25. SIGNIFICANCE OF CONTRASTING VESICULARITY IN BASALT FROM DSDP SITES 407, 408, AND 409 ON THE WEST FLANK OF THE REYKJANES RIDGE

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ABSTRACT

During Leg 49 of the Deep Sea Drilling Project, holes were drilled at magnetic anomalies 13 (35 to 36 m.y. B.P.), 6 (19 to 20 m.y. B.P.), and 2A (2.2 to 3.2 m.y. B.P.) on the west flank of the Reykjanes Ridge. Average vesicularity of basalt from the three holes increases from about 6 to 13 to 27 per cent with decreasing age, the opposite trend of that to be expected if controlled by concomitant changes in rock chemistry. Apparently, increasing vesicularity reflects decreasing water depth (confining pressure) at the ridge where the lavas erupted. The ridge may have grown upward as much as 1846 meters since about 35.5 m.y. ago, suggesting a long-term dynamic evolution rather than steady-state existence. The time of formation of Iceland proposed by others is within the first period of ridge growth indicated by increasing vesicularity. Thus, Iceland and its south flank, the Reykjanes Ridge, may have grown simultaneously during the latter half of the Cenozoic Era.

INTRODUCTION

During Leg 49 of the Deep Sea Drilling Project, Holes 407, 408, and 409 were drilled on the west flank of the Reykjanes Ridge. These holes are aligned in a N60° W direction, virtually perpendicular to the ridge, along a flow line defined by the direction of spreading at the ridge crest (Figure 1). The sites are positioned over sea-floor magnetic anomalies 13 (Site 407), 6 (Site 408), and 2A (Site 409), corresponding to basaltic basement rocks that are estimated to be 35-36 m.y., 19-20 m.y., and 2.2-3.2 m.y. old, respectively (LaBrecque et al., 1977). These ages are consistent with ages of immediately overlying sediment as determined from fossils, with the possible exception of Site 407 where the first basalt drilled may be as much as 5 m.y. younger than the age suggested by the sea-floor magnetic anomaly (see biostratigraphy chapters, this volume).

Basalt recovered at the three sites increases in vesicularity from about 6 per cent at Site 407 to 13 per cent at Site 408 to 27 per cent at Site 409. This dramatic increase presumably reflects a similarly time-related decrease in confining pressure induced by the column of water overlying the spreading ridge where the lavas were extruded, and/or an increase in volatile content of the successively younger lavas at the time of their eruption. Comparison of vesicularity and rock chemistry with that reported by Moore (1970,1973) suggests that the effect of confining pressure was principally responsible for differences in vesicularity of the basalt of this study. Thus, the depth of water at the site of eruption along the Reykjanes Ridge spreading center apparently decreased between 35-36 m.y. and 19-20 m.y. ago, and again between 19-20 m.y. and 2.2-3.2 m.y. ago. The detailed history of such decrease in water depth is conjectural, but I propose that it occurred more or less continuously throughout the entire period between eruption of basalt recovered at Sites 407 and 409, and that it reflects the upward growth of the Reykjanes Ridge from depths that initially were probably comparable to present depths along the Mid-Atlantic Ridge to the south.

VESICULARITY, CONFINING PRESSURE, AND ROCK CHEMISTRY

The degree of vesiculation that a lava undergoes during eruption on the sea floor is controlled primarily by the volatile content of the lava at the time of eruption and by the confining pressure induced by a column of overlying seawa-

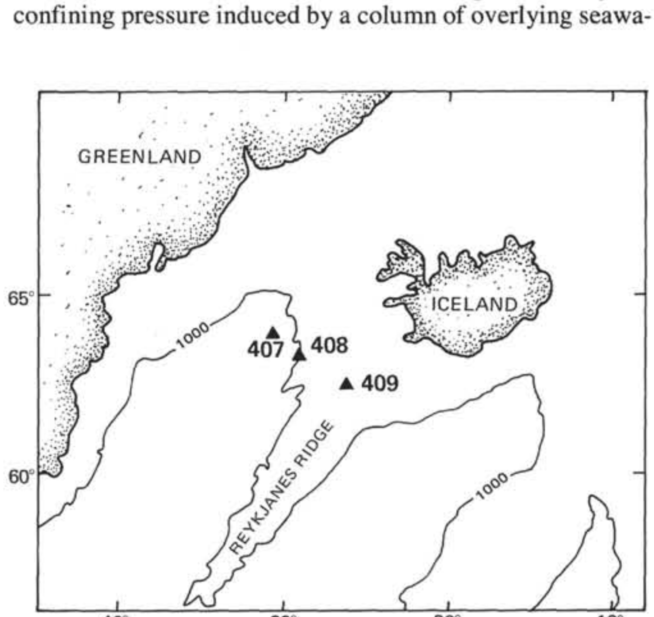

Figure 1. *Index map showing location of DSDP Sites 407, 408, and 409. One-thousand-fathom line outlines shape of Reykjanes Ridge.*

ter. Moore (1970) has shown that vesicularity of sea-floor basalt, when plotted against depth of eruption, defines a family of three curves, which are related to rock chemistry; at any given depth of eruption, relatively more vesicular rocks are richer in H_2^+, K_2O, P_2O_5, Cl, and F. The least vesicular and thus most K_2O-poor group of lavas studied by Moore (1970) includes basalt from the crest of the Reykjanes Ridge, and defines a parabolic vesicularity-versus-depth-of-eruption curve, reproduced here for reference (Figure 2). The fact that basalt with relatively high levels of K_2O is more vesicular than its counterparts low in K_2O is consistent with many field observations that indicate alkalic basalt is generally richer in volatiles than tholeiitic basalt (Moore, 1970).

Rock chemistry reported elsewhere in this volume indicates that basalts recovered at Sites 407, 408, and 409 belong to the group of basalts lowest in K_2O content that Moore (1970) studied. Rock chemistry analysis also indicates that oldest lavas are most enriched in the constituents that show positive correlation with vesicularity. Thus, the observed increase in vesicularity from older to younger lavas runs counter to change expected from the effect of differences in rock chemistry, and can confidently be ascribed to differences in confining pressure at the time of eruption. Theoretically, vesicularity of Leg 49 basalt may be compared with the data of Moore (1970) for a direct determination of water depth at the time of eruption. Unfortunately, a less direct comparison is necessary, because of differences in samples from which vesicularity was determined.

Vesicles typically are distributed very unevenly in lava flows, so that meaningful interflow comparisons of vesicularity require careful sampling of comparable vesicle zones from different flows. Jones (1969) discussed this sampling problem in his study of vesicularity versus depth of eruption for pillow lava extruded beneath snow and ice on Iceland; he chose to measure vesicularity of samples from near the base of pillows for inter-pillow comparison. Moore (1970)

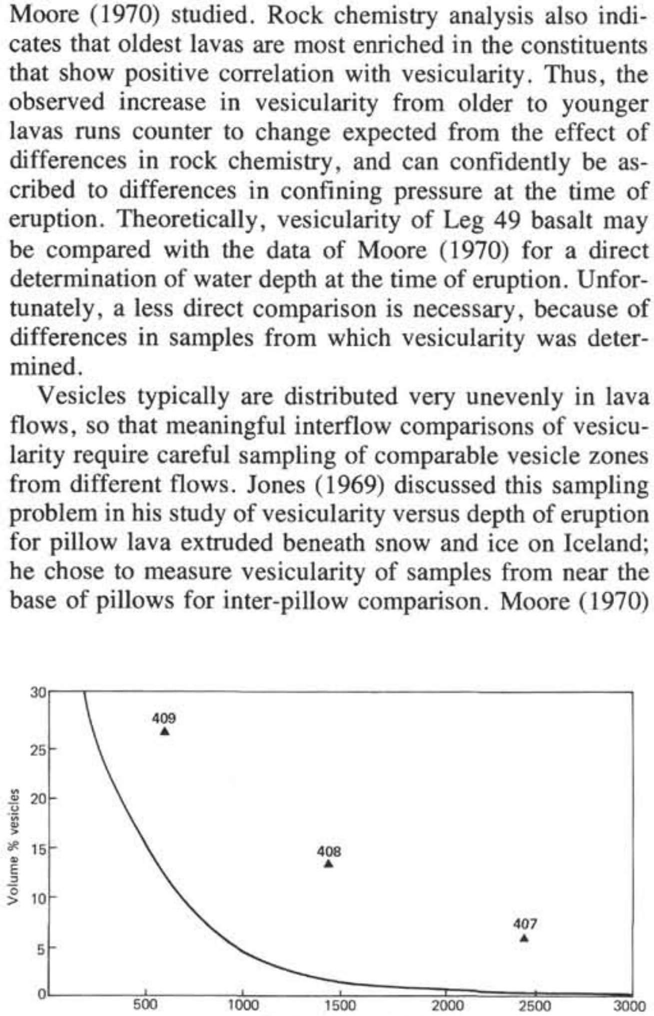

Figure 2. *Curve showing relationship between volume percentage vesicles in quenched glass margins of pillow lava and depth at which lava erupted for low-K tholeiite (from Moore, 1970). Horizontal bars show possible depth range for eruption of basalt from DSDP Sites 407, 408, and 409, as calculated in text. Vesicularity from Table 1. The bars plot above the curve of Moore because samples used to determine vesicularity are from relatively frothy interior of pillows, rather than quenched margins.*

attempted to minimize the sampling problem by using only the glass of quenched pillow margins. The sampling problem for the present study was aggravated by the fact that, other than glassy pieces, which are few and dear, the original position of a sample from within a flow of the many penetrated at each site is unknown. Lacking such intraflow control, I chose to study the most vesicular portion of recovered core, reasoning that these samples would be most nearly representative of relative degree of vesicularity for inter-site comparisons. Modal counts of vesicles were made on flat surfaces of split drill core (Figure 3) as the core became available aboard ship. The modal data are summarized in Table 1. Drilling rate records provide independent evidence that vesicularity determined by modal counts is at least a semiquantitative characterization of true vesicularity at each site and, thus, that the indicated inter-site differences are not artifacts of sample selection.

During drilling of basalt at Sites 407, 408, and 409, the weight on the bit was maintained at 10,000 to 12,000 pounds and the bit was turned as closely as possible at 50 rpm (Donald Collins, oral communication, 1976). A new drill bit of the same type was used at each site and other drilling conditions were comparable, so that differences in resistance to penetration must have resulted primarily from differences in basalt being drilled. Examination of penetration rate recorded continuously during drilling shows that the average time required to drill one meter of basalt was about 6, 5, and 3 minutes for Holes 407, 408, and 409, respectively. The only apparent physical difference among basalts from the three sites is an increase in vesicularity from 407 to 408 to 409, consistent with concomitant increasing ease of drilling. At Hole 409, a *Glomar Challenger* record was established for total penetration through basalt by a single bit, a feat almost certainly made possible by the remarkably high vesicularity of the basalt there. Moreover, after early termination of drilling in Hole 409, the bit showed very little wear—further evidence of the ease of penetrating such vesicular rock, and supporting evidence that vesicularity determined by modal counts reflects real inter-site differences.

In addition, preliminary examination of benthic foraminifer assemblages from samples intercalated with or immediately overlying basalt suggests lower bathyal depths (1000 to 2000 m) at the time of deposition of the fossils at Sites 407 and 408, and upper bathyal depth (200 to 600 m) at Site 409; water depth at Sites 407 and 408 may have been closer to 1000 meters than 2000 meters, with that at Site 408 somewhat shallower than that at Site 407 (W. A. Berggren, written communication, 1977).

These conclusions are tentative and subject to refinement after further study of the foraminifer assemblages, but the preliminary indication is of a history of decreasing water depth at the Reykjanes Ridge, similar to that indicated by contrasting vesicularity.

The depth of water in which lava was erupted may be calculated for the two older sites on the assumptions that (1) the Reykjanes Ridge has grown upward to shallower water depths at a constant rate since 35.5 m.y. ago, the approximate age of basalt drilled at Site 407; (2) lithosphere generated along the ridge crest has subsided during this period in response to thermal contraction, as described by Sclater et al. (1971); and (3) basalt of Site 409 was emplaced in about

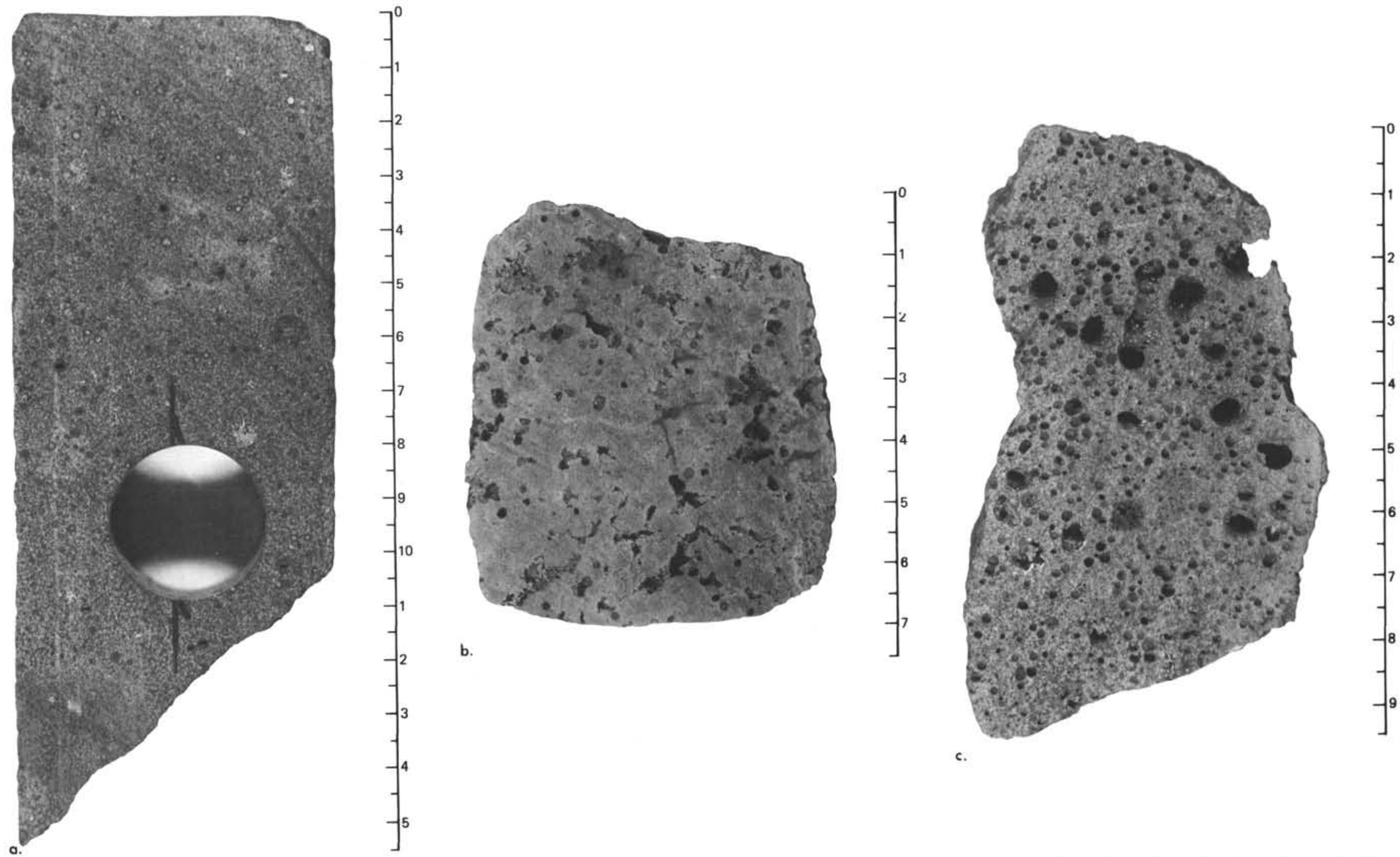

Figure 3. *Photographs of split drill core from which modal counts of vesicularity were determined. Most vesicles are roughly spherical and less than 3 mm in diameter. Pipe vesicles as long as several centimeters are present in some samples from Site 409.* (A) *Site 407, Core 3b, Section 2, Piece 2B. Most vesicles are partly or wholly filled by secondary minerals. Barbed line across 2.5-cm hole points to stratigraphic top.* (B) *Site 408, Core 37, Section 2, Piece 14.* (C) *Site 409, Core 25, Section 2, Piece 7. Secondary minerals line some vesicles. Largest holes are parts of pipe vesicles, some of which penetrate through sample.*

TABLE 1
Vesicularity in Volume Per Cent of Basalt Recovered at DSDP Sites 407, 408, and 409[a]

Core-Section-Piece	Vesicularity	Average
Site 407		
36-2-2A	5.9	
37-2-5	6.0	
37-2-7	3.9	
39-2-8	7.1	5.6
Site 408		
36-4-3A	13.4	
37-2-8	11.2	
37-2-14	13.6	
38-2-9	14.6	13.2
Site 409		
7-6-3	18.9	
9-1-6	38.1	
9-2-10	31.3	
9-3-5	13.7	
12-1-9	20.3	
13-1-4	22.8	
13-3-6	32.6	
14-1-1	37.7	
14-1-5	33.1	
15-2-15	28.6	
16-1-6A	20.8	
16-2-12	20.4	
18-1-13	19.9	
20-1-14	27.9	
24-3-2A	19.1	
25-2-7	27.6	
31-1-15	34.9	
31-2-7	30.4	26.6

[a]Each determination represents a minimum of 1000 counts on a grid fit to the size of available samples.

600 meters of water, the present depth of water at the crest adjacent to that site.

Basalt of Site 409 is now about 900 meters below sea level, and the amount of subsidence expectable from thermal contraction since eruption 2.7 m.y. ago is about 440 meters (Figure 4, Table 2). Accordingly, the rate of uplift of the ridge is 52 m/m.y.

$$\frac{600 \text{ m} + 440 \text{ m} - 900 \text{ m}}{2.7 \text{ m.y.}}$$

This rate may be used to calculate the water depth at which basalt of the older sites was erupted, through the relationship

$$D_e = D_p + U - C$$

where D_e = depth at eruption, D_p = present depth, U = uplift related to the growth of the Reykjanes Ridge since eruption, and C = subsidence resulting from thermal contraction since eruption. The 52 m/m.y. rate of uplift corresponds to eruption depths of 2446 meters and 1439 meters for basalt of Holes 407 and 408, respectively. These figures (Table 2) are reasonable when compared with present depths of about 3000 meters along most of the Mid-Atlantic Ridge to the south. The rate of uplift and the corresponding calculated depths of eruption for the older sites would be greater if basalt of Site 409 was assumed to have been erupted in water somewhat deeper than that at the present nearby ridge crest. However, the general result remains the same.

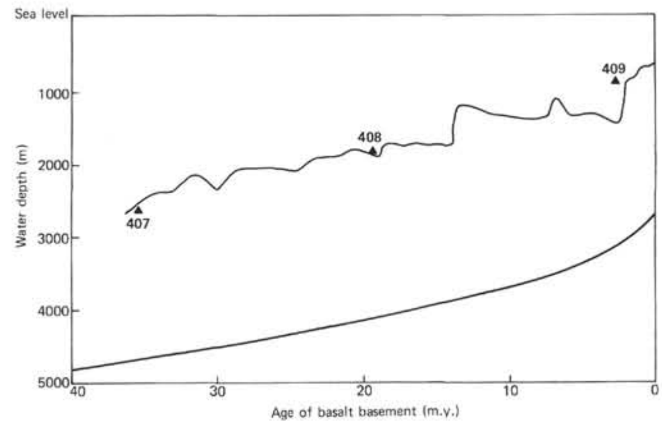

Figure 4. *Idealized age-depth curve for spreading sea floor (from Sclater et al., 1971), and sea-floor topography along track of* Glomar Challenger *from crest of Reykjanes Ridge to Site 407, constructed from echo-sounder records obtained during Leg 49. Positions of top of basaltic sections drilled at Sites 407, 408, and 409 shown by triangles, with depth corrected for isostatic settling associated with overlying sediments. Age of basalt at each site is average for appropriate magnetic anomalies (from LaBrecque et al., 1977). Sites 408 and 409 lie somewhat off charted track.*

TABLE 2
Depth of Eruption (depth to crest of Reykjanes Ridge), Based on Assumptions Explained in Text

	Site 407	Site 408	Site 409
Age, m.y.	35.5	19.5	2.7
Rate of Ridge Uplift, m/m.y.	52	52	52
D_p, m	2615	1840	900
C, m	2015	1415	440
D_e, m	2446	1439	600

The calculations do not prove that the ridge has indeed risen steadily during the past 35.5 m.y., but they do show that such uplift may have occurred at a rate of about 52 m/m.y. or slightly more, a history of ridge evolution consistent with the original observation on contrasting vesicularity, and with depths indicated by contrasting benthic foraminifer assemblages at each site. Calculated eruption depths and corresponding vesicularity at each site are plotted with Moore's (1970) data for comparison (Figure 2).

DISCUSSION

Increasing vesicularity of basalt from Site 407 to Site 408 to Site 409 is explained reasonably through a concomitant decrease in the depth of water at the spreading ridge where these lavas erupted. The change in water depth during the 32.8-m.y. period between eruption of the oldest and youngest lavas is speculative, but may have been as much as 1846 meters. Whatever the change was, the marked increase in vesicularity with time suggests considerable shallowing of the Reykjanes Ridge since at least 35.5 m.y. ago, the age of basalt at Site 407. Such a history for the ridge contrasts with earlier descriptions.

Through comparison of the present profile of the Reykjanes Ridge with an age-versus-depth curve considered to represent a typical sea-floor profile (Sclater et al., 1971), Vogt and Avery (1974) described the present shallow depth of the ridge as an essentially steady-state feature that persisted throughout the Cenozoic era. Similarly, Talwani and Eldholm (1977) concluded that the ridge has existed at anomalously shallow depth since initiation of spreading there at about the beginning of the Cenozoic. Changes in basalt vesicularity and benthic foraminifer assemblages in the oldest sediments recovered from Holes 407, 408, and 409, require, however, a dynamic evolution for the ridge for at least the last half of the Cenozoic. Since the ridge forms the tapering south flank of Iceland, this evolution may be related to the growth and emergence of the island.

Talwani and Eldholm (1977) described the plate tectonic history of the North Atlantic and concluded that the formation of Iceland probably dates from about 27 m.y. ago, the time of a westward jump in the spreading center north of Iceland. This timing is consistent with the idea that the Reykjanes Ridge grew upward contemporaneously with the formation of Iceland, and that it began sometime between anomaly 13 time (Site 407) and anomaly 6 time (Site 408). Nilsen and Kerr (in press) conclude that the Iceland-Faeroe Ridge, part of a Tertiary land bridge between Greenland and Europe, subsided below sea level about 30 m.y. ago, contemporaneous with the initial formation of Iceland. This timing is also consistent with the idea that the Reykjanes Ridge and Iceland grew contemporaneously, beginning sometime between eruption of basalt drilled at Sites 407 and 408. If these two features did in fact evolve together since about 30 to 27 m.y. ago, a 20 m.y. age for the oldest subaerial lavas on Iceland (Dagley et al., 1967; Moorbath et al., 1968) suggests about 7 to 10 m.y. of submarine growth before the island emerged above sea level.

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REFERENCES

Dagley, P., Wilson, R. L., Ade-Hall, J. M., Walker, G. P. L., Haggerty, S. E., Sigurgeirsson, T., Watkins, N. D., Smith, P. J., Edwards, J., and Grasty, R. L., 1967. Geomagnetic polarity zones for Icelandic lavas, *Nature*, v. 216, p. 25-29.

Jones, J. G., 1969. Pillow lavas as depth indicators, *American Journal of Science*, v. 267, p. 181-195.

La Brecque, J. L., Kent, D. V., and Cande, S. C., 1977. Revised magnetic polarity time scale for late Cretaceous and Cenozoic time, *Geology*, v. 5, p. 330-335.

Moorbath, S., Sigurdsson, H., and Goodwin, R., 1968. K-Ar ages of the oldest exposed rocks in Iceland, *Earth and Planetary Science Letters*, v. 4, p. 197-205.

Moore, J. G., 1970. Water content of basalt erupted on the ocean floor: *Contributions Mineral. and Petrol.*, v. 28, p.272-279.

________, 1973. Vesicles, water, and sulfur in Reykjanes Ridge basalts, *Contributions Mineral. and Petrol.*, v. 41, p. 105-118.

Nilsen, T. H. and Kerr, D. R., in press. Paleoclimatic and *paleogeographic implications of a lower Tertiary laterite (latosol) on the Iceland-Faeroe Ridge, north Atlantic region, Geol. Mag.*, v. 115.

Sclater, J. G., Anderson, R. N., and Bell, M. L., 1971. Elevation of ridges and evolution of the central eastern Pacific: *Journal of Geophysic Research*, v. 76, p. 7888-7915.

Talwani, M. and Eldholm, O., 1977. Evolution of the Norwegian-Greenland Sea: *Geologic Society of America Bulletin*, v. 88, p. 969-999.

Vogt, P. R. and Avery, O. E., 1974. Detailed magnetic surveys in the Northeast Atlantic and Labrador Sea, *Journal of Geophysic Research*, v. 79, p. 363-389.