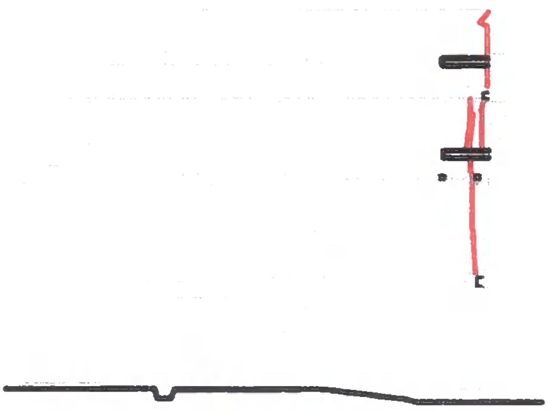
1796

Repair of 1st floor collapse, instllation of octagonal columns on ground floor, reconstruction of 1st floor level floor. Possible construction of basement columns. 1st floor columns not placed above basement columns.

Removal of 13th century tower

Removal of north section of tower

Construction of windows in central section



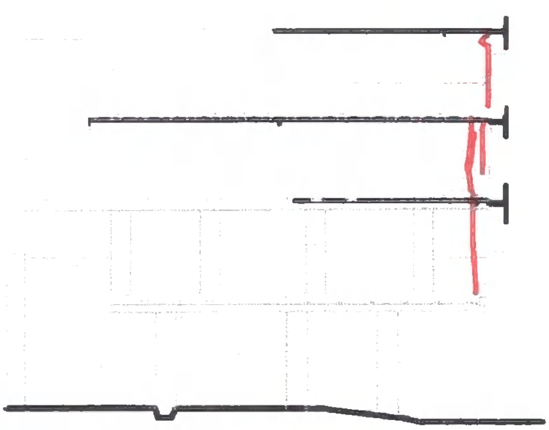
After 1796

Continued lean of gable end causes alarm.

Placement of timber beams tying the gable end to the perpendicular walls at the roof and 1st floor level. Reconstruction of the ceiling arches at the 1st, ground and basement levels. Reuse of timbers at the basement and 1st floor, additional timbers placed at arch crowns at ground floor.

Cracking of floor at 1st and ground level, suggesting differential settlement of gable end.

Possibly reconstruction of the roof.



2000

Continued movement of gable end

Placement of H bars, placed at the face of the rammed earth, and bolted to the ceiling beams

Figure B.20 Chronology of Ambel North East Tower - 3

B.4 Daroca

The city of Daroca is encircled by a number of different rammed earth walls, with watchtowers and forts on high points surrounding the city. A historic rammed earth wall encircled the city (Da1). Torre Jaques (Da1) was built in many stages as indicated by the numerous rammed earth construction techniques which can be seen in the face. The base of the tower is constructed completely in random rubble masonry, and the only entrance to the tower is around 6m above ground level. The Great Hall at Daroca (Da3) is constructed in rammed earth, but it appears that vertical timbers were used every 5m, either to prevent shrinkage, or to support a roof structure. When the building was abandoned the timbers were removed, leaving only the rammed earth which is visible today. In 1837 the town of Daroca came under attack and a rammed earth defensive wall was built around important sites (Da4). This wall still survives, and the holes in the wall are rifle ports, overlooking the city.

Date	**Activity**
	Roman town of Agiria with a castle constructed on the route between Zaragoza and Valencia
862	Town conquered by Muslims and renamed *Calat-Darawca*
1120	Alfonso I conquers town, becomes a major centre in the south of Aragon
1239	Christian troops gather at Daroca to conquer the Muslim castle of *Chio* in Jativa. Miracle of Daroca.
1357	Pedro IV of Castille attempts, to invade Aragon but is held at Daroca.
1706	Daroca sides with Austria against France, but is occupied and sacked. Influence of town reduces.
1808-1813	Spanish war of Independence. Napoleon enters Daroca and leaves a permanent garrison.
1834, 1837, 1872	Daroca central in the Carlista civil wars, sporadically occupied. Reconstruction of the castle walls in rammed earth (Da4)

Table B.2 Chronology of Daroca

Figure B.21 Aerial photograph of Daroca, showing location of the sites

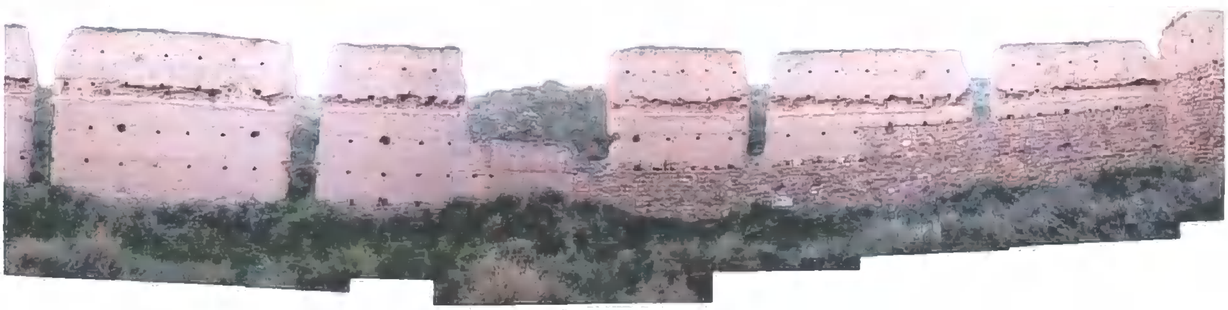


Figure B.22 Da2 Daroca Great Hall

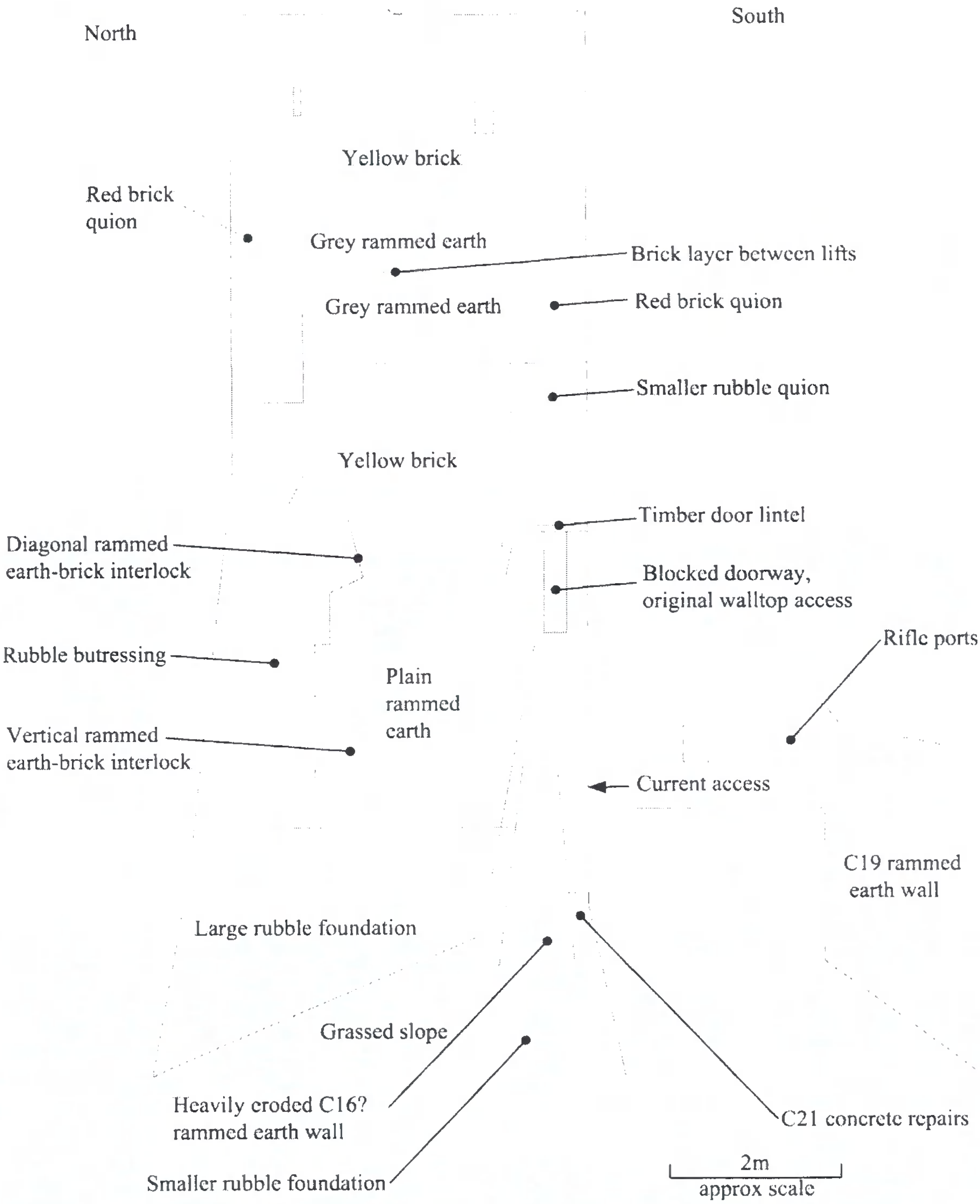


Figure B.23 Da1 Daroca *Torre Jaques* elevation

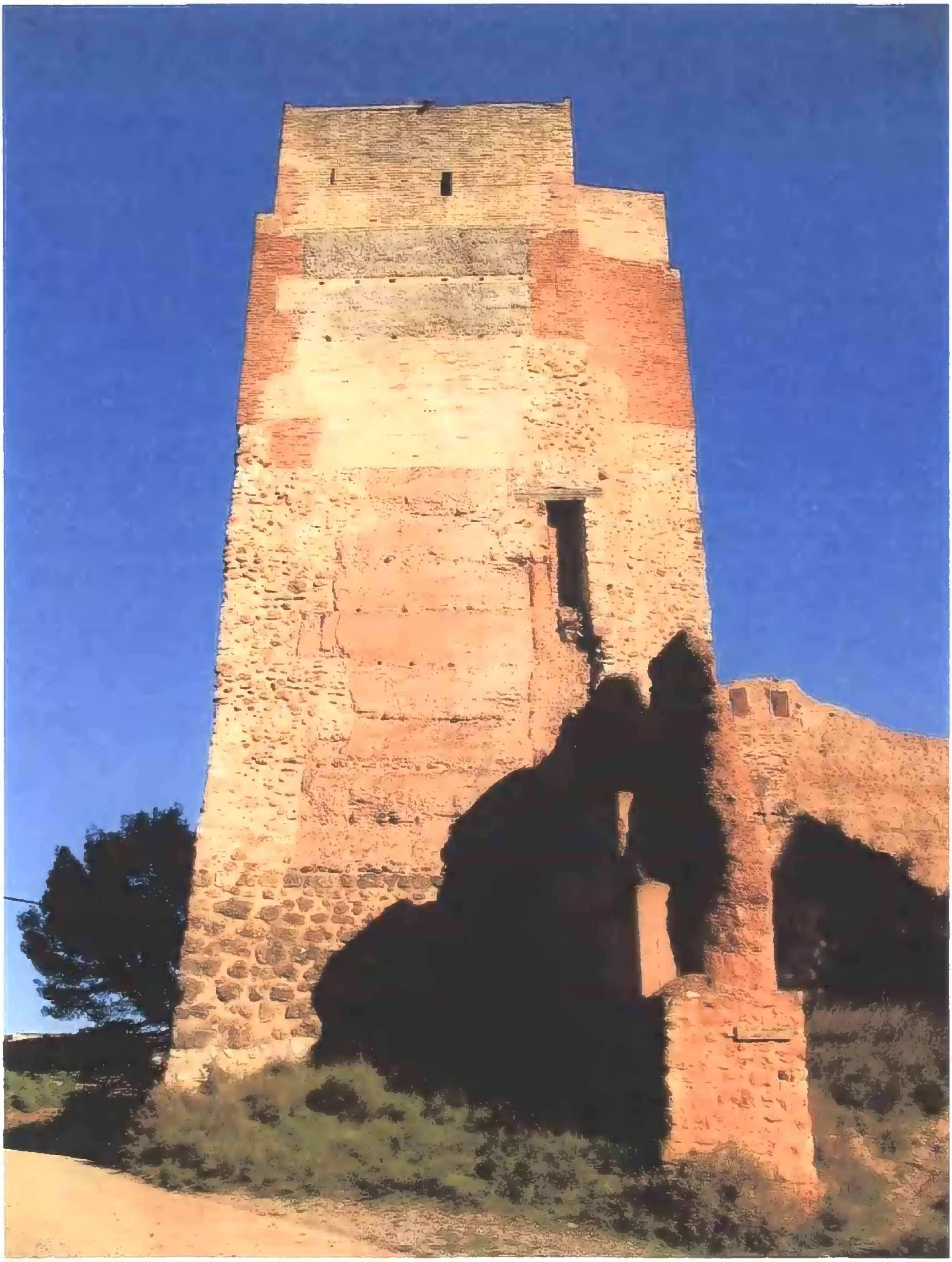


Figure B.24 Dal Daroca *Torre Jaques* photograph

Figure B.25 Da3 Daroca 1837 castle walls

Figure B.26 Da4 Daroca city walls north

B.5 Villafeliche barn

A barn observed at Villafeliche provides an excellent example of combined water and structural problems. The method of construction is similar to that found in southern France, but known in Spanish as *Tapial con Lunetos* as a reference to the half moon shaped lime sections in the corners of each rammed earth block. The barn is situated on the main thoroughfare into the village and appears to still be in use. The historic building abuts a concrete barn but does not appear to be structurally connected to it. The rear wall of the historic structure may be acting as a retaining wall, but this was impossible to establish. Unfortunately access internally was not possible. A diagram of the building is shown in Figure B.27.

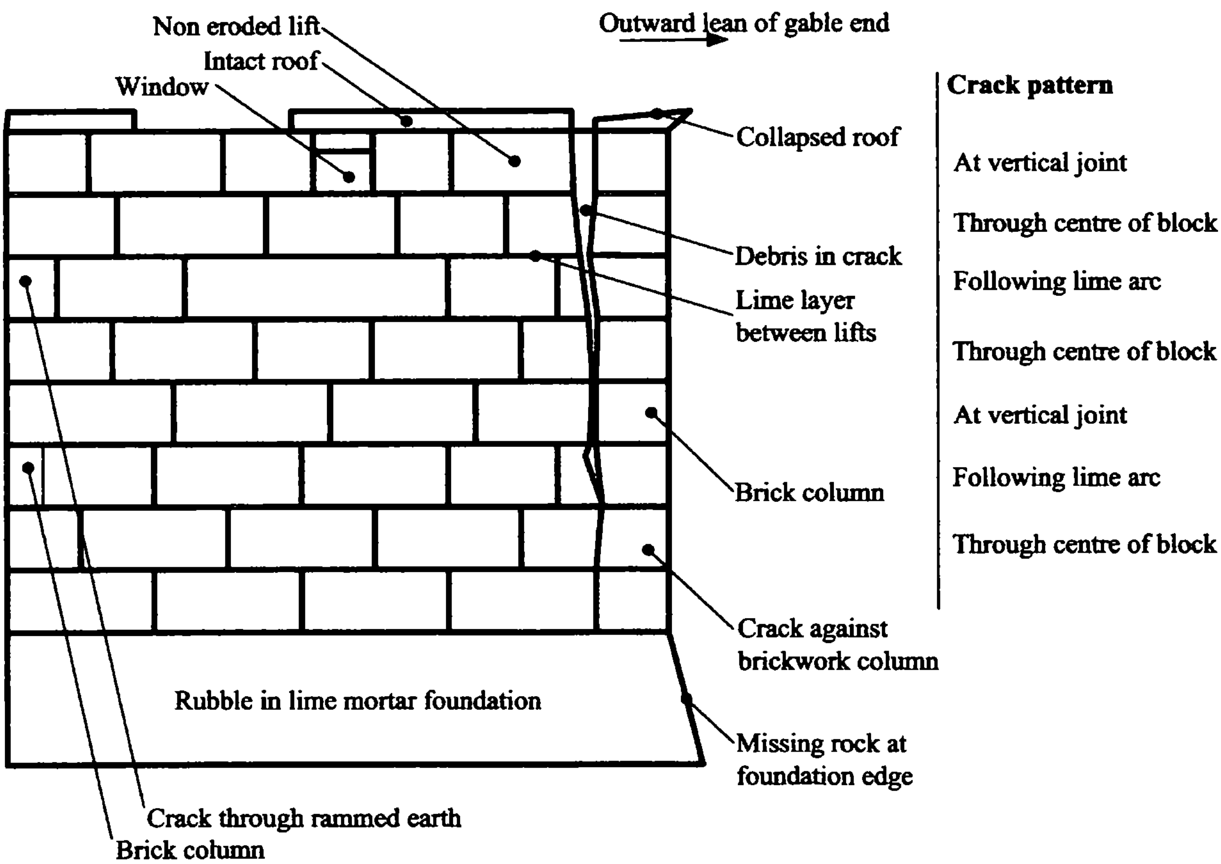


Figure B.27 Vil Villafeliche barn elevation

Figure B.28 Vi1 Villafeliche barn elevation photograph

Figure B.29 Vil Villafeliche barn crack photograph

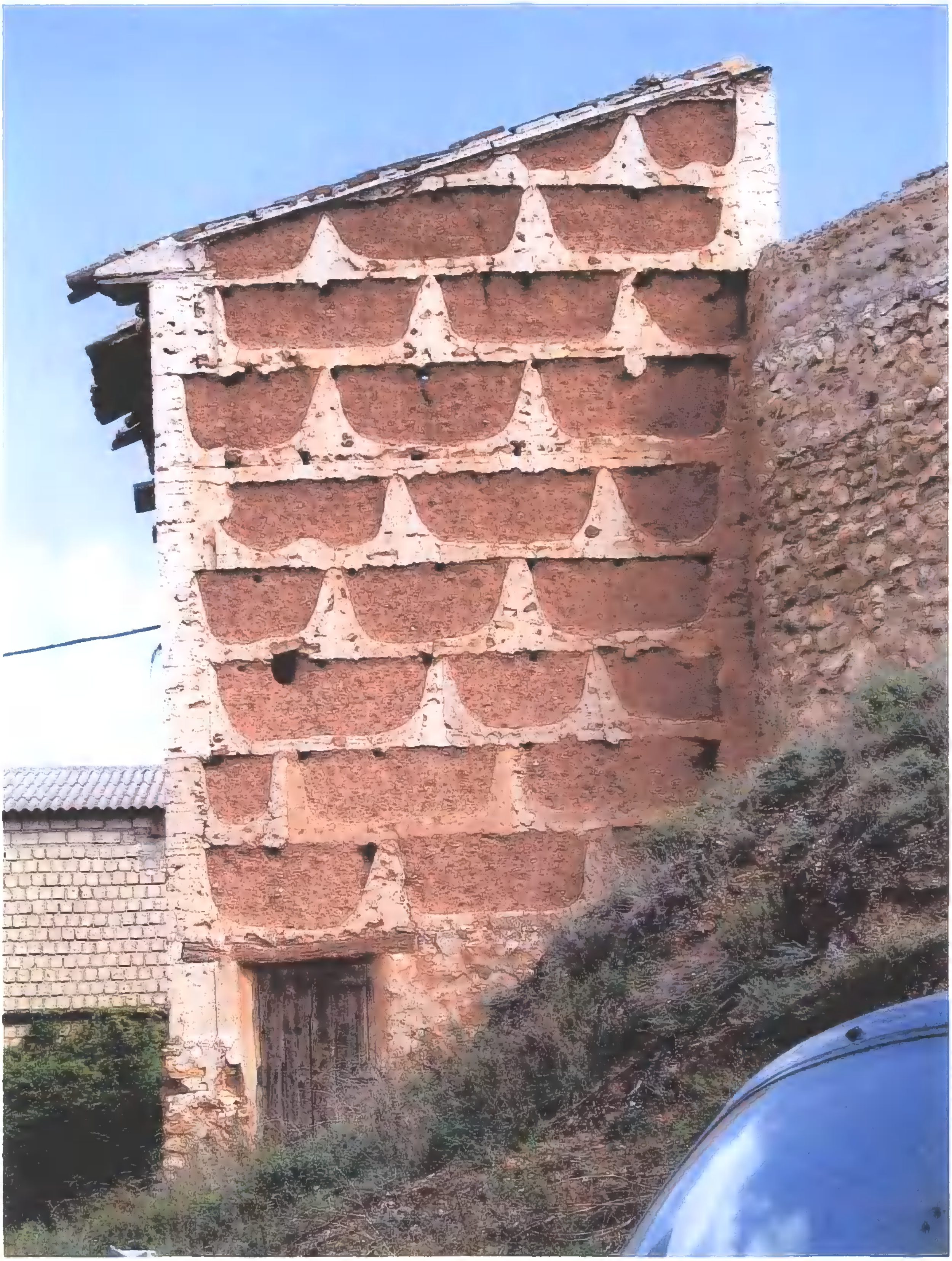


Figure B.30 Vi1 Villafeliche barn gable end photograph

B.6 Villafeliche Church

The chapel in Villafeliche was probably built in the 19th century, and is located on the outskirts of the village. The distinctive patterns of brickwork beams and columns with rammed earth infill is similar to that found at Ambel and Buretta. However, the placement of red tiles in the centre of the rammed earth section appears unique to the village, being found at a number of sites in the village and on garden walls in the surrounding area. The chapel consists of a core square of sixteen columns, with semicircular extensions to the north, south and east sides. The nave and entrance is to the west of the structure and appears to have been added at a later date. A plan of the structure is shown in Figure B.31 and an elevation of the east face in Figure B.32 and Figure B.33. A photograph of the west elevation, showing the majority of the destruction is shown in Figure B.34, and an internal composite photograph, looking north east is shown in Figure B.35.

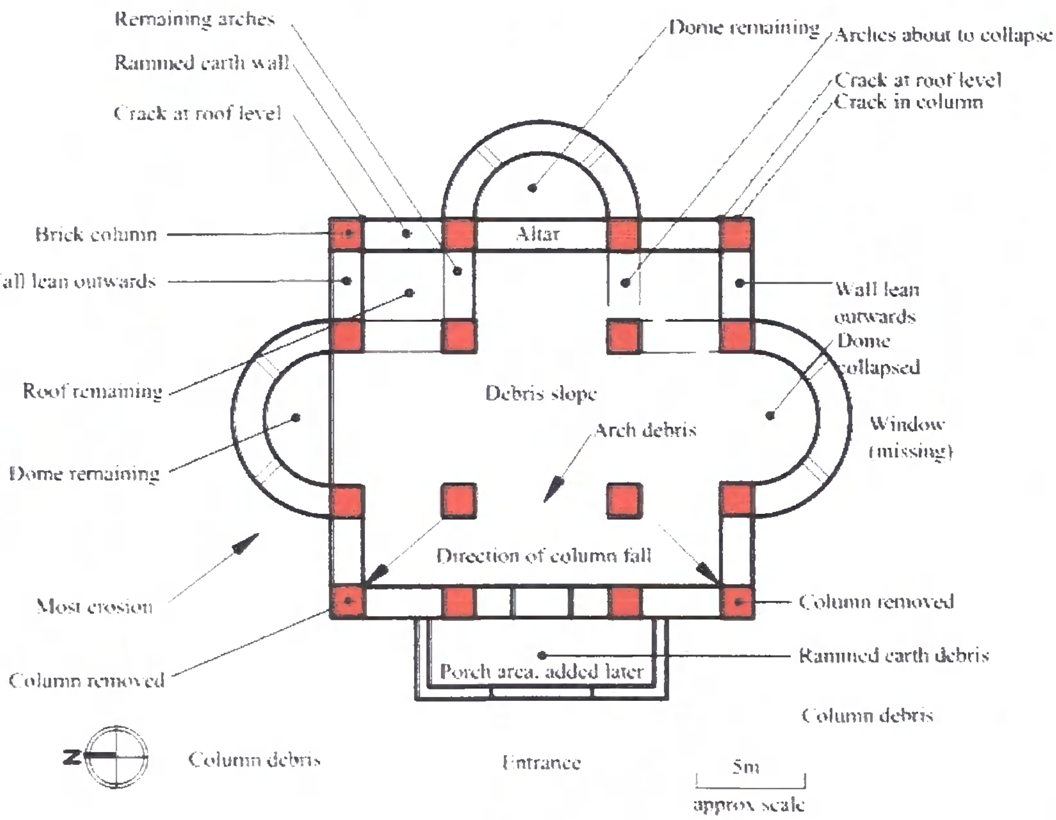


Figure B.31 Vi2 Villafeliche church plan

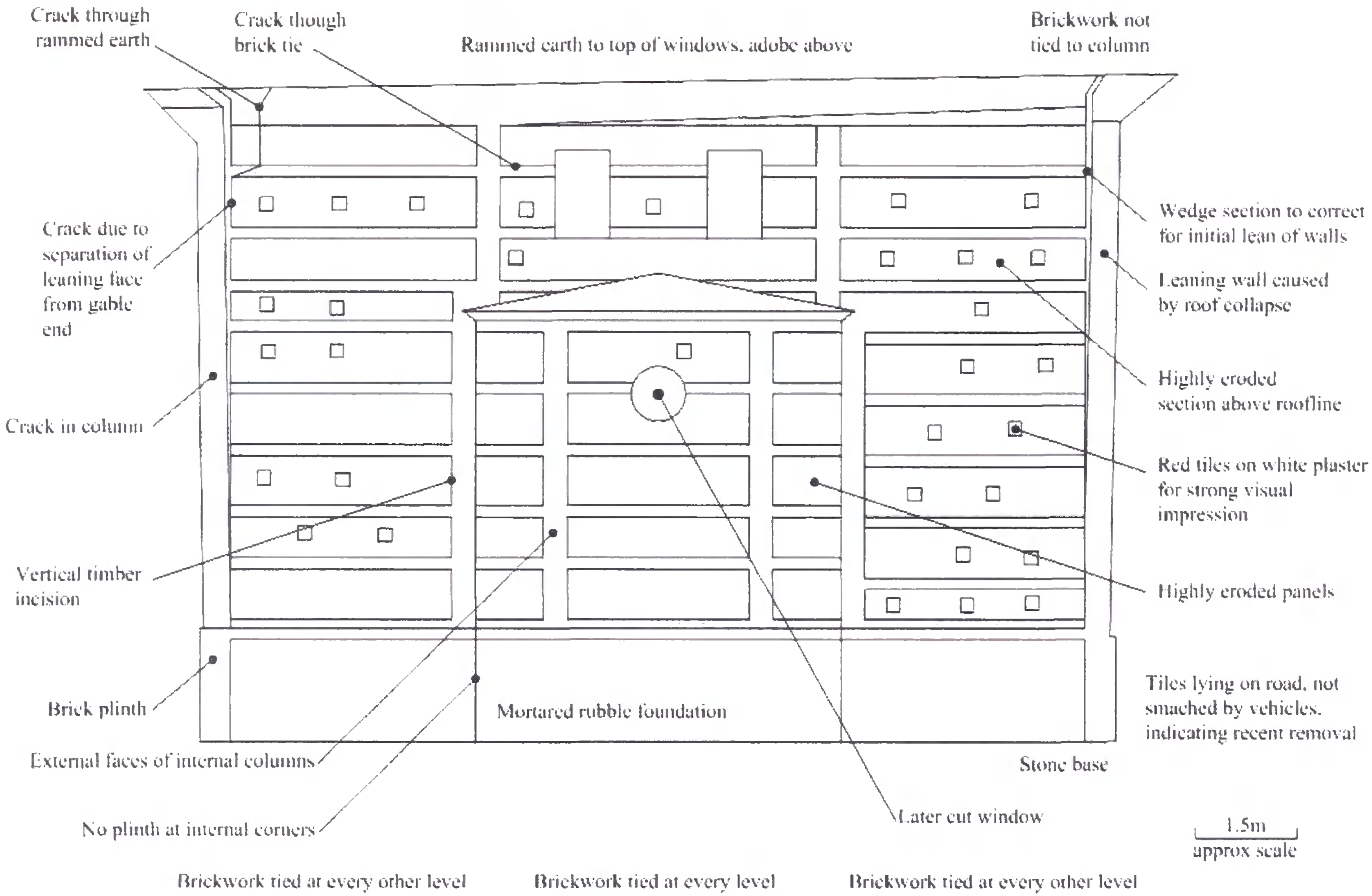


Figure B.32 Vi2 Villafeliche church east elevation

Figure B.33 Vi2 Villafeliche church east face photograph

Figure B.34 Vi2 Villafeliche chapel west elevation

Figure B.35 Vi2 Villafeliche chapel internal, looking north east

Appendix C

South Spain

C.1 Introduction

Seventeen locations in southern Spain were visited in January 2006. Over a two week period I travelled from Murcia in western Spain to Seville in southern Spain. The seventeen locations have been further split into individual sites which range from whole castle complexes through individual to individual walls or parts of city walls and are listed in Table C.1. The locations of the sites are shown in Figure C.1, Figure C.2 and Figure C.3

Site	**ID**
Alcala de Guadaira. *Alcazar* Real	Al1
Alcala de Guadaira. Stone towers	Al2
Alcala de Guadaira. Curtain walls	Al3
Alcala de Guadaira. Patio de la Sima wall	Al4
Alcala de Guadaira. Mudejar quarters	Al5
Alcala de Guadaira. Arab baths	Al6
Baños de la Encina castle	Ba1
Biar castle	Bi1
Carmona castle. Earthquake damaged tower	Ca1
Carmona castle. Ruined hall	Ca2
Carmona castle. Exterior wall	Ca3
Cordoba. Perimeter wall of Christian *Alcazar*	Co1
Cordoba. Perimeter wall of Christian *Alcazar*	Co2
Cordoba. Perimeter wall of Christian *Alcazar*	Co3
Cordoba. Perimeter wall of Christian *Alcazar*	Co4
Cordoba. Muslim city wall	Co5
Cordoba. Muslim city wall	Co6
Cox castle	Cx1
Elche. Altamira castle	El1
Elche. Town hall	El2
Elche. Ruins	El3
Granada Alhambra. *Alcazar*	Gr1
Granada Alhambra. Bell tower	Gr2

Granada Alhambra. Partial Gardens walls	Gr3
Granada Alhambra. Tower of Seven floors	Gr4
Granada Alhambra. Justice Gate	Gr5
Granada Alhambra. Water tower	Gr6
Granada Alhambra. Tower Balthazar of Cross	Gr7
Granada Alhambra. Spiked Tower	Gr8
Granada Alhambra. Princess Tower	Gr9
Jaen town walls	Ja1
La Rambla tower	Ra1
La Rambla wall	Ra2
Lorca tower	Lo1
Novelda castle. Tower	No1
Novelda castle. Rammed earth tower	No2
Novelda castle. Concrete repair	No3
Novelda castle. Eroded wall	No4
Malaga castle rammed earth wall	Ma1
Malaga castle brick and stone repair	Ma2
Palma del Rio. Muslim castle	Pa1
Palma del Rio. Eroded wall section	Pa2
Palma del Rio. Wall repair in concrete	Pa3
Palma del Rio. Octagonal tower	Pa4
Palma del Rio. Town walls	Pa5
Salobrena castle	Sa1
Seville *Alcazar*	Se1
Seville city walls	Se2
Seville double city walls	Se3
Tabernas castle. Rubble faced rammed earth	Ta1
Tabernas castle. Destroyed tower	Ta2
Tabernas castle. Rammed earth wall section	Ta3
Tabernas castle. Repaired face	Ta4
Tabernas castle. Interior of castle	Ta5
Villena castle	Vi1

Table C.1 Site IDs north Spain

Figure C.1 North western sites

Figure C.2 Southern sites

Figure C.3 South western sites

C.2 Alcalá de Guadaira

The site at Alcalá de Guadaira, to the east of Seville was surveyed in the rain. This provided an opportunity to see rammed earth behaviour during a severe rainstorm. The history of the site is given in Table C.2 (García 2006).

Date	**Activity**
	Bronze Age settlement on the site
12th century	*Almohad* fortress built in response to internal conflicts within. Construction of the *Qalat Yabir* and *Patio de los Silos* courtyard. Construction of the Arab baths. Construction of the Patio de la Sima courtyard of which only north wall remains.
1247	Fortress conquered by Ferdinand III. The two 8 sided towers constructed sometime after this.
1312-1350	Castle owned by Leonor de Guzman during the reign of Alfonso XI, Royal *Alcazar* complex built.
1471-1477	Owned by the Marquis of Cadiz, rammed earth curtain walls and a moat added. Reconstruction of the enclosing walls in the Patio de la Sima.
1530	Owned by Enriquez de Ribera family, *mudejar* quarters added
1940	Restoration by Felix Hernandez
1970	Restoration by Rafael Manzano
1999	Archaeological excavations of the Patio de la Sima courtyard

Table C.2 Chronology of Alcalá de Guadaira

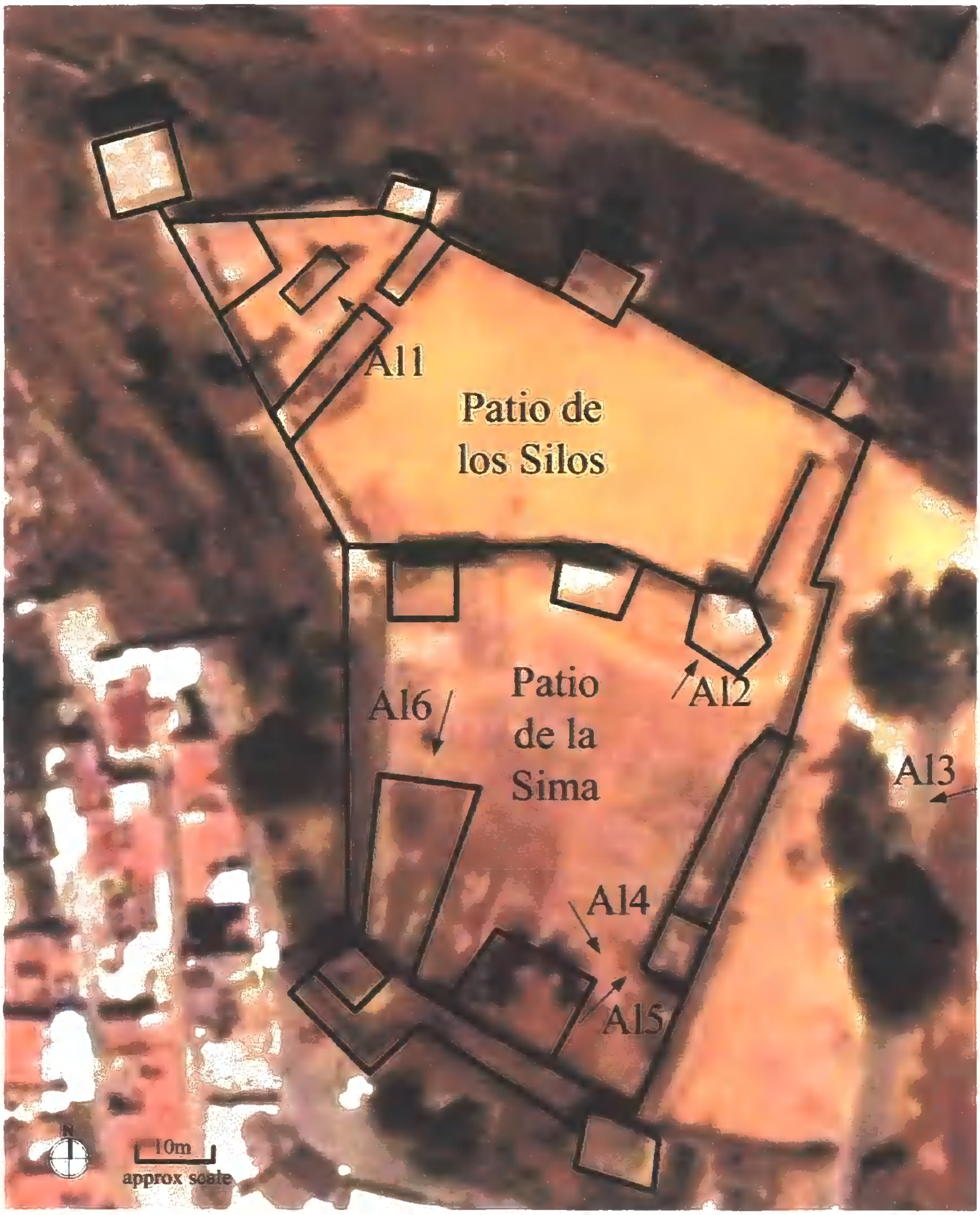


Figure C.4 Alcalá de Guadaira site map

Figure C.5 All *Alcazar Real*, constructed 1312

Figure C.6 Al2 Stone towers constructed 1247

Figure C.7 Al3a Curtain walls constructed 1471

Figure C.8 Al3b Retaining section of curtain wall, probably constructed 1471

Figure C.9 Al4 South wall of Patio de la Sima

Figure C.10 Al5 South wall of *mudejar* quarters, constructed 1530.

Figure C.11 Al6 Arab baths, constructed 12th century

C.3 Baños de la Encina

The castle at Baños de la Encina was constructed in 967, as described by a plaque fixed next to the door. The castle was given over through treaty by the Muslims to the Christians in 1225 It was used continually until the middle of the 17^{th} century. The site was redundant until 1850 when it began to be used as the village cemetery. This practice continued until 1928, and as a result the internal level is much higher than the external (Ramos Vazquez 2003). Cement repairs are evident to the bottom of the walls (Figure C.17) and an archaeological dig in 2007 aims to reduce the internal ground level to bedrock. There are 14 rammed earth towers, and stone keep at the north of the site. Pigeons are nesting in the towers. There are two main cracks, in the wall between towers 2 and 3 and on tower 8.

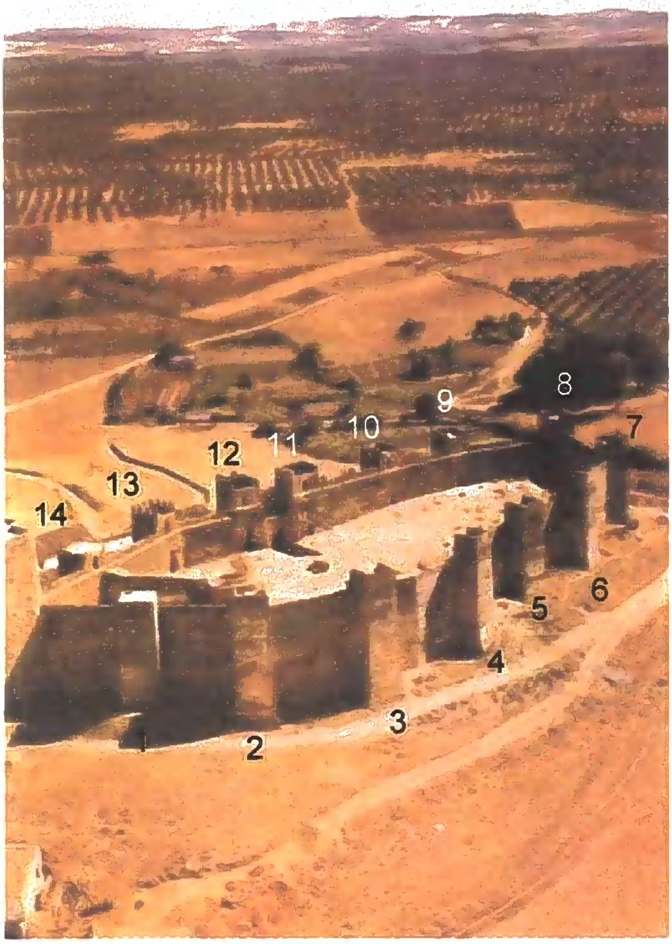


Figure C.12 Castle of Baños de la Encina with tower location numbers

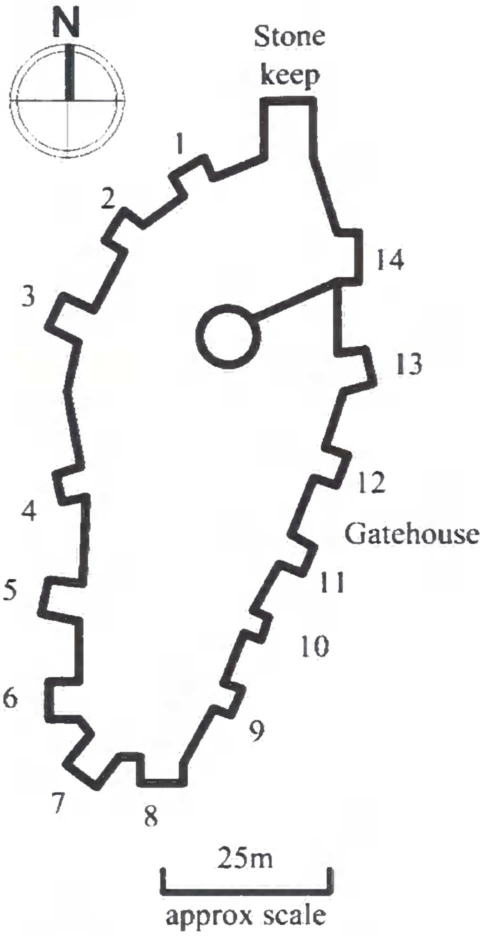


Figure C.13 Baños de la Encina castle

Figure C.14 Bala Towers 1 to 6

Figure C.15 Ba1b Towers 8 to 14

Figure C.16 Ba1c Towers 1 to 14 anticlockwise, taken from the stone keep

Figure C.17 Bald Tower 11

Figure C.18 Bale Crack between towers 2 and 3, note cement repair at base

C.4 Biar

The date of construction of Biar castle is unknown, but the treaty of Cazorla in 1179 denotes Biar castle as being part of a dividing line between the kingdoms of Aragon to the north and Castille to the south. In 1244 the castle was surrendered to Aragon and in 1265 was used by the Muslims as a base for an unsuccessful rebellion against Castille. In 1276 a further unsuccessful Muslim revolt led to their expulsion from the town of Biar. The final military use of the castle was as a base in 1808 during the Spanish war of Independence.

There are stone protrusions at the top of the building which would have been used to support a temporary timber structure. Internal access was not possible, but each external face of the tower was observed and photographed. The tower is 20 lifts high and assuming each lift is 85cm, the tower is 17m tall. On the north facing sides of the structure, which are always in shadow there appears to be lichen surrounding each putlog hole. A concrete beam has been placed around the top of the tower, and a water spout protrudes in the centre of each face.

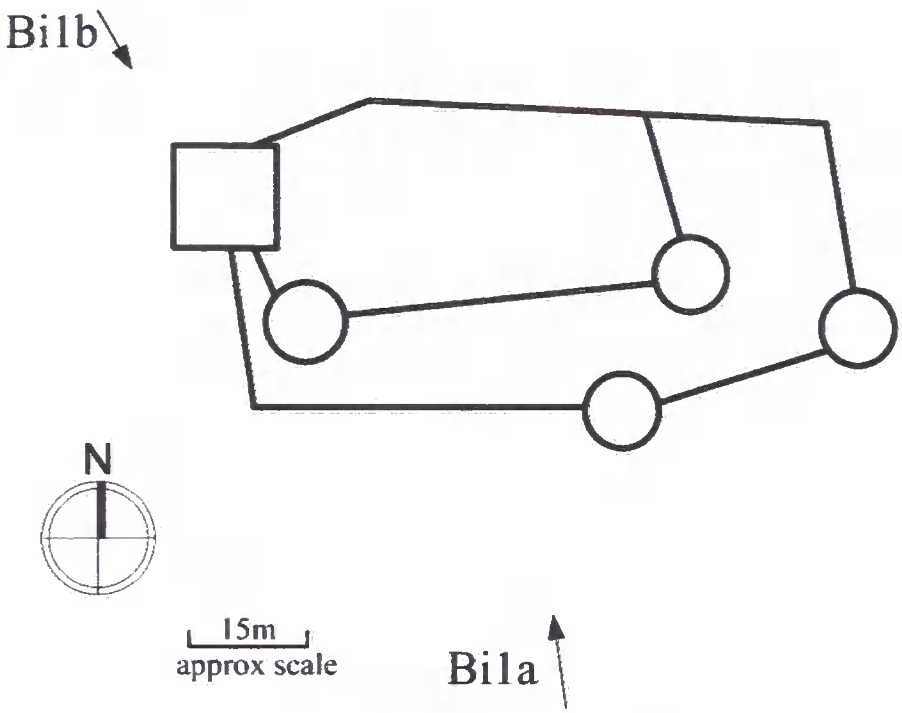


Figure C.19 Bil Biar castle

Figure C.20 Bila Biar castle external photograph

Figure C.21 Bilb Biar tower

C.5 Carmona

The site at Carmona consists of a curtain wall (Figure C.23 and Figure C.27) and a number of towers. Part of the structure has been converted into a hotel. A chronology of the site is given in Table C.3. While a fortification has existed on the site since Neolithic times, the majority of the current structure dates from 1502. The castle appears to have been abandoned following an earthquake in 1504. There is evidence of recent repairs (Figure C.24). Carmona was unique amongst sites surveyed in southern Spain because a great deal of pottery was used in the rammed earth mix (García 2006).

Date	**Activity**
	Fortifications on the site since Neolithic times. Phoenician, Carthagean and Roman remains have been found.
884	The town of Carmona became a refuge for Muslim Sevillians who fled from the Christian Normans
895	The town of Carmona conquered by Al-Mudaffar
1247	The castle of Carmona conquered by St Ferdinand III
1350-1369	Castle used as the summer residence of Peter of Castile (Pedro the Cruel)
1502	Following a siege the town of Carmona was incorporated into the region of Seville, and the castle was reconstructed
1504	The region was hit an earthquake. This is the first recorded earthquake in modern Spain, and was centred on Carmona. The castle was substantially destroyed and abandoned.

Table C.3 Chronology of Carmona castle

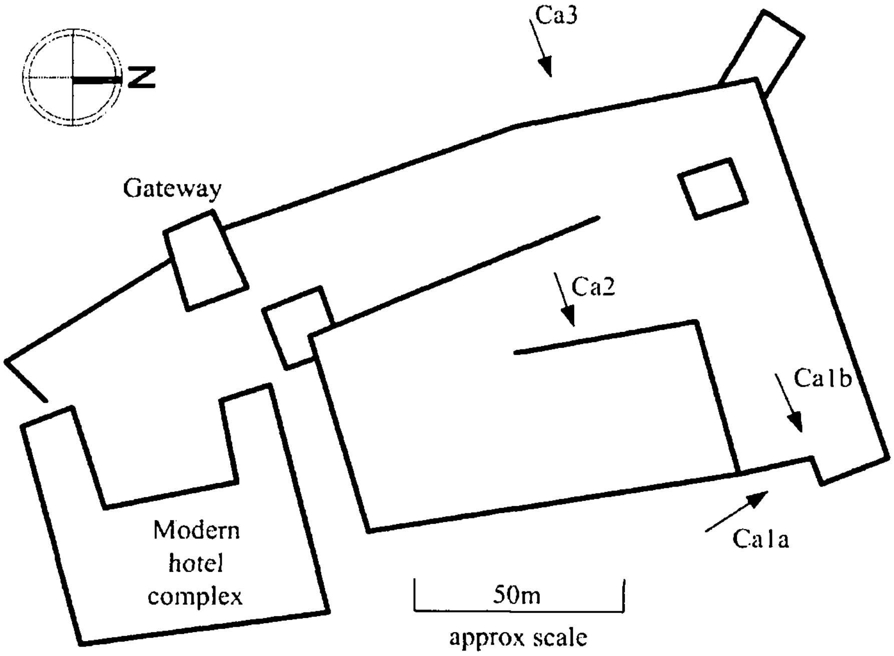


Figure C.22 Plan of Carmona castle

Figure C.23 Aerial view of Carmona castle

Figure C.24 Cala Earthquake damaged tower, Carmona. Constructed 1502

Figure C.25 Ca1b Bricks over putlog hole

Figure C.26 Ca2 Ruined hall. Constructed 1502

Figure C.27 Ca3 Exterior wall. Rock foundation with masonry levelling course.

C.6 Cordoba

Cordoba is a major city in southern Spain, and has played a large part in the history of Iberia since Roman times. Cordoba was taken by the Muslims in 711, and retaken by Christians in 1236. The city was under the control of Napoleon for a short time in 1806, and is now a thriving tourist and business centre (Reed 2006). A condensed history of the city is given in Table C.4. Six sites (shown in Figure C.28) were investigated in various parts of the city.

The perimeter wall of the Christian castle (*Alcazar*) (Co1, *Calle de la Trasera a San Basilio*) is a highly eroded section of wall which has been heavily repaired using concrete. A timber walkway exists at one side of the site, making it impossible for the public to touch the wall. A further section (Co2, *Calle Martin de Rosa*) is in a good state of repair with only a few cracks to the face. Two curved towers (Co3, *Ronda de Isasa*) were also part of the perimeter wall of the Christian castle. There was erosion at the base of these towers, and repairs were being carried out to the section of wall between the towers. A crenellated section of the castle wall (Co4, *Avendia de Corregidor*) has a brick top and rammed earth below, with some erosion at the base of the wall. A section of the Muslim city wall (La Axerquia, Co5, *Avenida de las Ollerias*) is on a main road through the city, and now vehicles are parked in front, along most of its length (Figure C.33). There are many different failures of the wall along this length, and many repair techniques have been attempted. Behind the wall is a park (Figure C.34) where clear erosion is visible up to shoulder level. A final section of this wall (Co6, *Plasa de Colon*) is heavily eroded on one side and repaired on the other.

Figure C.28 Cordoba aerial photograph and site map

Date	Activity
	Roman occupation of Cordoba, construction of the city walls in cut stone. During Roman civil war Julius Caesar reduced the city to ruins.
711	City taken by seven hundred Muslim soldiers and Cordoba becomes a centre of the Muslim world (see Appendix A)
1031	Fall of the Cordoba Caliphate leads to civil war and the formation of many *Taifa* kingdoms
1085	Walls built around Cordoba (the *Axerquia*). These walls were stone in the lower parts and rammed earth in the upper parts.
1236	Christians take control of the. Repairs to the walls in both stone and rammed earth were done by Muslims living under the Christian rule (*Moriscos*).
1328	Castle of the Christian Monarchs (*Alcazar de los Reyes Cristianos*) constructed. This was the headquarters of the Spanish Inquisition
1369	Perimeter walls of the *Alcazar* incorporated into the city walls
1500	South west wall embellished when a public promenade was built along the riverbank.
1806	Spain invaded by Napoleon, parts of the walls torn down to make way for new streets.

Table C.4 Chronology of Cordoba

Figure C.29 Co1 Christian *Alcazar* walls, constructed 1369

Figure C.30 Co2 Christian *Alcazar* walls, constructed 1369

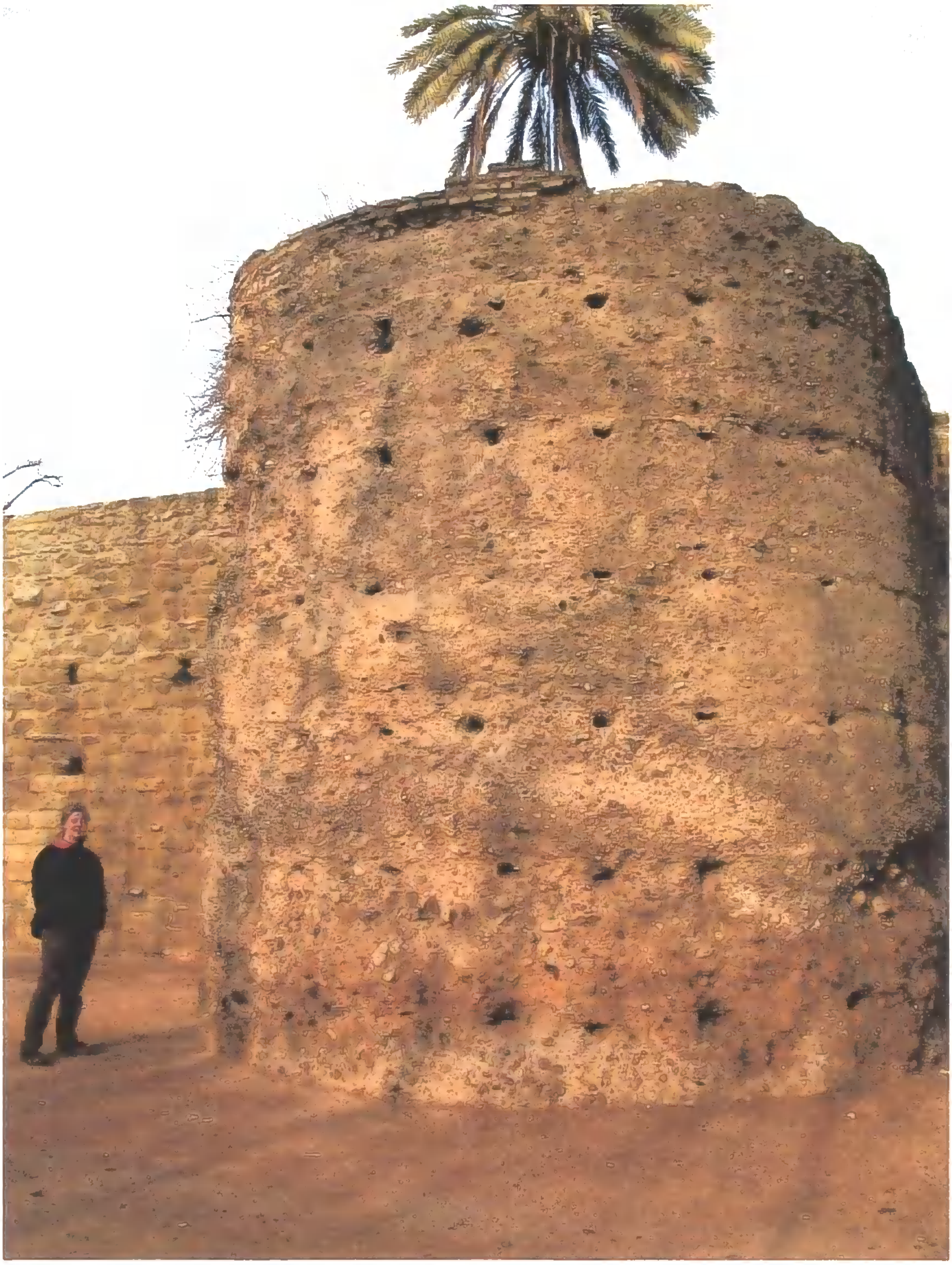


Figure C.31 Co3 Christian *Alcazar* walls, constructed 1328

Figure C.32 Co4 Christian *Alcazar* walls, constructed 1328

Figure C.33 Co5a *La Axerquia* walls, constructed 1085

Figure C.34 Co5b *La Axerquia* walls, constructed 1085

Figure C.35 Co6b *La Axerquia* walls, constructed 1085

C.7 Cox

The castle at Cox was first constructed as a Muslim farm house, and also goes by the names of Castillo de Santa Bárbara, Castillo de Ayala and Castillo de Cox. A history of the building is given in Table C.5.

Date	**Activity**
	Constructed as a Muslim farmhouse
	Conquered by Alonso X (king of King of Galicia, Castile and León, 1252-1284)
1304	Incorporated to the Kingdom of Valencia
1320	Yielded to the Muslim Arardo
1339	Sold to the Vidal family
1522	Becomes property of Orihuela district of Alicante
1822	Integrated into the province of Murcia
1833	Passed to the province of Alicante

Table C.5 Chronology of Cox castle

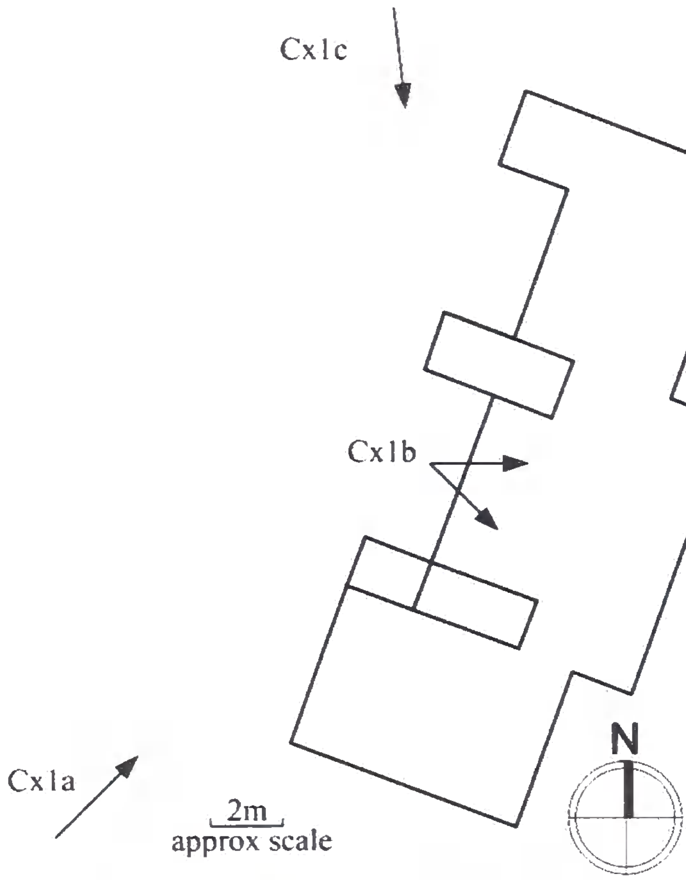


Figure C.36 Cox map showing photograph locations

Figure C.37 Cx1a Cox external

Figure C.38 Cx1b Internal with concrete repairs

Figure C.39 Cx1c Cox external

C.8 Elche

The town of Elche (also know as Elx) contains three rammed earth sites. The *Altamira* castle (El1) is now an archaeological museum, but was unfortunately closed for refurbishment at the time of visit. The mosque, now attached to the current church (El2) now operates as the town hall, and a small section of wall between the two sites has been extensively repaired using concrete (El3). The locations of the sites are shown in Figure C.40 and a brief history of the town is given in Table C.6.

Date	**Activity**
	Iberian, Carthaginian, Roman, Byzantine and Gothic sites to the south of the current town
1121–1269	El1 Altamira Palace, aka Alcázar de la Señoría built during *Almohad* times
1265	James I of Aragon takes city from Muslims
1450	Brick exterior added to Altamira Palace
1913	El1 becomes a cloth factory
1936	El1 used as a prison during the Spanish Civil War
2001	El1 becomes the town archaeological museum

Table C.6 Chronology of Elche

Figure C.40 Aerial photograph of Elche showing site locations

Figure C.41 El3 Elche consolidated ruins, note concrete repairs

Figure C.42 Ell *Altamira* castle, now Archaeological museum

Figure C.43 El2 Elche Town Hall, situated at the end of the church. Once a mosque, there is a large Muslim Crescent on the roof

C.9 Granada

The Alhambra of Granada is a world famous UNESCO heritage site. The complex is 700m long and 200m at its widest point. The oldest part is the *Alcazar* (castle) at the western end of the site where a fortification has existed since Roman times. In 1348 the current site was defined by encircling walls. Granada was an important city throughout the Muslim Caliphate, and was the last bastion of Islam in Spain prior to its falls in 1492. After 1492 the site continued to be used, but the heights of Islamic architecture were not bettered in Christian times, and the site stands as a tribute to medieval Muslim architecture. The Alhambra is now a popular tourist destination (Gallego Roca and Valverde Espinosa 1993; Valverde Espinosa, Lopez Osorio et al. 1993; Acedo 2006).

A fortification has long existed at the site and foundation stones in *Plaza de las Armas* (The Arms square, Gr2) are thought to be Roman. The first reference to a structure on the site is during a civil war when the Arabs were defeated in battle and forced to take refuge in a primitive 'red earth' castle in Granada. The documents record that the castle was quite small and not capable of deterring an army intent on conquering. Those sheltering in the castle rebuilt it in 889, and the site was again renovated around 935.

The current structure was built in 1238 by Muhammad I the founder of the Nasrid dynasty, who came to Granada following persecution by Ferdinand III of Castille. Muhammad I moved to the old castle at Granada, but laid out foundations for a new castle which is the basis of the *Alcazar*.

The *Alcazar* consists of the Keep (*Torre Homenaje*) and the 'Cracked Tower' (Gr1); and the Bell tower (*Torre de la Vela*, Gr2). The Bell tower was the feudal residence of Muhammad I and is 16m square and 27m high, with a solid base but four floors above. It remained in use following the Christian conquest but since then had a troubled history. In 1522 it was hit by an earthquake, in 1590 a gunpowder factory directly below the tower exploded, and in 1882 the tower was struck by lightning.

The current Alhambra site was encircled with rammed earth walls in 1348 by Yusuf I, giving the Alhambra its final outline as shown in Figure C.44. There are 15 towers, the most significant of which are mentioned here.

The Justice Gate (Gr5) carries an inscription explaining it was completed in June 1348, and during this period was the main entrance to the *Alcazar* from the city. The Tower and Gate of Seven Floors (Gr4a) at the south end of the Alhambra is similar in construction to the Justice Gate, but was significantly damaged in 1813 when Napoleon withdrew from the city (see Appendix B). The Water tower (Torre Agua) (Gr6) protected the royal waterway which carried water to the city of Granada. The tower of Balthasar of the Cross (Gr7) and the Spiked tower (named for its pyramid shaped merlons on the ramparts) (Gr9) were also constructed in 1348. The tower of the Captive Princesses (Gr8) is a romanticised name and is a actually a small palace astride the battlements. It was constructed in the 15th century before the fall of Granada and is one of the last Muslim constructions in the Alhambra.

Date	Activity
	Roman foundations found in Plaza de las Armas (Gr1b)
889	Historical documents refer to a small 'red earth' castle at Granada. This structure was damaged an repaired during a civil war. May form the base of Keep (Gr1)
935	Small castle on the site renovated. May form base of Keep (Gr1)
1238-1273	Muhammad I founds the Nasrid dynasty in Granada. Alcazaba (Gr1) rebuilt and extended. The Watchtower (Gr2) used as feudal residence
1273-1302	Muhammad II. Construction of the Wine Gate and the Spiked tower (Gr9)
1348	Yusuf I walled much of the Alhambra site, adding towers such as the Tower and Gate of Seven Floors (Gr4), Justice Gate (Gr5), Water tower (Gr6), Tower of Balthasar of the Cross (Gr7)
1408	Construction of the Palace of Yusuf III and the Partial Gardens (Gr3)
1445	Tower of the Princesses, the Spiked tower extended. (Gr9)
1492	Granada falls and Muslim rule in Spain ends
1812	Napoleon occupied the Alhambra, destroys parts of the walls

Table C.7 Chronology of the Alhambra of Granada

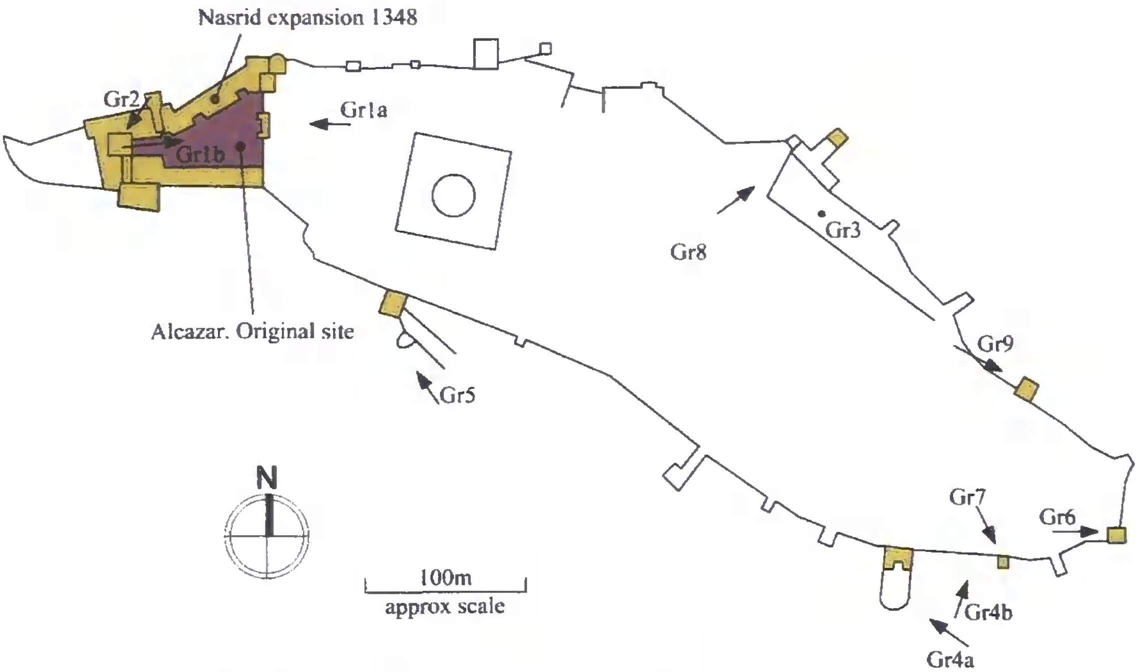


Figure C.44 Plan of Granada Alhambra, showing photograph locations

Figure C.45 Aerial photograph of the Alhambra

Figure C.46 Gr1a Cracked tower (*Torre Quebrada*) (right) and Keep (*Torre Homenaje*) (centre)

Figure C.47 Gr1b Arms Square (*Plaza de las Armas*) from the Watchtower. Keep (centre) and Cracked Tower (left)

Figure C.48 Gr2 The Bell tower (*Torre de la Vela*)

Figure C.49 Gr3 Partial Garden walls

Figure C.50 Gr4a Tower and Gate of the Seven Floors

Figure C.51 Gr4b Nasrid wall repaired

Figure C.52 Gr5 Justice Gate (*Puerta Justica*)

Figure C.53 Gr6 Water tower (*Torre Agua*)

Figure C.54 Gr7 Tower of Balthasar of the Cross (*Torre de Baltasar de la Cruz*)

Figure C.55 Gr8 The Spiked tower. Spikes visible below crenellations, casting long shadow.

Figure C.56 Gr9 Tower of the Infant Princesses (*Torre de las Infantas*)

C.10 Jaen

Jaen was a major Celtic-Iberian settlement centre, and was then occupied by the Carthaginians. It was captured by the Romans following the 2nd Punic War (218-201BC) and flourished under Emperor Flavian (69-96AD). The city developed as a trade centre during the Muslim Caliphate which led to the construction of a castle on hilltop site outside of the town. It is possible that this castle was constructed with rammed earth walls. In 1246 the city was conquered by Ferdinand III of Castille who built the castle of St Catherine in stone masonry on the site of the previous castle. Rammed earth walls extend down the hill from the castle towards the town and are a mix of rammed earth and other building materials (Figure C.57 and Figure C.58).

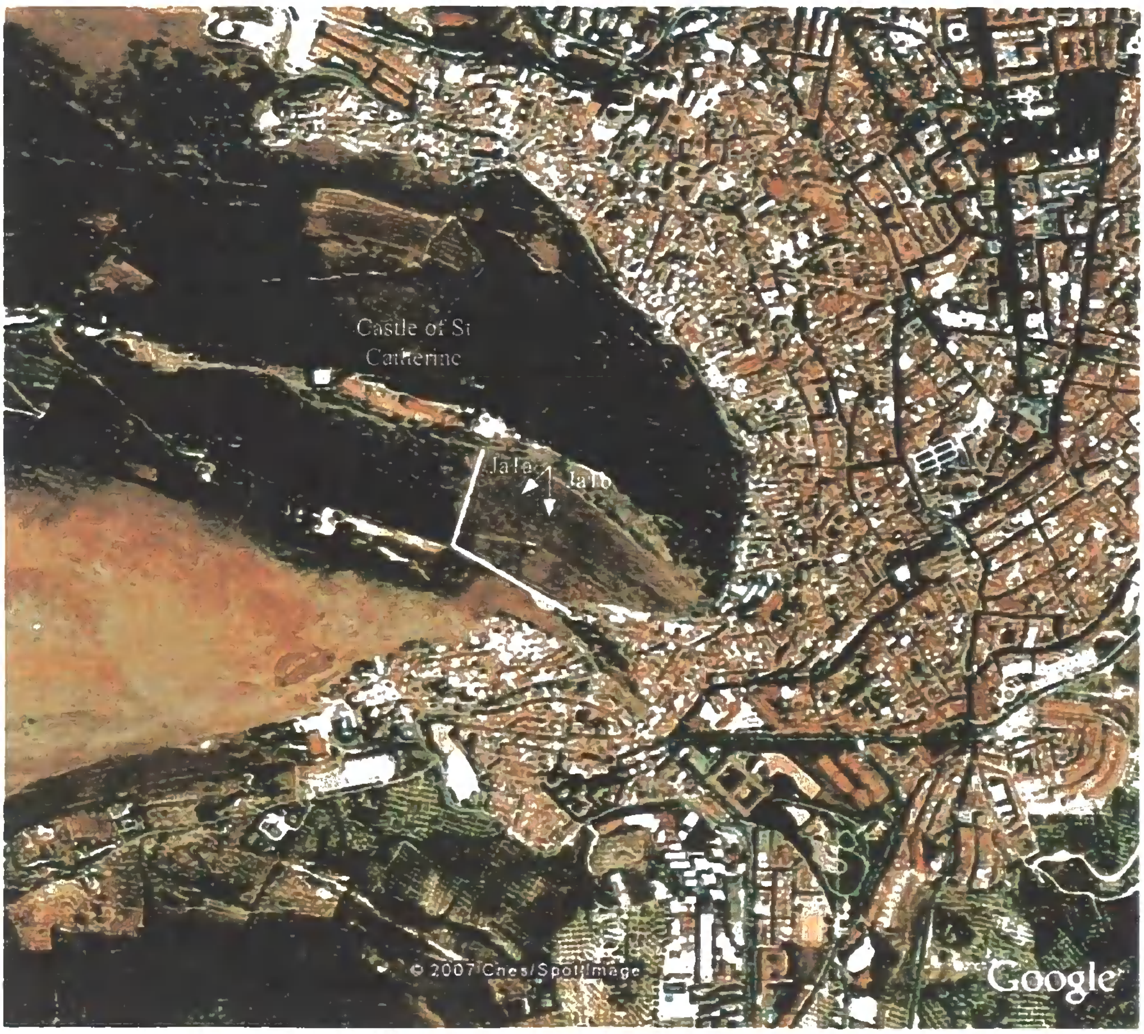


Figure C.57 Aerial photograph of Jaen Moorish walls

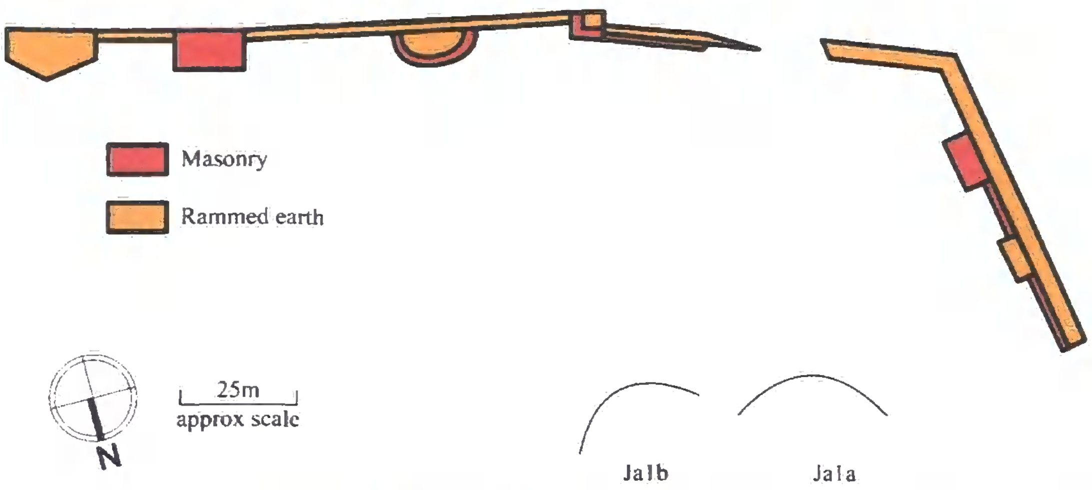


Figure C.58 Plan of Jaen walls

Figure C.59 Ja1a northern section of Jaen Moorish walls

Figure C.60 Ja1b southern section of Jaen Moorish walls

C.11 La Rambla

The town of La Rambla has two rammed earth sites, a tower in the centre of the town (Ra1) and a wall (Ra2) which historically encircled the town. The only remaining section of wall is now in a park adjoining the tower (Figure C.61). The tower is now a pottery museum, but unfortunately internal access was not possible. An information board outside provided a history of the building, which is given in Table C.8. The tower is rectangular in plan (15.3m x 12.8m) and is 17.3m high. There are brick reinforcements at the corners of the tower which are 2.7m thick. The tower is three stories high, and is very similar to the towers at Carpio, constructed 1325 (not visited) and Villena (described in Section C.19).

Date	**Activity**
1333	First documentation of tower, when Señorio de Aguilar rose up against King Alfonso XI
1464-1469	Occupied by Alonso Fernadez of Cordoba who repaired the tower
1469-1483	Used by the wife of Alonso Fernadez while he was fighting in Granada
1650-1821	Used as a prison
	City wall adjoining tower demolished
1988	Passed into private hands
1990	Work undertaken to consolidate the structure
1996	Archaeological work carried out in order for building work to take place
2001-2002	Building work undertaken, now a pottery museum

Table C.8 Chronology of La Rambla

Figure C.61 Aerial photograph showing location of La Rambla tower and wall

Figure C.62 Ra1 La Rambla Tower South East face

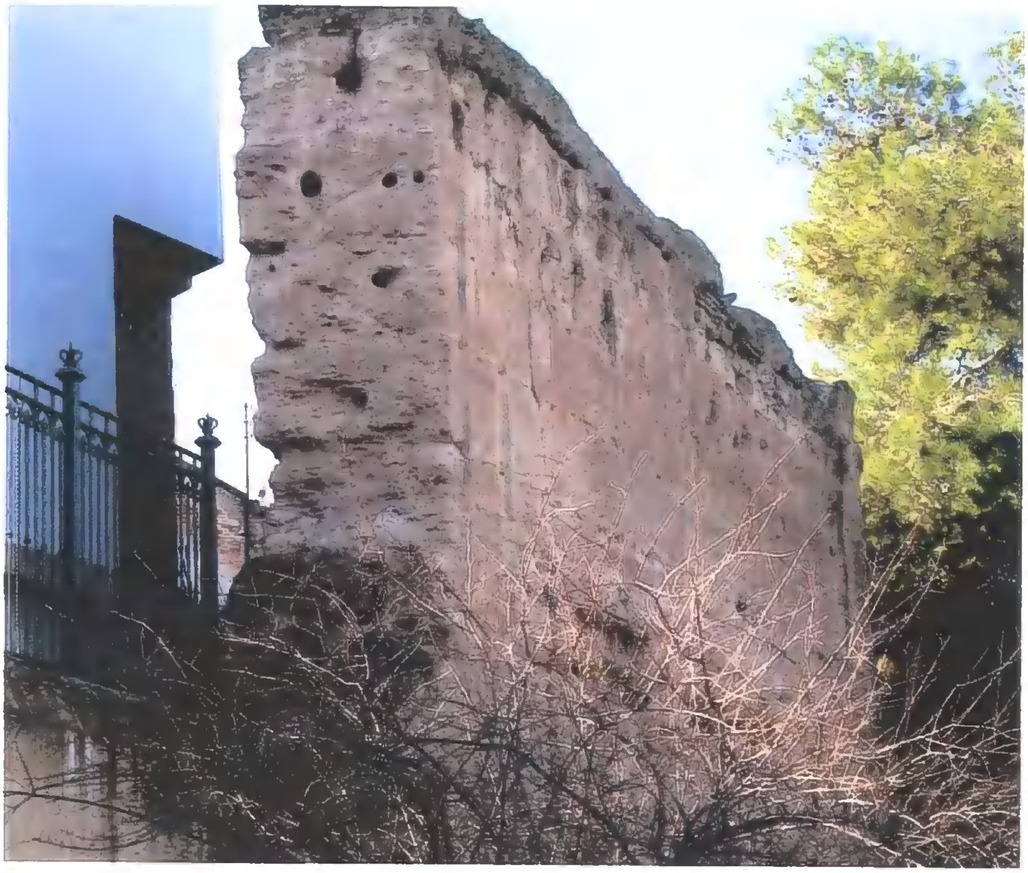


Figure C.63 Ra2a Section of La Rambla town wall

Figure C.64 Ra2b Section of La Rambla town wall

C.12 Lorca

The castle at Lorca is an extensive site, built on a hill overlooking the town. A brief history is given in Table C.9. The only rammed earth sections are the bases of two towers at the western extremity of the castle, which appear to have been constructed at different times due to their different mix design and slight physical separation. Construction of a road tunnel beneath the west end of the site began in 2006.

Date	Activity
	Region around Lorca inhabited by the Iberians and Romans
713	Town of Lorca mentioned in Muslim literature at the Pact of Teodomiro
1031	Lorca becomes a garrison town of the *Taifa* kingdom of Cordoba
1244	Lorca town surrendered to Christians, becomes a border town between the Christian Kingdom of Castille and Moorish Granada
1264	Muslims rebelled and expelled from the town
1452	Battle of the Alporchones fought around Lorca
2006	Construction of a tunnel beneath the west end of the site

Table C.9 Chronology of Lorca

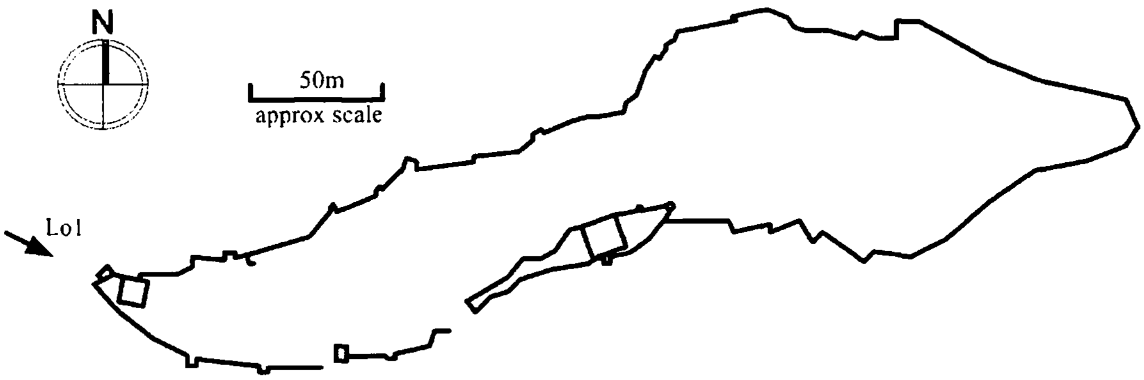


Figure C.65 Plan of Lorca castle, showing site Lo1

Figure C.66 Aerial photograph of Lorca castle, showing line of tunnel

Figure C.67 Lo1 Rammed earth tower base at west end of Lorca castle

C.13 Malaga

The castle at Malaga is on two sites, an earlier Muslim castle (called *Gibralfaro*) at the bottom of the hill, and a newer Christian site at the top. They are joined by a wall which has a stone base and rammed earth above (Ma1, Figure C.68). A name refers to a Phoenician lighthouse and significant Roman structures have been found at the site. The Cordoban Emir Abderraham I (756-788) built the castle by adding to structures already present. In 1065 the castle came under the kingdom of Granada. In 1487 the castle was besieged and surrendered to the Christian Monarchs. In 1624 the castle was inhabited by King Philip VI of Spain, and in the mid 18th century Carlos III ordered the destruction of some of the castle walls for the construction of homes. In the 19th century the castle was used as a home for the destitute and in 1931 was declared a national monument. A large amount of restoration was carried out in the 1930s, such as facing much of the rammed earth with a brick and stone skin (Ma2, Figure C.69). The castle is now a fully fledged tourist attraction, housing an interpretative centre and extensive grounds (Information leaflet 2006).

Figure C.68 Ma1 Rammed earth wall above masonry base

Figure C.69 Ma2 Brick and stone repair to rammed earth wall

C.14 Novelda

The hilltop site of Novelda castle (*Castillo de la Mola*) is shared with a famous 19th century church, and as a result the castle is frequented by tourists intent on visiting the church. A history of the site obtained from local signage is shown in Table C.10. The site is encircled by a rammed earth curtain wall. Inside are a triangular stone tower and rectangular rammed earth tower (No2). There is a tower in the wall at the north west of the site (No1). Part of the south curtain wall has been extensively repaired with concrete (No3) while the north part of the wall is heavily eroded (No4).

Date	Activity
1150	Constructed
1250	Conquered by Prince Don Alfonso de Castilla
1305	Incorporated into the Castalonian-Aragonese crown by King Jamie II. Construction of the Triangular tower
1600	Castle goes into decline and is abandoned
1950	Consolidation work starts
1980	Archaeological work begins on the castle ramparts

Table C.10 Chronology of Novelda

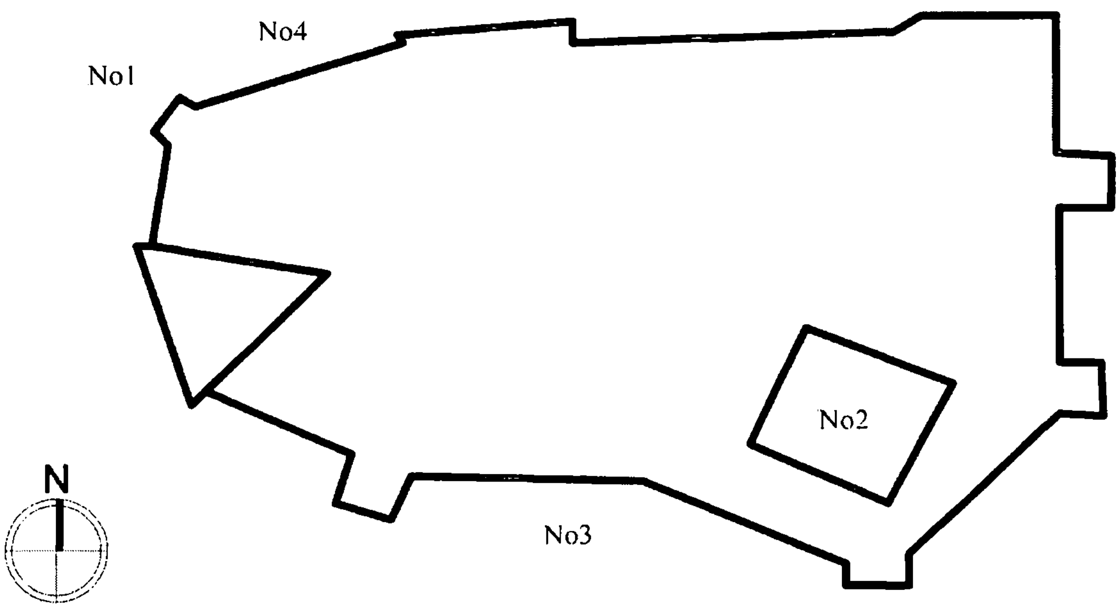


Figure C.70 Novelda plan showing site locations

Figure C.71 No1 Rammed earth corner tower

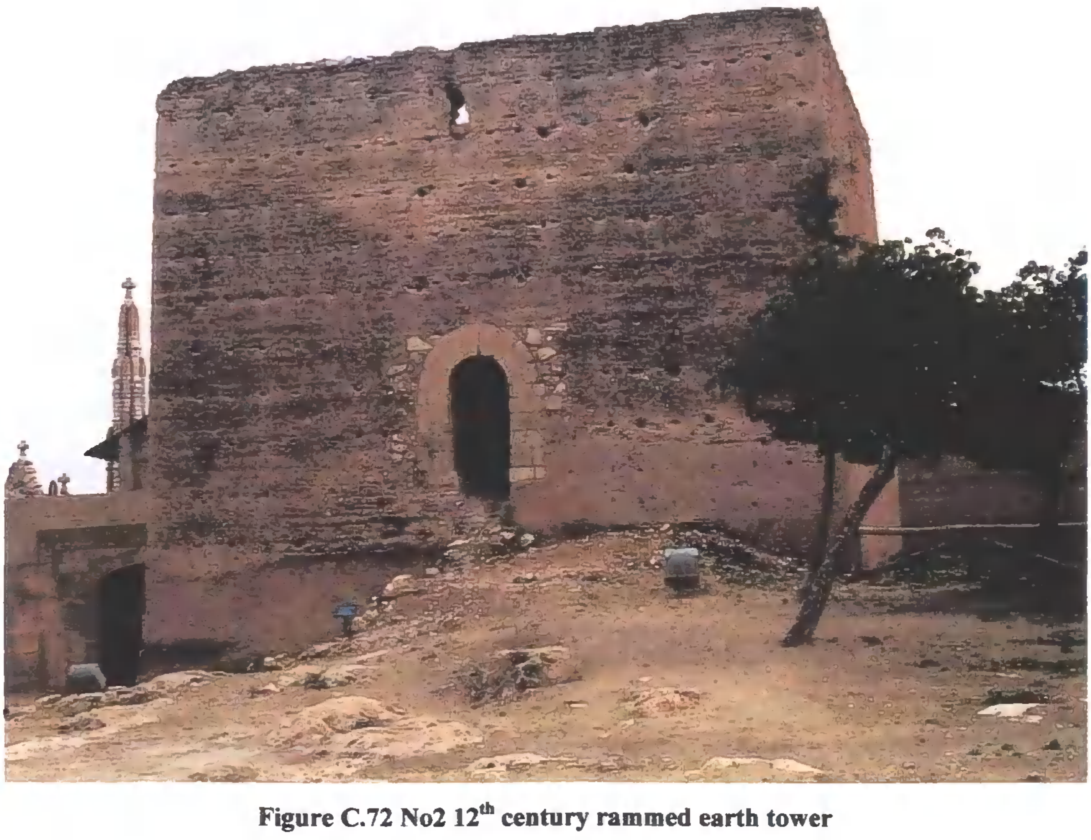


Figure C.72 No2 12th century rammed earth tower

Figure C.73 No3 Eroded north face of curtain wall

Figure C.74 No4 Concrete repair to south face of curtain wall

C.15 Palma del Rio

The town of Palma del Rio (literally Bend in the River) has a large, ruined *Almohad* castle, which is now used as municipal parking. A rammed earth wall extends from the castle into the present town, and is of original height (Figure C.75). The castle (Pa1, Figure C.76) was constructed during the *Almohad* period (after 1121) but was conquered by Christians in 1231, who repaired part of the curtain wall (Pa2, Figure C.77, Pa5, Figure C.80). An octagonal tower, (Pa4, Figure C.79) now part of a private residence, is built in rammed earth and brick. Concrete repairs to the rammed earth town wall were observed (Pa3, Figure C.78).

Figure C.75 Map and aerial photograph. Palma del Rio

Figure C.76 Pa1 Muslim castle internal. Now used as town garbage wagon park

Figure C.77 Pa2 Heavily eroded section, Palma del Rio

Figure C.78 Pa3 Concrete facing repair to eroded rammed earth wall.

Figure C.79 Pa4 Octagonal and brick tower

Figure C.80 Pa5 Town walls

C.16 Salobreña

The castle at Salobreña was constructed by the Muslims as a retirement place and a prison, and it is known that in 1408 the Muslim king Yusuf I lived at site. In 1489 it was conquered by the Christians, and from 1849 the site was used by Spanish customs officials as a signal place because of its position on the coast. Internal access to the castle of Salobrena was not possible.

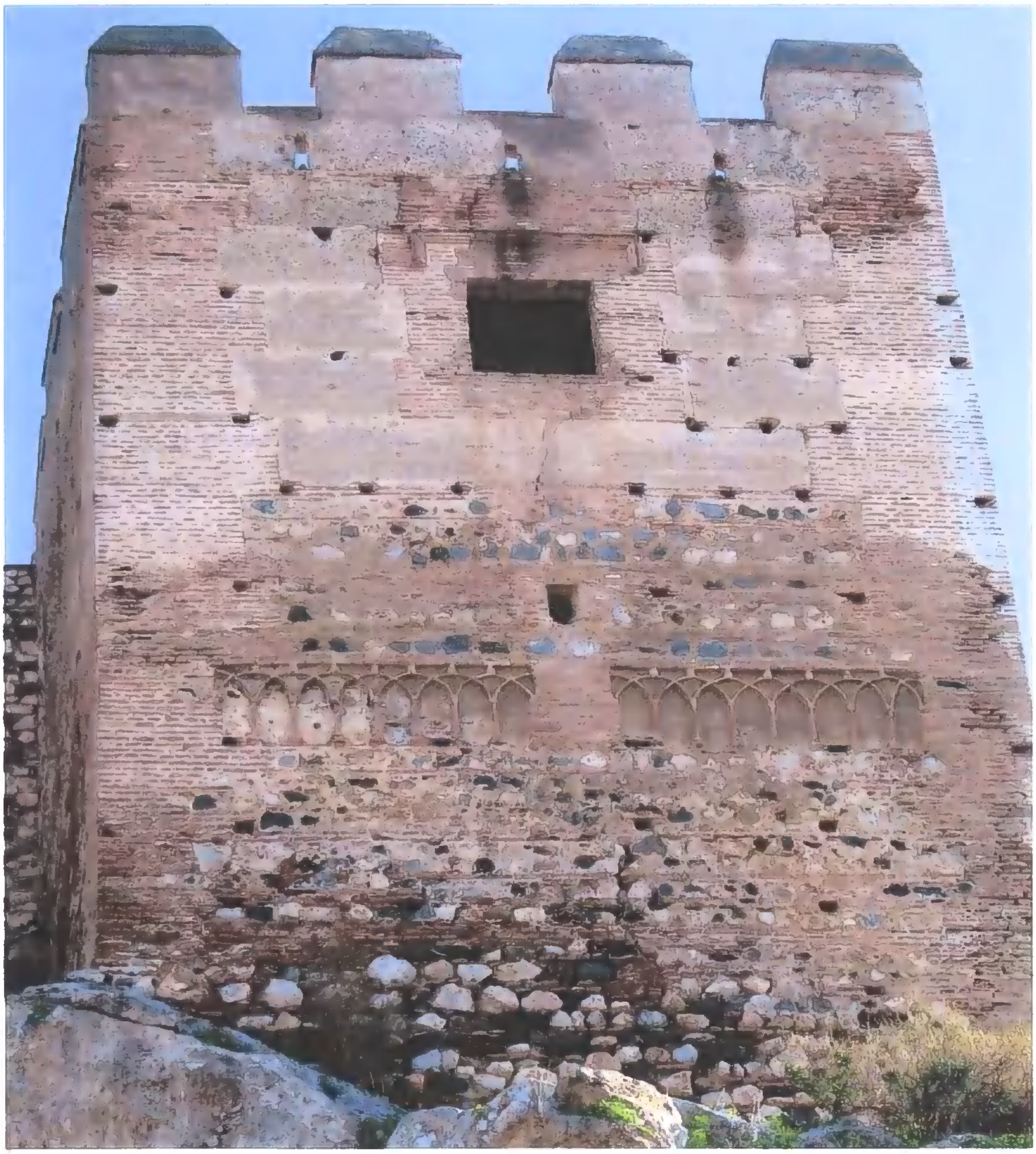


Figure C.81 Sa1 Salobreña castle, constructed before 1408

C.17 Seville

Seville is a major city in Spain, but in the past was overshadowed by both Granada and Cordoba. The *Alcazar* in the centre of the city contains a single rammed earth wall (Se1, Figure C.82) which is heavily eroded. In 1023 the king Abud-Qasim Muhammad ordered the reconstruction of the city wall to stop the advance of the Christian troops (Se2, Figure C.83). These walls are around 6km long and have approximately 150 towers. In 1222 the walls were reinforced with a smaller wall and a ditch (Se3, Figure C.84), but in 1248 the city was taken by Ferdinand III of Castille. In 1861 parts of the wall were demolished due to repeated flooding and movement of the Guadalquivir river which runs through the city.

Figure C.82 Se1 Seville *Alcazar* rammed earth wall

Figure C.83 Se2 Seville city walls

Figure C.84 Se3 Seville double city walls

C.18 Tabernas

It is probable that a Roman fortification existed at Tabernas, but the date of construction of the remaining castle is uncertain due to the lack of evidence. Rammed earth points to Muslim construction. In 1489 the castle was integrated in the Catholic Kingdom of Isabel and Ferdinand, and in 1560 was partially destroyed by Royal decree. The Spanish war of Independence (1808-1814), led to many of the structures at the site destroyed.

Much of the site is ruined but the base of two small towers remain. The main tower, which overlooks the town, has recently been reconstructed in concrete. A rammed earth wall is acting as a retaining wall on the north of the site, and this wall has been faced in two difference layers of masonry (Ta1). One wall of one of the towers has been removed to provide access to the site, leaving evidence of internal beams lined with lime and straw embedded within the wall. The tower has a hole for an octagonal roof beam with a wall plate and has cut stone *male* layers (Ta2). One wall with large putlog holes was found (Ta3). The main tower of the castle was rebuilt recently in concrete, and is visible from the town. It is the symbol of the town and the local olive oil press (Ta4).

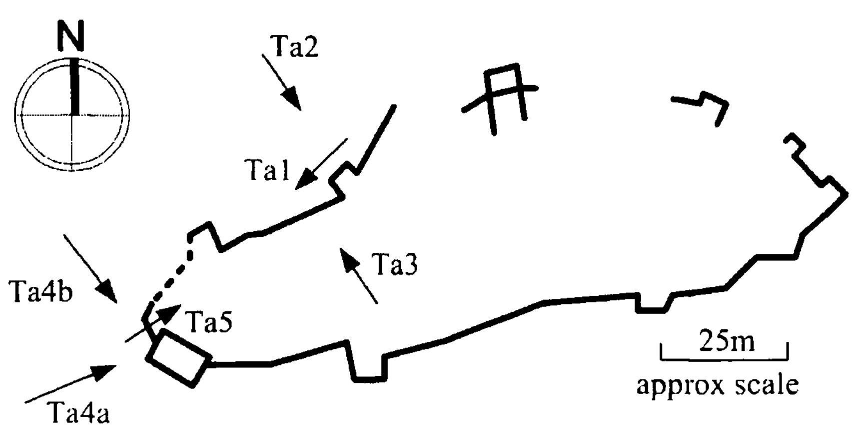


Figure C.85 Map of Tabernas castle site

Figure C.86 Aerial photograph of Tabernas castle

Figure C.87 Ta4 Tabernas repaired face

Figure C.88 Ta1 Rubble facing to rammed earth

Figure C.89 Ta4b Tabernas repaired face

Figure C.90 Ta5 Tabernas internal view

C.19 Villena

The castle of Villena is open as a tourist attraction, and a brief history of the castle as recorded at the site is reproduced in Table C.11. The tower has a Muslim rammed earth base with later brick above. Rammed earth walls on the approach to the castle have been extensively repaired, but the rammed earth section of the tower is original. The tower has three stories with an open roof. The thickness of the walls decreases from 3.6m at the base to 3.13m at the top of the rammed earth where it is flush with masonry. At the top of the masonry the walls are 1.5m thick. The rammed earth tower is surrounded by two masonry curtain walls (Figure C.91), and it is likely that the original rammed earth tower was increased in height when the curtain walls were added (Figure C.94).

Date	**Activity**
1172	First mention of castle in Muslim literature.
1240	Villena captured by King James I of Aragon, brick tower and castle walls added.
1445	Passed to the Pacheco family
1476	Rising against Isabel of Castille. Catholic monarchs (Isabel and Ferdinand 1479-1516) annex the castle
1808	Spanish war of Independence, French troops damage the castle
20th century	Extensively repaired

Table C.11 Chronology of Villena castle

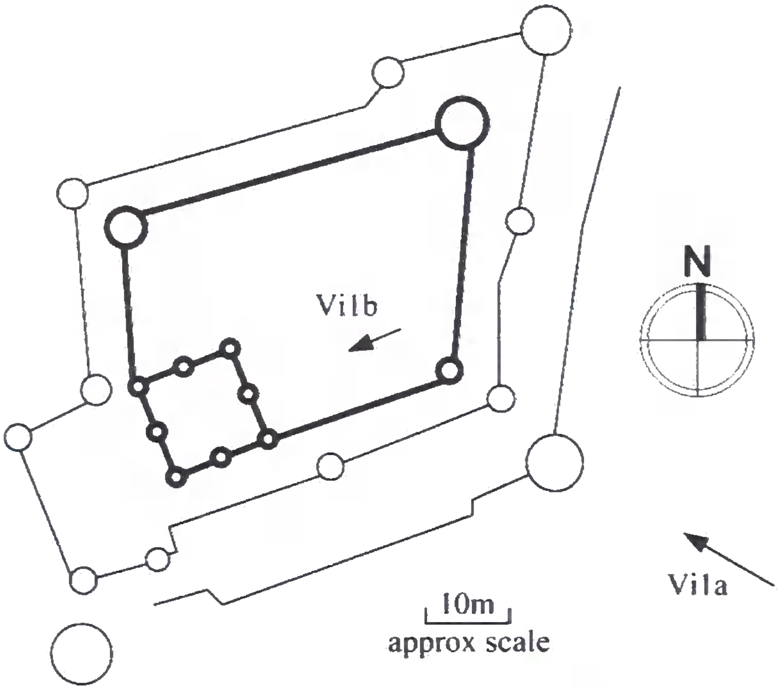


Figure C.91 Plan of Villena castle

Figure C.92 Aerial photograph of Villena castle

Figure C.93 Vi1a Villena castle exterior

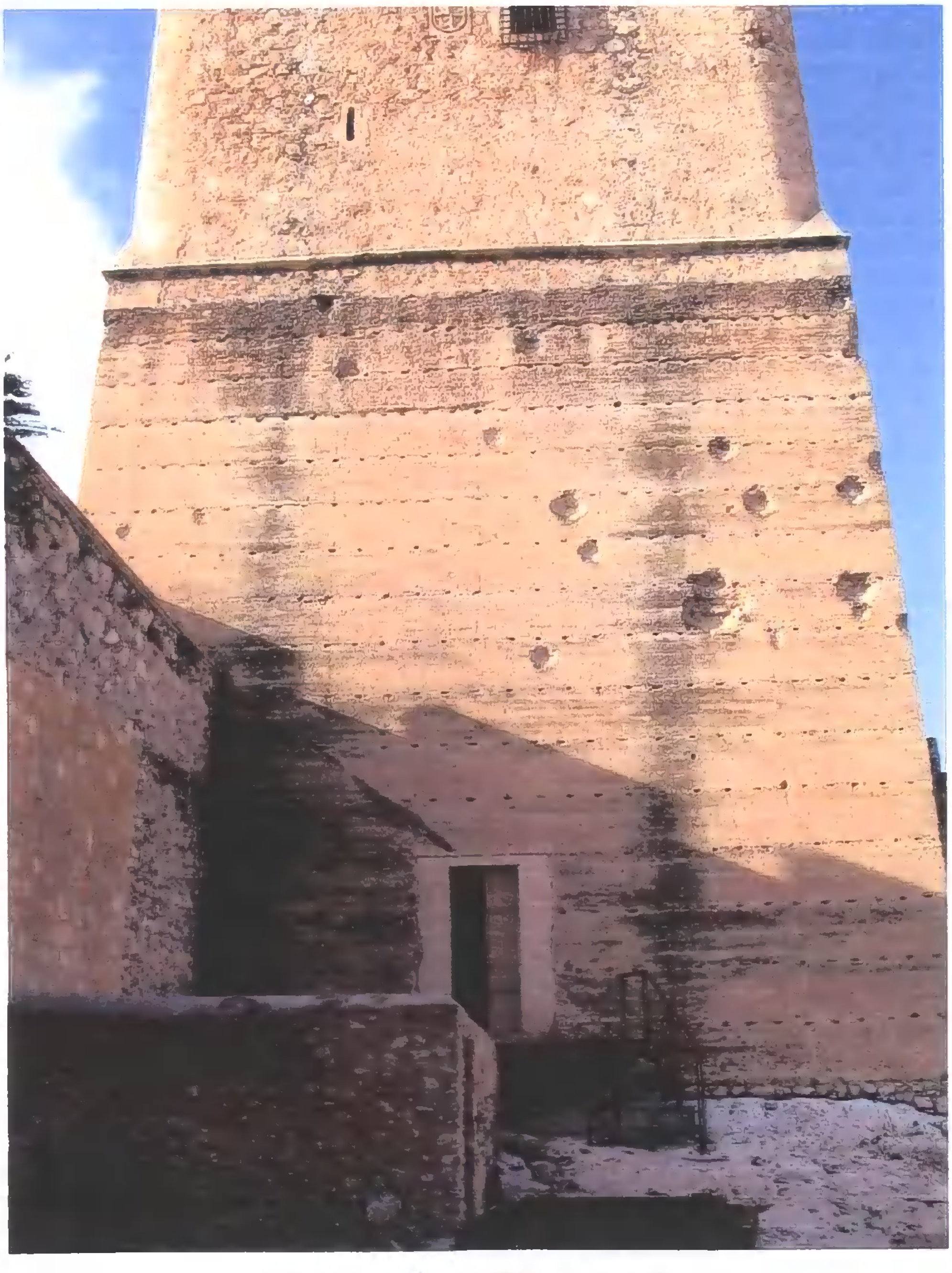


Figure C.94 Vi1b Villena castle keep

Appendix D

North India

D.1 Introduction

A short field trip to northern India was undertaken prior to a conference in the region in late October and early November 2006. A number of historic sites were visited, of which three rammed earth ones (shown in Figure D.1 and Figure D.2) are described in this appendix.

The region of Ladakh lies on the Tibetan plateaux to the north of the Indian subcontinent, at the western end of the Himalayas. To the north lie the former Soviet states of Uzbekistan and Turkmenistan, to the west Afghanistan and Pakistan, and to the east China and Nepal (Figure D.1). The region has acted as a melting pot of cultures, being part of the Silk road, and witnessing episodes of the Great Game between Russia and Great Britain in the 19th century. Opened to tourists in 1972, Ladakh has become a popular tourist destination, but its proximity to Pakistan and the Kashmir region mean its fortunes and future are far from certain. The Indus river flows south to north through the centre of Ladakh, and the sites mentioned all existing in tributary valleys to the north of the river.

Ladakh as an independent entity came into existence in the 7th century, when an invasion of Tibetan peoples replaced earlier peoples known as Dards (Crook and Osmaston 1994). This led to an extensive penetration of Buddhism in the 7th to 10th centuries. Between the 10th and the 14th centuries Ladakh became an important trading post, situated on a branch of the Silk Route and a crossing point between the Chinese, Indian and Central Asian empires. Although the history of the period is unclear, it is obvious that a Ladakhi empire existed in the 11th and 12th centuries, exercising control as far east as Mustang in Nepal and west to Gilgit in modern Pakistan.

After the 12th century, Ladakh fractured, and was separated into two kingdoms, upper Ladakh centred on Leh and Shey and lower Ladakh, with its capital at Basgo. In 1532 Ladakh was invaded by a Central Asia Muslim force led by Mirza Haidar Daughlat, who then used Ladakh as a base for invading Tibet. The invasion failed, and Haidar fell back to Shey, were he stayed for two years before pulling out in 1536. Raids by a Muslim General named Ali Mir from Baltistan (in modern Pakistan) in 1569 destroyed many of the valley monasteries and temples in Ladakh (Cunngingham 1854; Cunningham 1854; Rizvi 1996). Peace was established when Ali Mir's daughter married the Buddhist King of Ladakh.

Ladakh was prominent in Tibetan politics the 17th century. In 1684 the Tibetan Dali Lama wanted to expand his religious domination over the rival Panchen Lama, based in Bhutan. The Ladakhis offered to side with the Bhutanese against the Tibetans. The Dali Lama then ordered the invasion of Ladakh, and a combined Tibetan and Mongolian army invaded Ladakh, laying siege to Basgo. Francke (1907) records a Mongolian song in which describes the siege. This siege lasted for three years, with the Ladakhis holding out due to the large grain supplies and perennial water supply. Eventually the desperate Ladakhi king asked the ruler of neighbouring (Muslim) Kashmir for assistance in repelling the Tibetan-Mongol force. At this time Kashmir was a province of the Mughal empire with Shah Jahan (builder of the Taj Mahal) on the throne, and thus the history of Ladakh is recorded in the history of the Mughals. The Muslims agreed to help on the condition that the King of Ladakh converted to Islam, and the desperate Ladakhis agreed. As a result an army was dispatched from Kashmir. The Muslim army marched on Basgo and the Tibetan force arranged itself for battle on the Jargan plain between Basgo and Nyemo. The Tibetans were routed and fled (Francke 1907; Jamspal 1993).

The Sikh ruler of the Punjab Maharaja Ranjit Singh invaded Ladakh in 1819 as part of a wider campaign encompassing parts of Peshawar and the state of Jammu and Kashmir. This Sikh army was the first modern army in the region, well trained and with European weaponry. A force of 10 000 men known as the Dogra army entered Ladakh in 1819 and met with the Ladakhi king at Basgo in 1819 before moving north to Leh and defeating and massacring the Ladakhi army at Mulki. This was the end of the Namgyal dynasty in Ladakh and Francke (1907) attributes the destruction of Basgo fort to this period.

Ladakh is now a popular tourist destination, and the sites at Leh, Shey and Basgo are regularly visited.

Site	**ID**
Leh Namgyal Tsempo	Le1
Leh Watchtower	Le2
Basgo fort	Bg1
Shey palace	Sh1

Table D.1 Site IDs north India

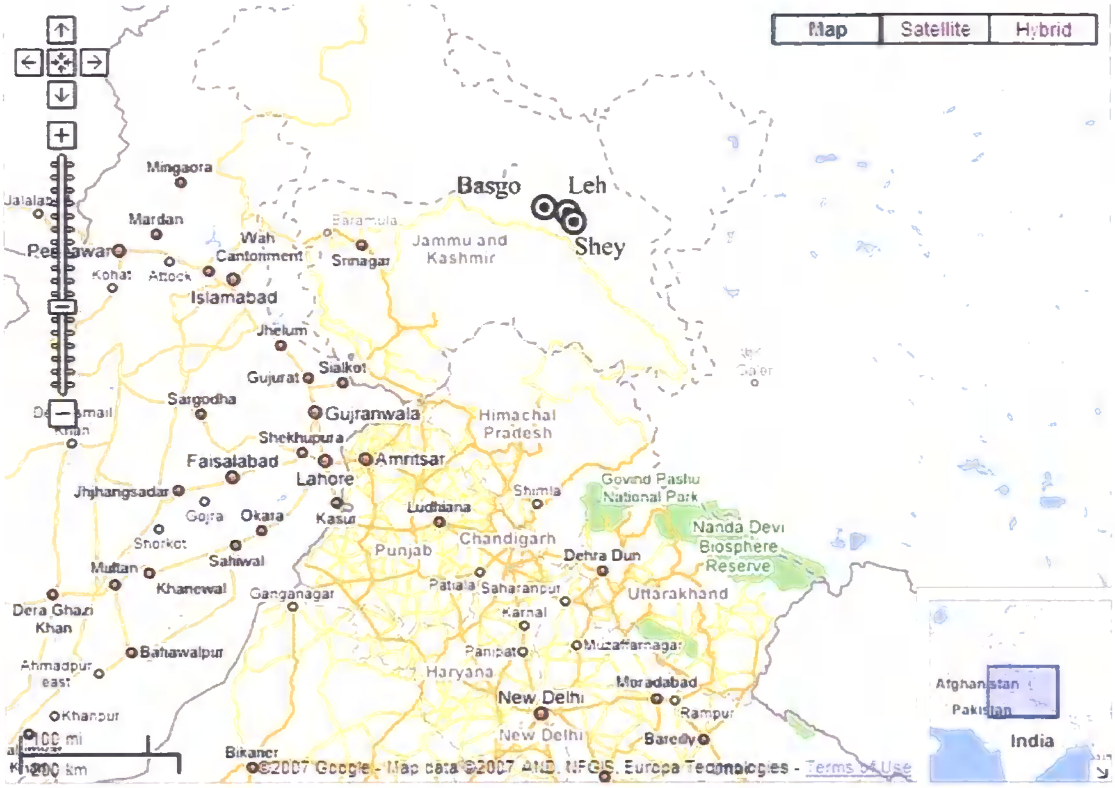


Figure D.1 Sites visited in northern India. Ladakh location

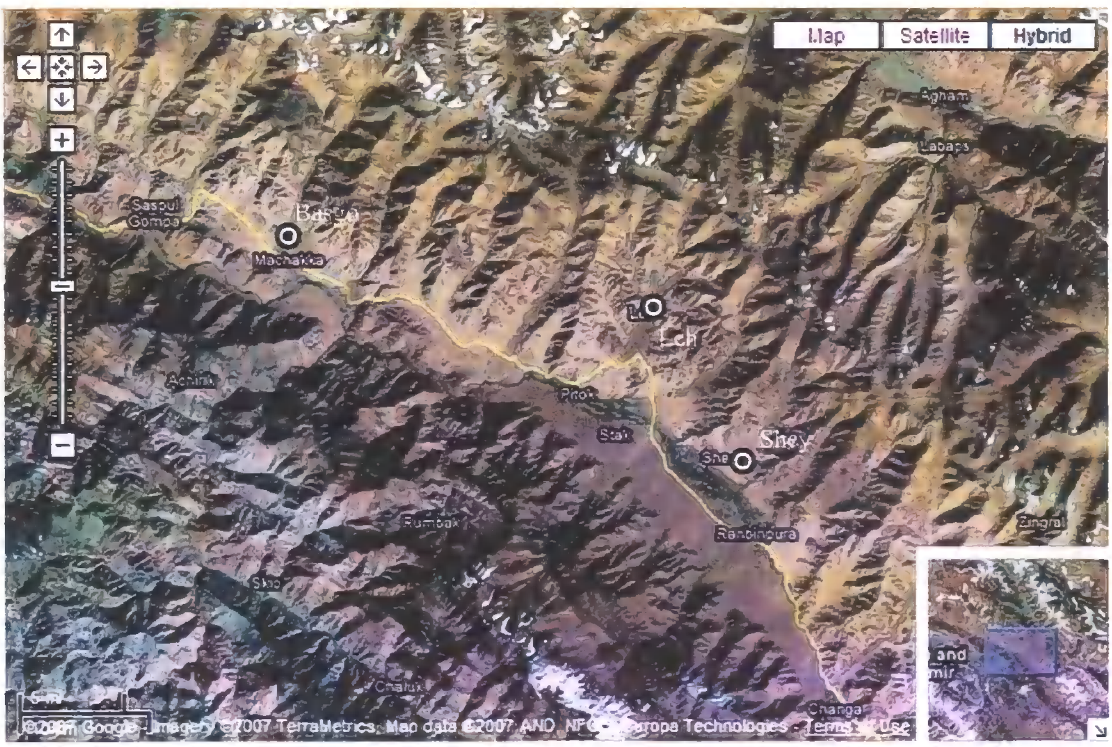


Figure D.2 Sites visited in northern India. Indus valley.

D.2 Leh

The fortress at Leh is called Namgyal Tsempo (Victorious Castle), and was constructed in 1555, after the movement of the capital of Ladakh from Basgo to Leh. The king who constructed it, Tashi Namgyal was one of the most successful kings of Ladakh, increasing the size of the kingdom and defeating Muslim invaders. Little else is known of the history of the fortress, although another larger fortress was built below Namgyal Tsempo in the mid 17th century, which probably led to the abandonment of the castle.

The castle is on a ridge outside of the town (Figure D.3) and consists of a number of buildings (Figure D.4), of which the main castle structure (Figure D.5 and Figure D.6) of Namgyal Tsempo is described. A watchtower (Section D.2.2) to the north of the castle on the same ridge is also described.

Leh was visited on a number of occasions by western travellers in the late 18th and early 19th century (Cunningham 1854; Denwood 1989), who describe both the geographical, metrological and political aspects of life prior to westernisation. Of particular interest are the relative humidity and temperature reading taken at Leh during October 1847 which shows the low relative humidity of the region.

Date (1847)	**Relative humidity (%)**	**Temperature (min) °C**	**Temperature (max) °C**
October 3	22	-2.2	15.8
October 4		-4.4	15.8
October 8		-5.0	15.0
October 9	13.5	-8.3	11.7
October 13	25.5	-2.2	19.2
October 15	22.25	-3.3	18.8
Mean	**20.71**	**-5.4**	**16.0**

Table D.2 Relative humidity at Leh, October 1847 (Cunningham 1854)

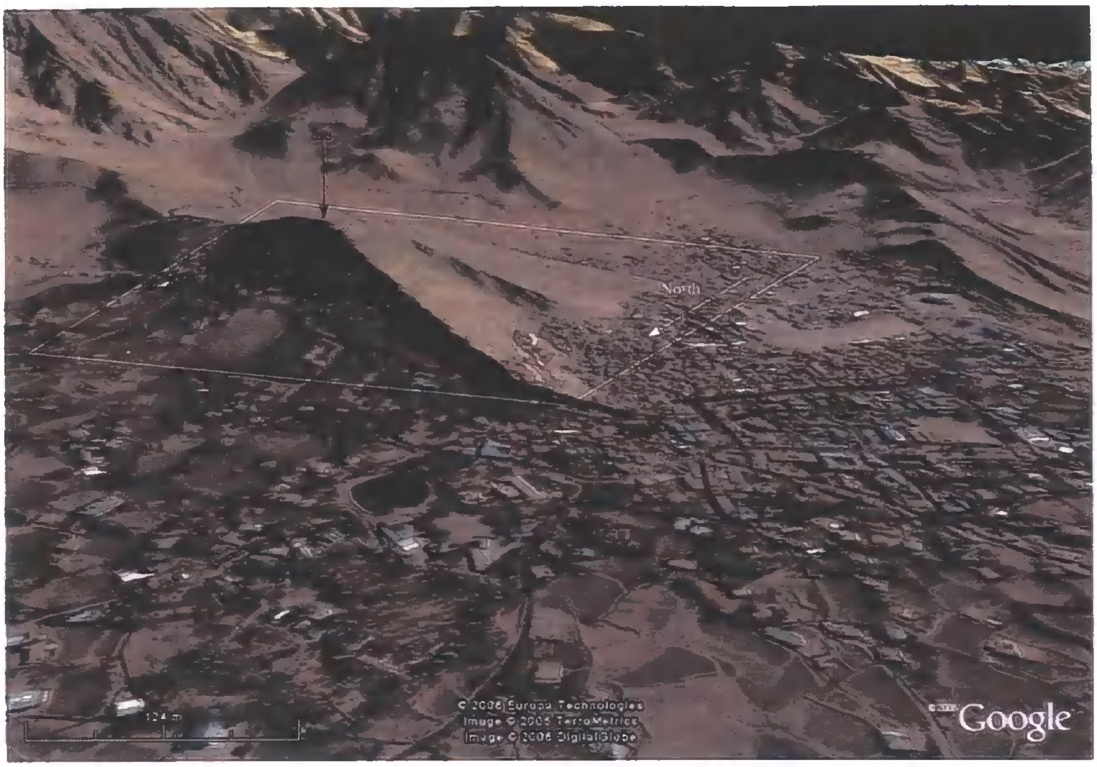


Figure D.3 Terrain mapped aerial photograph showing Leh sites. Box represents area shown in Figure D.4

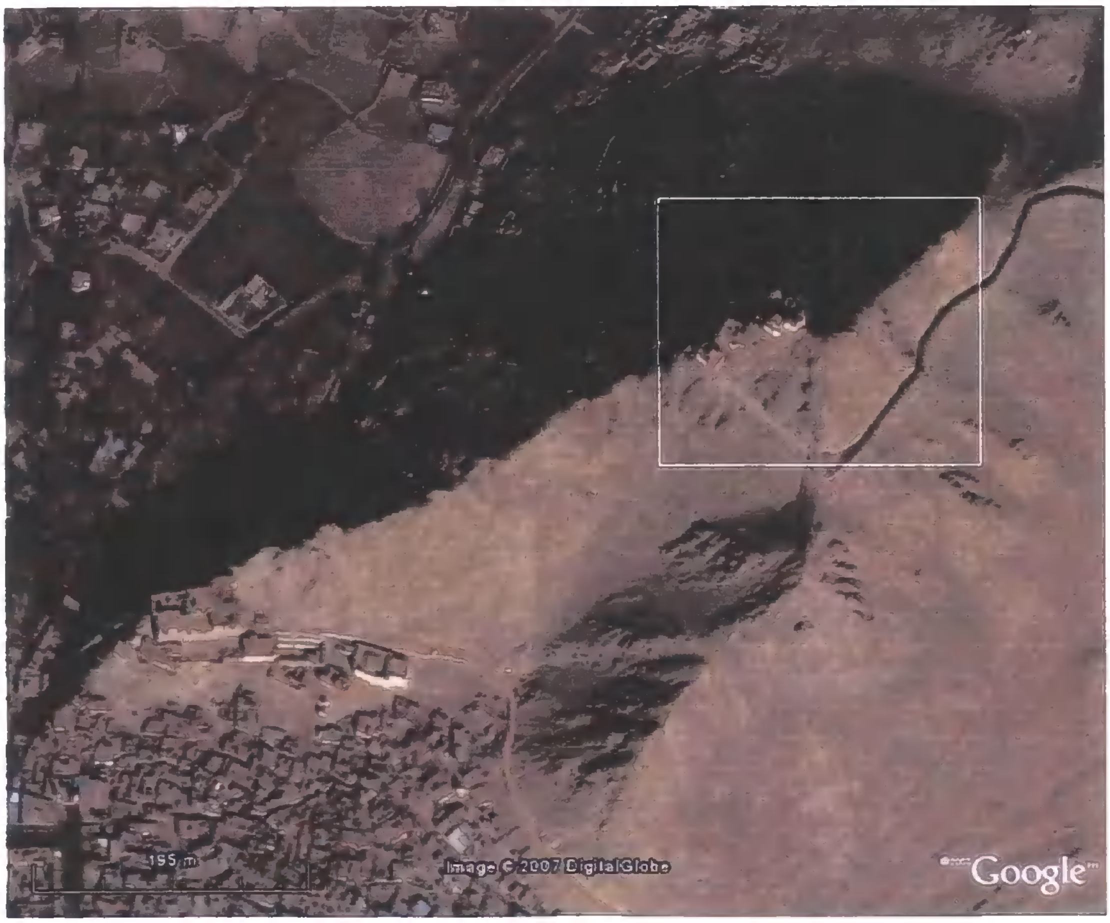


Figure D.4 Aerial photograph of Leh sites. Box shows location of Namgyal Tsempo

D.2.1 Namgyal Tsempo

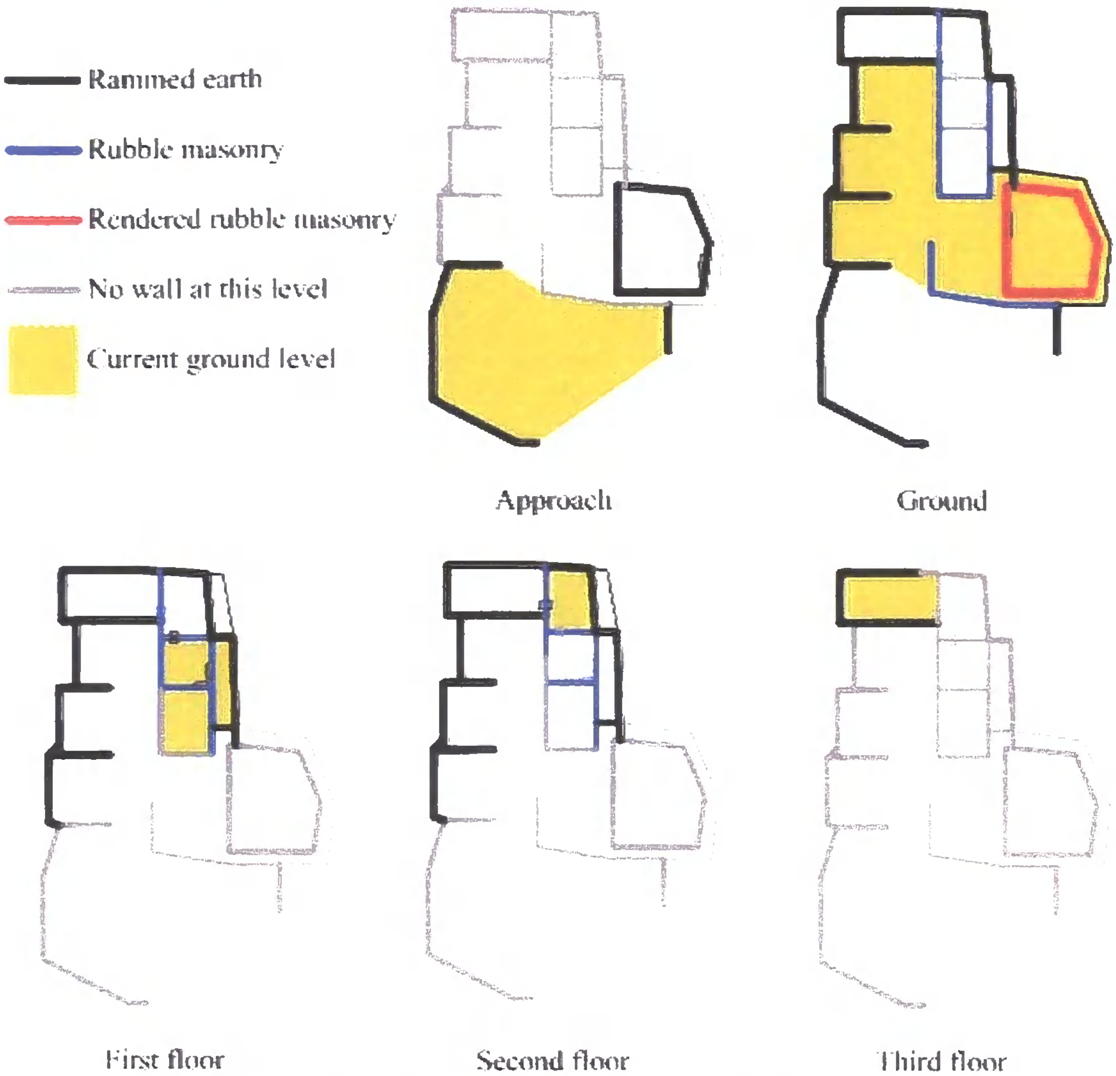


Figure D.5 Namgyal Tsempo floor level plan

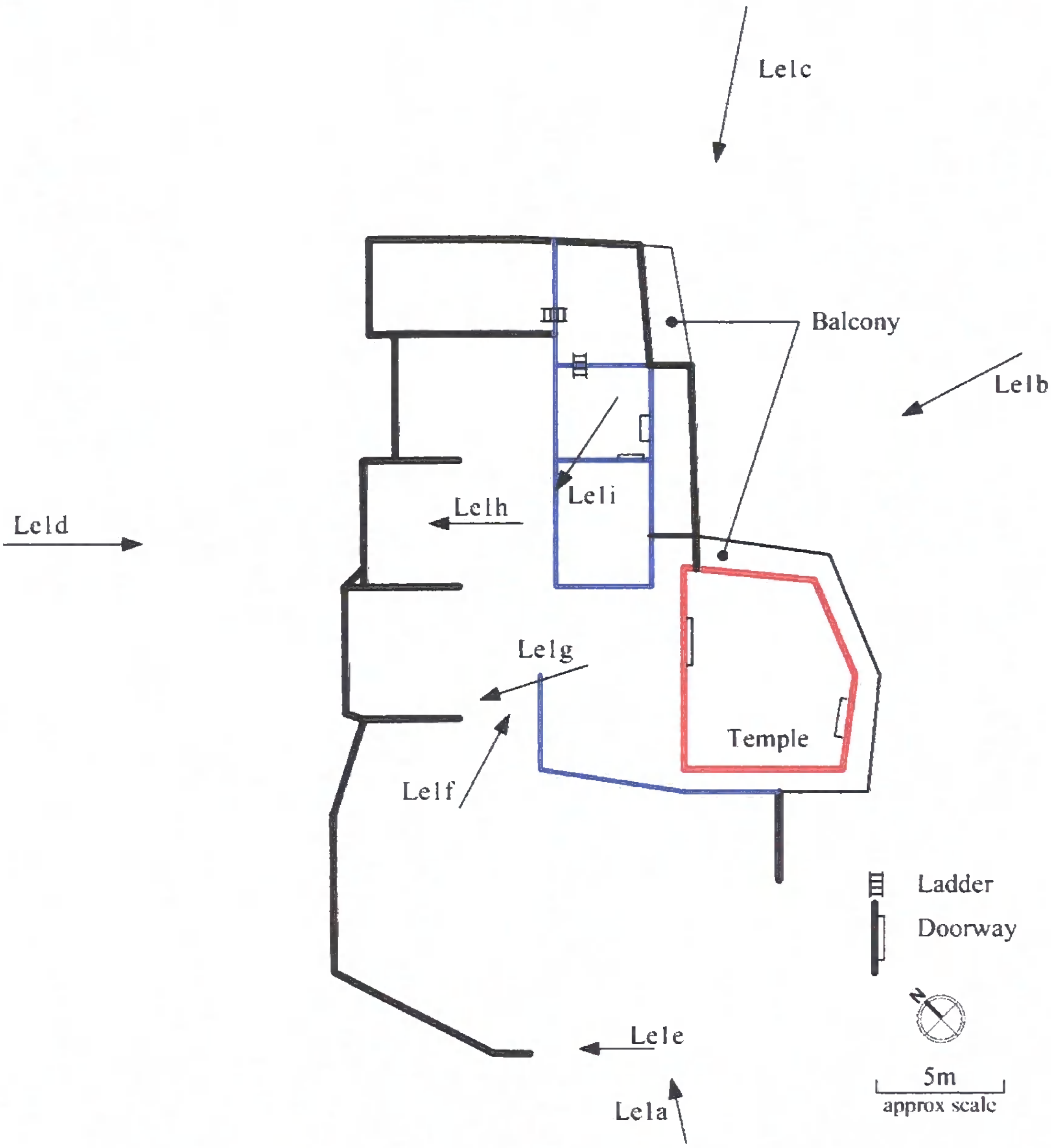


Figure D.6 Namgyal Tsempo plan showing photograph locations

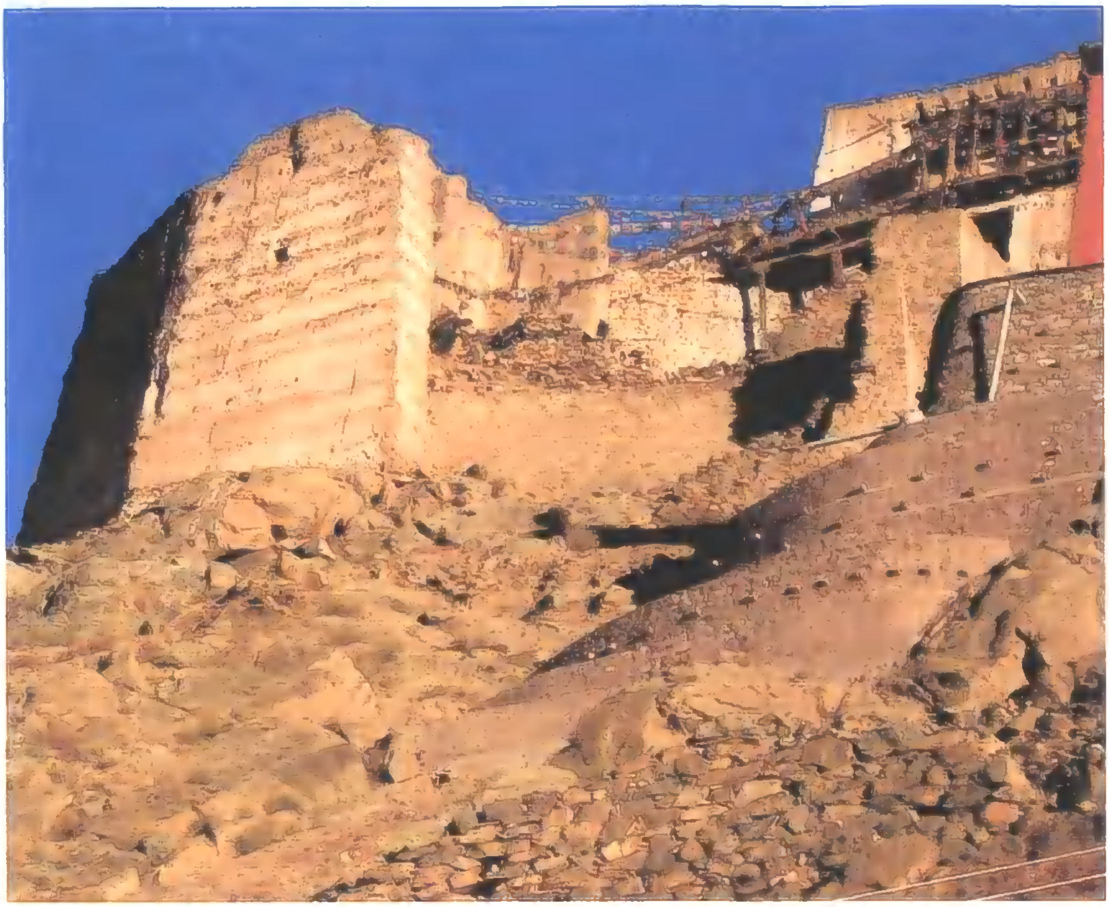


Figure D.7 Le1a Namgyal Tsempo entrance

Figure D.8 Le1b Namgyal Tsempo east elevation

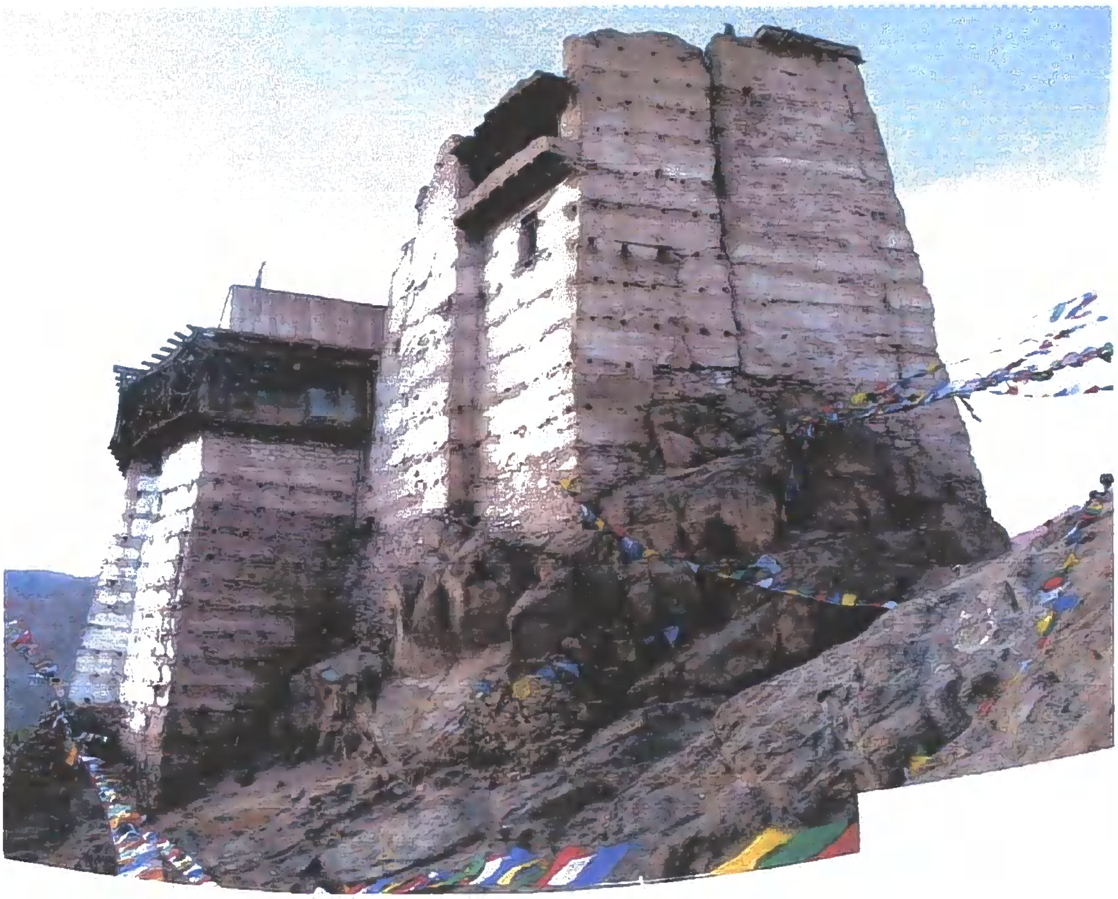


Figure D.9 Lelc Namgyal Tsempo north east elevation

Figure D.10 Leld Namgyal Tsempo

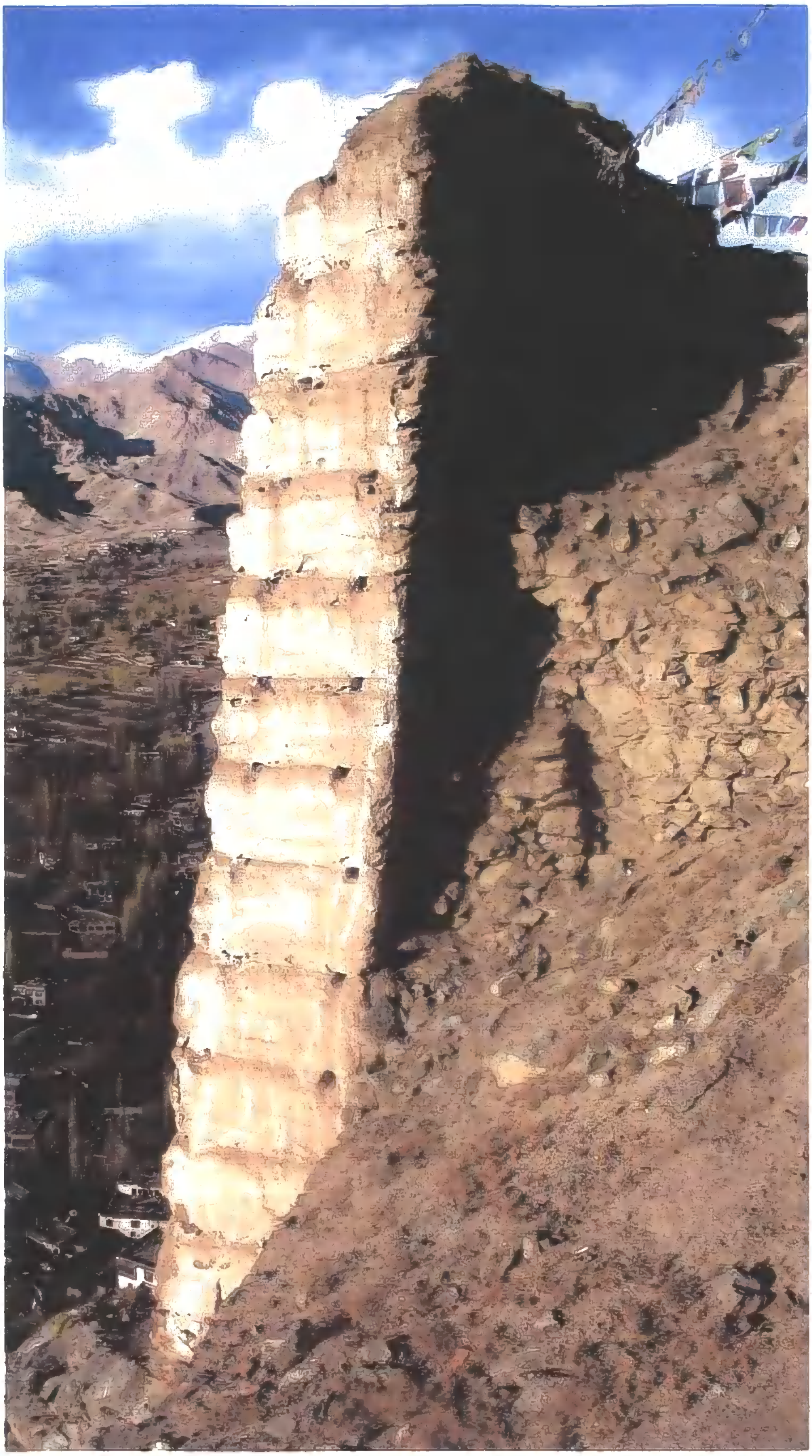


Figure D.11 Lele Namgyal Tsempo entrance wall

Figure D.12 Lelf Namgyal Tsempo internal

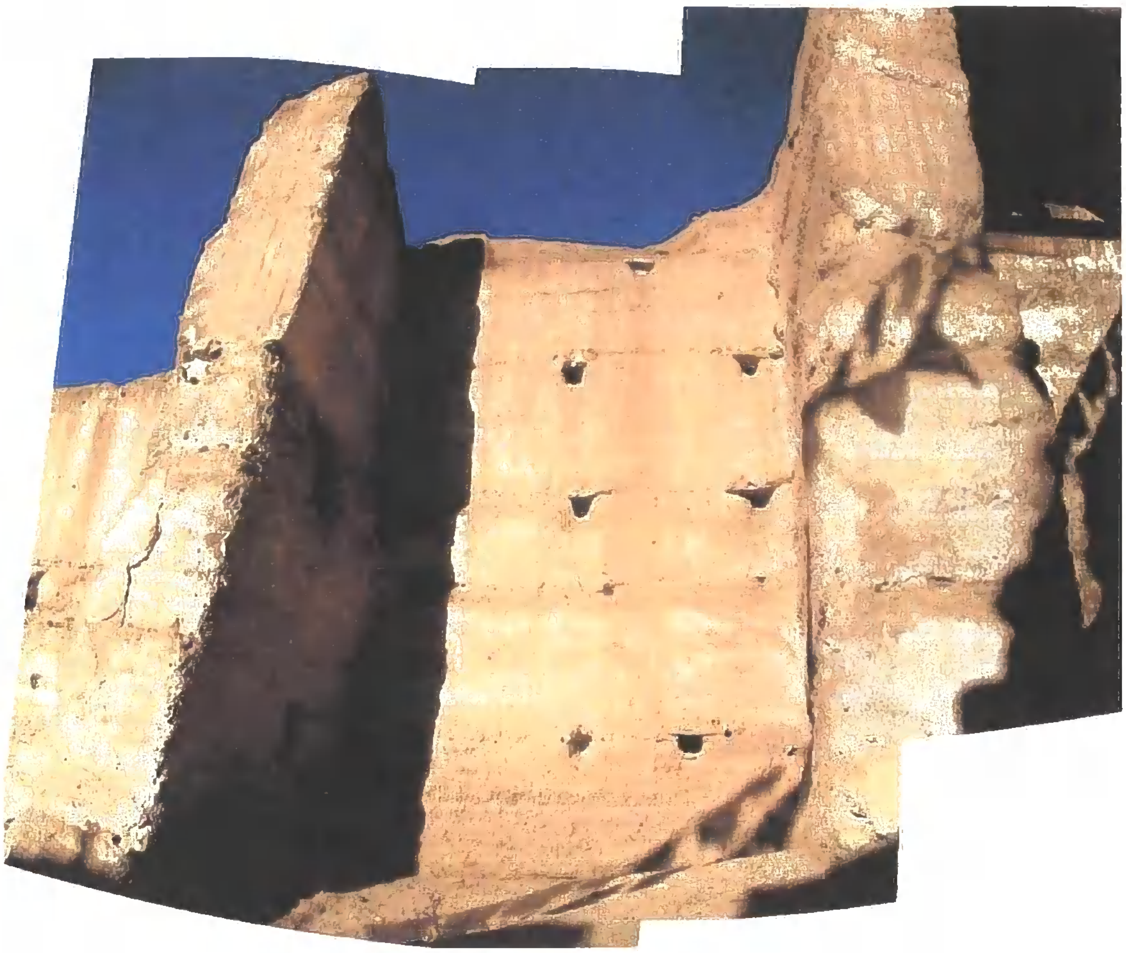


Figure D.13 Lelg Namgyal Tsempo internal rammed earth buttressing (1)

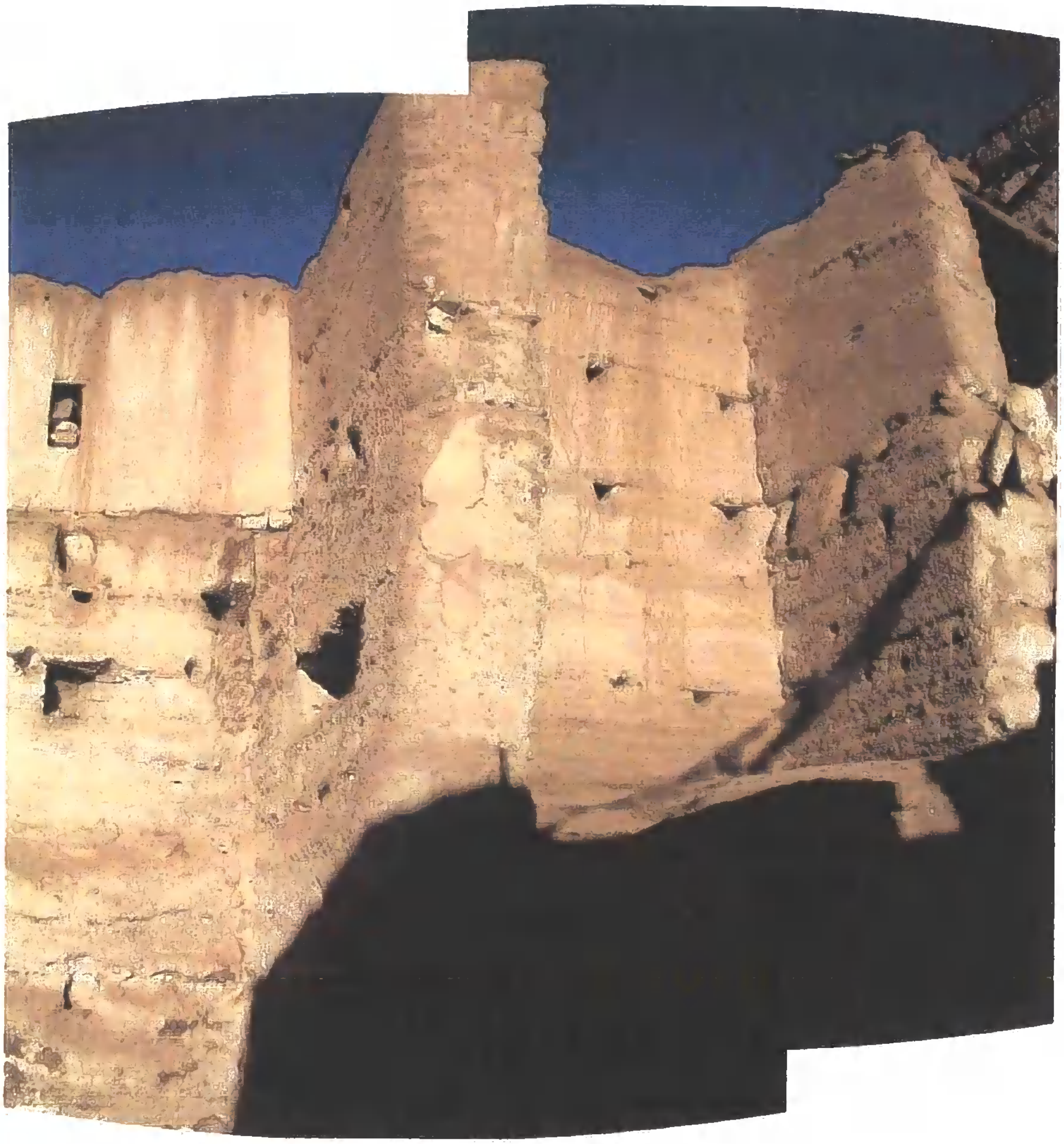


Figure D.14 Lelh Namgyal Tsempo internal buttressing (2)

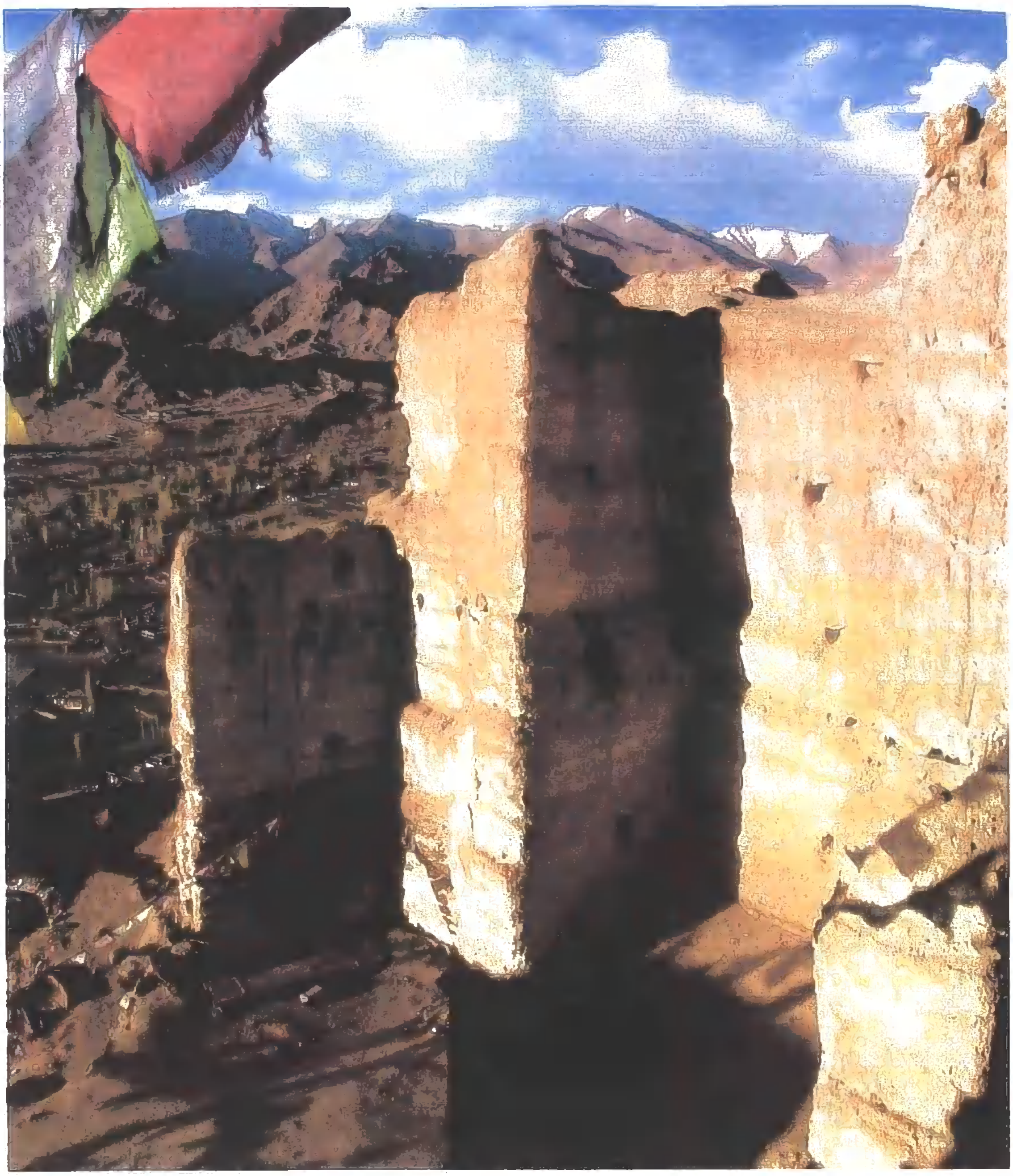


Figure D.15 Leli Namgyal Tsempo view south

D.2.2 Leh watchtower

The watchtower at Leh is situated on the same ridge as Namgyal Tsempo, and was probably constructed around the same time. Originally rectangular in plan (
Figure D.16), the south east wall of the structure is now missing, and the shorter walls are significantly cracked (Figure D.17). The construction is similar to that found at Shey, having angled joints between each rammed earth block (Figure D.18).

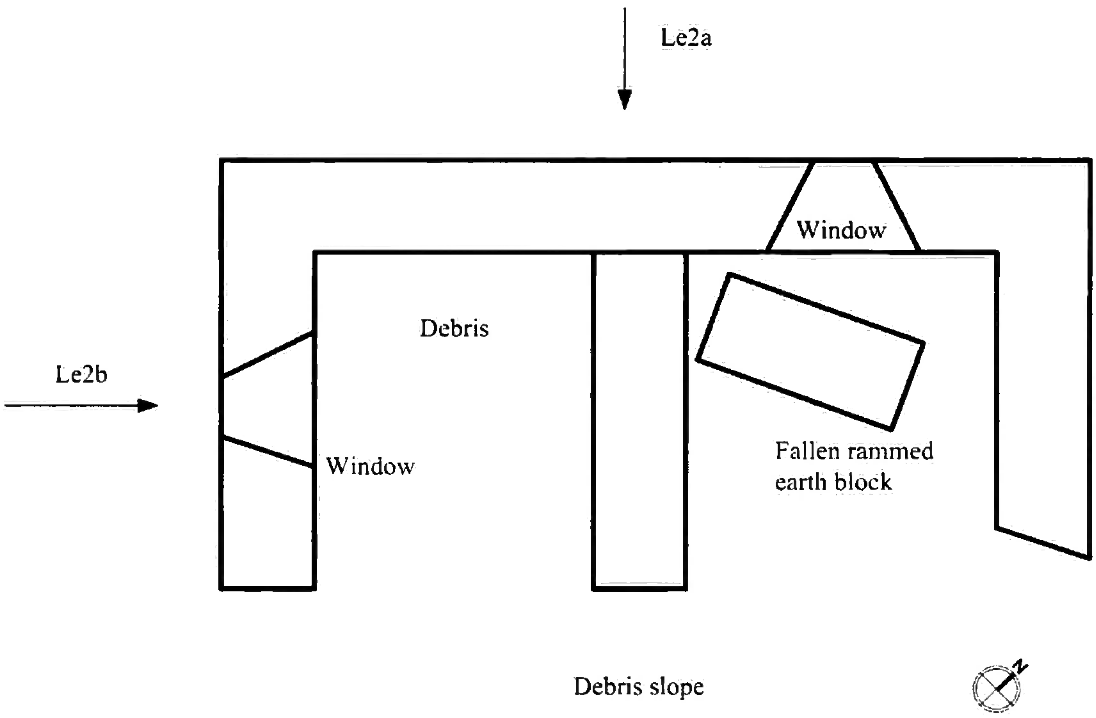


Figure D.16 Watchtower plan showing photograph location

Figure D.17 Le2a Watchtower southwest elevation

Figure D.18 Le2b Watchtower northwest elevation

D.3 Basgo fort

The site at Basgo consists of four distinct structures, three temples and a fort. The fort (Basgo Rabtan Lhartsekhar Castle) was built first and is the only structure made from rammed earth. Basgo was the capital of Ladakh before 1357, and it is possible that the castle dates from this period. The monasteries and Buddha images at the site began to be constructed around 1450. In 1550 the capital of Ladakh was moved from Basgo to Leh, but the site still retained military and religious importance. The first European account of Ladakh, by Portuguese merchant Diogo d'Almeida by just before 1600 mentions Basgo. The castle withstood a three year siege in 1684, but may have been destroyed by invading Sikhs in around 1819 and definitely by 1843. In 2000 the site was recognised as one of the world 100 most endangered heritage sites by the World Monuments Fund, and was repaired by local craftsmen under the supervision of John Hurd. The Basgo welfare committee, a social organisation comprising volunteers have taken up the responsibility for the preservation of Basgo, under the active guidance of the Tibetan classics translator guild of New York.

The rammed earth section stands in the centre of the site (Figure D.19), and consist of a mainly ruined set of walls, with no roof structure. A large crack is visible in the face of one of the walls (Figure D.20 and Figure D.21) which was repaired by in 2000 using the methods shown in Figure D.22.

Figure D.19 Bg1a Basgo fort, palace and monasteries

Figure D.20 Bg1b Basgo crack stitch photograph

Figure D.21 Bg1c Basgo fort photograph

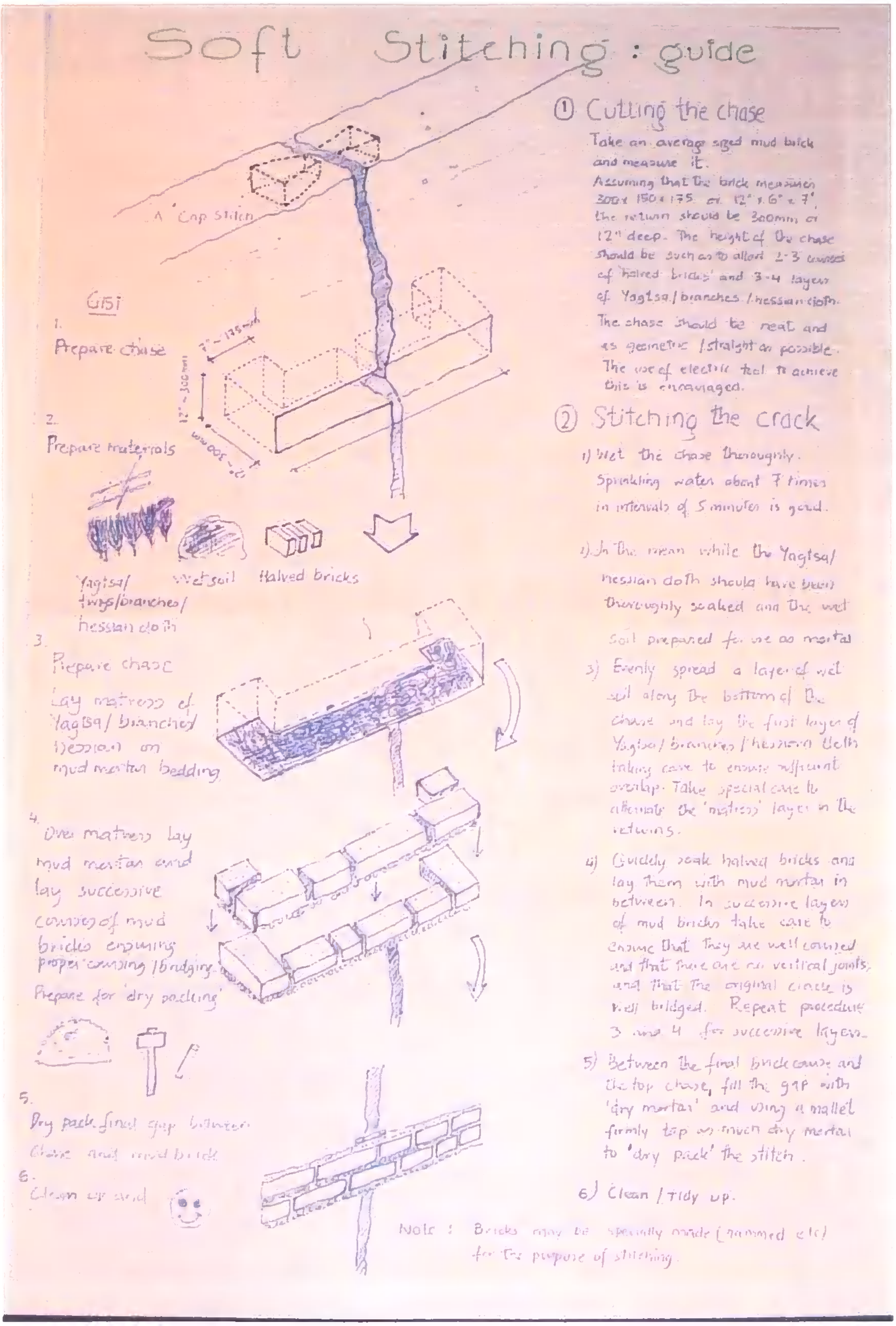


Figure D.22 Instructions on stitching at Basgo fort (Hurd 2006a)

D.4 Shey

The palace at Shey was capital of Lower Ladakh until 1550, when the kingdom was consolidated and power moved to Leh. Shey was used for two years as a base by the Muslim invader Mirza Haidar Daughlat, between 1534 and 1536, but beyond that little is known of the history of the fort. All that currently remains is a single rammed earth wall (Figure D.23 and Figure D.24), founded on bedrock and extending up from the road to the current monastery. Windows (Figure D.25) in the wall suggest that it originally formed part of a larger structure. The method of construction uses angled joints between the rammed earth, similar to that found at Leh.

Figure D.23 Sh1a Shey Palace rammed earth wall north side photograph

Figure D.24 Sh1b Shey palace rammed earth wall south side photograph

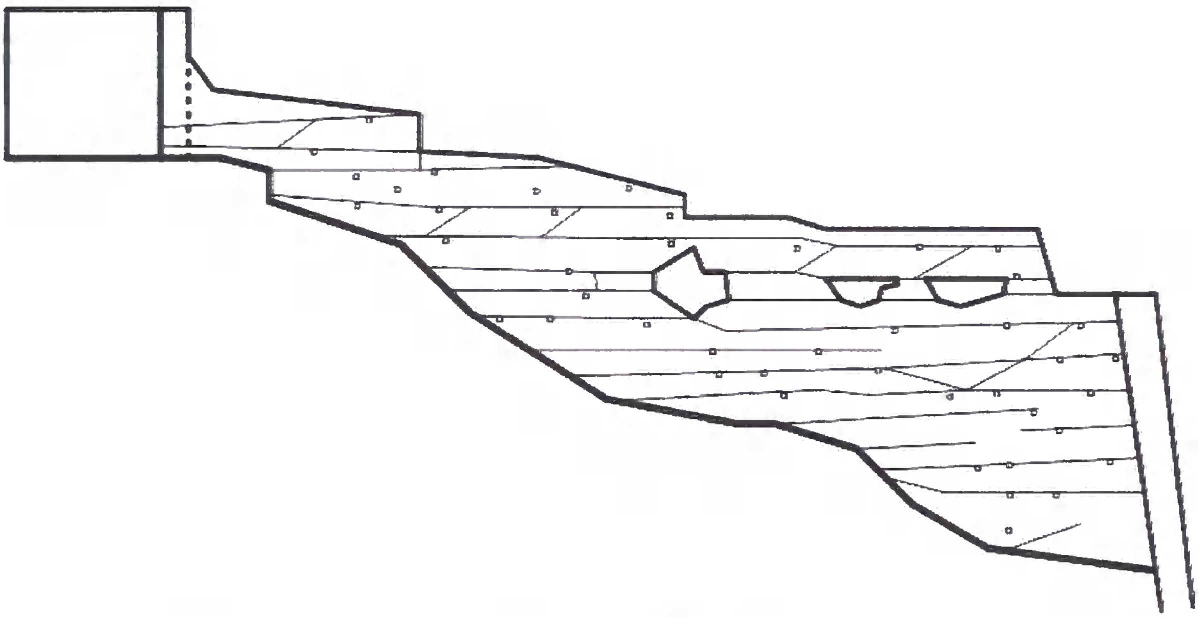


Figure D.25 Shey palace rammed earth wall south side elevation

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