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*Detailed studies of mid-ocean ridge volcanism at the
Mid-Atlantic Ridge (45°N) and elsewhere*

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25 flanks subside and are buried by episodic high-melt flux eruptions. This process involves two
26 distinct sources of magma: one, producing normal mid-ocean ridge basalt (N-MORB), is
27 located beneath the AVR; the other, producing enriched E-MORB, is located off-axis
28 beneath the median valley floor where it potentially drives hydrothermal circulation and
29 mineralisation on the ridge flanks.

30

31 Main:

32 One of the most striking features of slow-spreading MOR segments is the nearly ubiquitous
33 presence of a prominent and elevated AVR surrounded by the low-lying seafloor of the
34 median valley. For example, AVRs occur in fourteen out of eighteen well-mapped segments
35 along the MAR between 24° to 31°N^{11,18,19,20}; they are associated with rough hummocky
36 terrain compared to smoother seafloor covering the median valley floor.

37

38 At 45°N (MAR) this change from hummocky AVR to smoother seafloor covering the median
39 valley and uplifted ridge flanks is clearly demonstrated by a high-frequency roughness map
40 (Figure 1B). Generated from multibeam bathymetry, using a 5x5 (450 m by 450 m) high-
41 pass filter followed by a 3x3 standard deviation filter to isolate the high-frequency hummocky
42 morphology, the map shows a typical root-mean square roughness for the AVR of 31 m
43 (average peak-to-trough amplitude of 62 m for the hummocks).

44

45 The roughness of the AVR reflects its formation by ~3000 small volcanic cones with an
46 average volume of ~0.001 km³¹⁷. These result from frequent, short-lived, small volume,
47 eruptions of pillow lava¹⁷ that have extruded vertically from the crest and flanks of the AVR.
48 Occasionally, the summits of the hummocky volcanic cones are capped with 10-15 m high
49 pinnacles of basalt with slopes of ~60°. Together, these volcanic features indicate slow

50 effusion rates ($<1 \text{ m}^3$ per second)^{21,22} and are consistent with low eruption pressures due to
51 a close balance between magma pressure and the hydrostatic head of the column of melt
52 supplying the AVR^{23,24}. Using the maximum elevation of the AVR above the median valley
53 floor of 450 m, average densities for basaltic magma of $2.7 \pm 0.04 \text{ g cm}^{-3}$ ²⁵ and for mafic crust
54 of 2.9 g cm^{-3} ²⁶ and a hydrostatic eruptive model²³, we estimate a depth of between 5.4 km
55 and 8.1 km to the top of melt bodies located beneath the AVR (i.e. at or near the base of the
56 crust²⁷).

57

58 In contrast to the hummocky AVR, the low-lying median valley floor and uplifted ridge flanks
59 form smoother terrain (Figure 1B) with an average peak-to-trough amplitude of 16 m. The
60 median valley floor is covered in massive lava flows with only a thin ($<0.5 \text{ m}$ thick) veneer of
61 sediment. Where exposed, these massive lavas include multi-layered, ropey textured sheet-
62 flows, each up to several metres thick (Figure 1C), indicative of rapid eruption rates of 100s
63 of m^3 per second^{21,22}. Some of these sheet-flows (e.g. at the north-eastern end of the ridge
64 segment) appear to originate from flat-topped seamounts that are exclusive to the smooth
65 floors of the median valley and axial flanks (Figure 1D). Elsewhere, exposed high-up in the
66 fault scarps forming the median valley walls, massive lava flows of up to several metres thick
67 overlay pillow lavas (Figure 1E).

68

69 Since AVRs are the main locus of crustal accretion^{1,2}, the reduction in seafloor roughness
70 implies burial of the hummocky AVR flanks beneath the smoother floor of the median valley.
71 Sedimentation rates here are $\sim 5 \text{ cm}$ per thousand years²⁸ yielding an average sediment
72 thickness of less than 1 m, even at a distance of 6 km from the AVR crest. Also, sediment at
73 the top of the rift valley walls was observed by the ROV Isis to be less than 2 m thick. Hence
74 an accumulation of sediment alone cannot bury the hummocky flanks of the AVR. This,

75 instead, requires a cumulative thickness of at least 46 m for the massive lava flows that
76 cover the median valley floor.

77

78 Compared with the AVR, the relatively large volumes and long run-out lengths of the
79 massive lava flows burying the flanks of the AVR and covering the median valley floor
80 require more rapid effusion rates²¹. For example, assuming an effusion rate of 100m³ per
81 second^{21,22}, the 0.03 to 0.06 km³ volume for the north-eastern sheet-flow would have taken
82 between 3.5 and 7 days to erupt. These rapid eruptions indicate higher magma pressures
83 ^{23,24} and lower viscosities for melt sourced from deep and possibly hot reservoirs located
84 several kilometres off-axis under the outer-margins of the median valley floor.

85

86 Burial of the AVR beneath the median valley floor implies subsidence of its flanks. High-
87 resolution bathymetry profiles across the AVR at 45°N reveal a number of outward-facing
88 scarps on both its eastern and western flanks that dip at >45° (Figure 1F). These scarps
89 subdivide the flanks of the AVR into a series of linear terraces, several hundreds of metres
90 long, that progressively step down towards the smooth and flat-lying median valley floor
91 creating a structural horst. Some of the upper-surfaces of the terraces dip gently backwards
92 towards the centre of the AVR, consistent with back-rotation by shallow-rooted normal faults.
93 Visual observations reveal these as high-angle AVR-parallel fault scarps, a few tens of
94 metres high with broken pillow lavas forming steep cliffs (Figure 1G). Elsewhere, the faults
95 are inferred from outward-facing scarps that are partially draped by younger lavas (Figure
96 1H). The maximum accumulated throw for these outward facing faults, measured from the
97 profiles, is 260 m accommodating 50% of the subsidence of the AVR flanks. Hence the AVR
98 is as much a tectonic feature as it is a volcanic edifice and, as such, the accretionary axis of
99 slow-spreading MORs behaves in a similar way to the rise crest of fast-spreading MORs²⁹.

100

101 The contrast between the AVR hummocky lavas and median valley floor massive lavas is
102 reflected compositionally. While both have overlapping Cr and Ni concentrations, indicating
103 similar degrees of fractional crystallisation (Figure 2A), they show a bi-modal distribution of
104 incompatible trace element concentrations (Figure 2B) indicating derivation from different
105 primary melts and discrete magma bodies. The majority of AVR pillow-lavas form a group
106 that has lower concentrations and ratios of incompatible trace elements (i.e. N-MORB)
107 compared with the enriched compositions (i.e. E-MORB) of the massive-flows and flat-
108 topped volcanoes of the median valley floor (e.g. lower Zr for a given Y: Figure 2B). Some
109 flat-topped seamounts also have compositions that are nearly identical to their adjacent
110 massive sheet-flows indicating a close affinity between them.

111

112 Discussion:

113 The E-MORB composition of the massive lavas covering the median valley floor and the flat-
114 topped seamounts could indicate derivation from a lower degrees of partial mantle melting.
115 By comparison, the N-MORB composition of the hummocky AVR pillow lavas could indicate
116 derivation from a higher degree of partial mantle melting. Assuming bulk partition coefficients
117 for Zr and Nb during mantle melting are close to zero, the ~22% difference in Zr between the
118 average AVR lava and that of the enriched group corresponds to a ~20% reduction in melt
119 fraction for the median valley floor magmas. The equivalent change in Nb concentrations is
120 ~66%, indicating a ~60% reduction in melt fraction. Since this is impossible for a
121 homogeneous source, we propose that the E-MORB lavas are derived from a
122 heterogeneous mantle that is both enriched in highly incompatible trace elements and
123 melted to a smaller degree compared with the N-MORB AVR hummocky flows. At lower
124 degrees of partial mantle melting the magma composition is strongly influenced by the
125 preferential addition of melts from more fusible heterogeneities (e.g. streaks of eclogite

126 and/or pyroxenite)³⁰. These melts enrich the E-MORB magmas that supply both the flat-
127 topped volcanoes and the median valley floor sheet-flows. Larger melt fractions dilute these
128 enrichments and yield a more continuous supply of N-MORB magma to the AVR.

129

130 Eruption of different parental magma compositions require discreet magma reservoirs,
131 located both on-axis beneath the AVR and several kilometres off-axis beneath the median
132 valley floor, with separate melt pathways to the seafloor resulting in little opportunity for melt
133 homogenisation prior to eruption. Magma bodies located beneath the median valley floor,
134 that episodically erupt sheet-flows, can also supply heat to form off-axis hydrothermal
135 venting and seafloor massive sulphides away from the AVR crest³¹ and even on axial valley
136 walls³². This bi-modal volcanic distribution is remarkably similar to fast spreading MORs
137 where recent seismic imaging has shown off-axis (by 3-6km) melt lenses³³ that supply E-
138 MORB magmas to flat-topped seamounts and ridge-flank lavas while on-axis melt lenses
139 supply N-MORB magmas to volcanic accretion at the rise crest³⁴. Hence there appear to be
140 similar spatial scales of magma heterogeneity and focusing from the melt zone beneath both
141 fast and slow-spreading MORs.

142

143 Conclusions:

144 In contrast to previous models describing a cyclic evolution for AVRs, we propose that AVRs
145 are the product of frequent, small-volume, moderate-melt fraction, low-effusion rate
146 eruptions of pillow lavas at their crest and continuous subsidence of their flanks. These are
147 buried by episodic, large volume, low-melt fraction, fast-effusion rate eruptions of massive
148 lavas that cover the median valley floor (Figure 3). Variations in the flux and frequency of
149 eruptions result in interleaving of AVR flanks with massive-flows erupting across the median
150 valley floor. Hence there is no cyclicity per se for the AVR and no paradox for their near

151 ubiquitous presence throughout all slow-spreading MORs. In this scheme, the AVR behaves
152 like a glacier, accreting new material (i.e. lava) across the top while simultaneously it flanks
153 spread and subside (i.e. by faulting) towards its base. In both its tectonic and magmatic
154 processes, the behaviour of slow-spreading MORs is much more similar to fast-spreading
155 MORs than previously thought.

156

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163

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280

281 Figures:

282

283 Figure 1. Composite figure showing key geological and geophysical observations of the
284 AVR: A) EM120 swath sonar bathymetry, gridded at 50m and hill-shaded from the NE of the
285 segment at 45°N, showing the positions of inset figures 1C-F. B) Roughness map (derived
286 from the bathymetry) shows the AVR is dominated by hummocky terrain while the median
287 valley floor and flanks of the Mid-Atlantic Ridge are mainly smooth. C) Photograph (3 m x 4
288 m) showing a massive sheet on the floor of the median valley. D) Detail of sidescan sonar
289 imagery showing a massive sheet flow (bright backscatter, outlined in yellow) covering part
290 of the floor of the median valley. E) Photograph (2 m x 3 m) showing a massive lava flow at
291 least 1.5 m-thick exposed near the top of the western median valley wall. F) High-resolution
292 bathymetry profile across the AVR, obtained from the TOBI vehicle (see figure 1 for
293 location). The profile shows steep slopes related to linear scarps that trend N-S and face
294 down the flank of the AVR. These are interpreted as outward-facing normal faults on the
295 hummocky flanks of the AVR generating a horst structure for the AVR. On the median valley
296 walls, the scarps are inward facing, generating a graben structure. The profile also shows
297 the difference between the hummocky AVR topography and the smooth and flat-lying
298 seafloor of the median valley. Symbols denote: (pl) pillow lavas, (sf) sheet flows, (AVR) axial
299 volcanic ridge, (MVF) median valley floor, (RF) rift flank. G) Composite image (3m x by 8 m)
300 showing a westward-facing fault scarp of brecciated pillow-lavas cutting the western flank of
301 the AVR. H) Photograph (2m x 3m) showing lavas draped over a near vertical, outward
302 facing scarp interpreted as part of an outward facing fault.

303

304 Figure 2. Key geochemical indicators of magmatic fractionation and source variation.
305 Symbols: Blue filled diamonds are hummocky terrain forming the main body of the AVR;
306 green filled triangles are hummocky terrain forming a spur on the north-eastern flank of the
307 AVR; red filled squares are massive sheet flows filling the median valley floor; yellow filled
308 squares are flat-topped volcanoes on the median valley floor. All trace-element analyses
309 were made on pressed powder pellets from whole-rocks, determined by wavelength

310 dispersive XRF. Analytical errors are less than the size occupied by the figure symbols. A)
311 Cr vs. Ni co-variation diagram for lavas from the 45°N segment. All groups overlap in Cr vs.
312 Ni space indicating no systematic differences in the extent of crystal fractionation. B) Zr vs. Y
313 co-variation: There are two clear groups of volcanic compositions within the 45°N segment
314 of the Mid-Atlantic Ridge: the hummocky terrain of the AVR (forming a lower Zr group) and
315 the median valley massive-flows and seamounts (forming a higher Zr group). These
316 differences indicate derivation of the lavas from different parental melts. Oval fields enclose
317 flat-topped volcanoes and spatially adjacent sheet flow lavas of similar composition
318 indicating cogenesis.

319

320 Figure 3. Cartoon (not to scale) showing the essential elements of the steady-state AVR
321 process: large melt-fraction magmas segregate from the centre of the asthenospheric
322 melting zone and supply N-MORB to magma chambers (mc) located beneath the AVR.
323 Small melt-fraction magmas from the periphery of the melting zone supply E-MORB to
324 magma chambers located under the median valley floor. The AVR magmas frequently erupt
325 small volumes of pillow lava (pl) building an elevated ridge of hummocky volcanic mounds.
326 Simultaneously, the flanks of the AVR subside toward the median valley floor where less
327 frequent but larger volume eruptions of E-MORB bury the hummocky terrain of the AVR
328 beneath sheet flows (sf).

331





