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Morphology and Magnetic Anomalies North of Iceland

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Abstract. Detailed low-level aeromagnetic data between Iceland and 70° N are combined with published bathymetric, seismic reflection, and other data to yield a new tectonic synthesis of this region of anomalously shallow sea floor. On Kolbeinsey Ridge short transform faults have repeatedly formed and disappeared over the last 7–8 Ma. Spreading from Kolbeinsey Ridge began about anomaly 6C time (24 Ma); total opening rates increased from 1.5 cm/a to 2 cm/a about 12–13 Ma ago. The Intermediate-Iceland-Plateau extinct axis thus does not exist, and oceanic crust must underlie much of the Greenland margin, perhaps up to the coast itself. This in turn implies locally over 100 km prograding, much of which probably occurred during Plio-Pleistocene glacial periods. The Iceland shelf has been prograded locally 25 km or more. The plate acceleration a 12–13 Ma ago correlates with time-transgressive basement ridges or escarpments previously found on Reykjanes Ridge and here identified north of Iceland as well. The features are proposed to reflect an abrupt mid-Miocene increase in discharge from the Iceland plume. Other time-transgressive basement structures are found on younger Kolbeinsey Ridge crust. Lower Tertiary anomalies 13 to at least 22 are identified in the Denmark Straits, ruling out the hypothesis that the Iceland platform resulted from a westward jump of the spreading center at anomaly 7 time. The magnetic smooth zones being formed where the Kolbeinsey and Reykjanes Ridges enter Iceland have a multiple origin: degassing at depths less than 500 m, coupled with crustal reheating as a result of burial by sediment may be the most important processes.

Key words: Rock magnetism – Magnetic smooth zones – Magnetic anomalies – Sea-floor spreading – Plate tectonics – Iceland – Iceland platform – Iceland plateau – Fracture zones – Hot spots – Aeromagnetics.

Introduction

The region between the Greenland-Iceland-Faeroe aseismic ridge and the Jan Mayen fracture zone exhibits unusual complexities such as jumps in the spreading axis (Johnson and Heezen, 1967; Vogt et al., 1970a; Talwani and Eldholm, 1977) and depth anomalies ranging from near zero in the Norway Basin to over 2 km on the Kolbeinsey Ridge (Vogt and Johnson, 1975; Cochran and Talwani, 1978). These complexities have been attributed to the Iceland hot spot, whose effects extend from the Charlie Gibbs Fracture Zone (52.5° N) northward at least to Mohns Ridge 1,000 km northeast of Iceland (Vogt, 1974). Whether the Iceland hot spot consists of a narrow plume under Iceland, feeding mantle materials north and south under the Mid-Oceanic Ridge (Vogt, 1974; 1976; Vogt and Johnson, 1975), or whether it is a broad hot spot in the upper mantle (Talwani and Eldholm, 1977; Cochran and Talwani, 1978), it is clear that the phenomenon is of regional dimensions and involves a variety of geophysical and geochemical parameters.

In this paper we examine the morphology and magnetic anomalies of the southern Iceland Plateau, a region of relatively shallow sea-floor extending from the Jan Mayen Ridge in the east to Greenland in the west, and from the coast of Iceland north to about 70° N (Fig. 1). The present spreading axis, Kolbeinsey Ridge, lies in part within the area of interest. (The entire 'Iceland Plateau' is defined as the relatively shallow area bounded by the shelf edges of Greenland and northern Iceland, by the Jan Mayen Ridge in the east, and the Jan Mayen F.Z. in the north).

Central to the present paper is an aeromagnetic survey program between the U.S. Naval Oceanographic Office and Iceland. The western part of the survey was published by Johnson et al. (1975). The Project MAGNET survey (Fig. 2) consisted of three parts, each flown at 500 ft (160 m) elevation at line spacings of 3 nautical miles (5.5 km) except on the southeastern Iceland Plateau (east of 15° W and south of 68.5° N) where the tracks were spaced 11 km apart. Navigational accuracy is ± 2 km or better. Analysis of these data is still in progress and the interpretations presented here should be considered preliminary.

Considered together with the new magnetic data are east-west bathymetric profiles across Kolbeinsey Ridge (Meyer et al., 1972; Figs. 7 and 8), a new bathymetric contour chart (Perry et al., 1977; Fig. 1), a sediment isopach chart (Grønlie and Talwani, 1978; Fig. 6) and some deep structural features dicovered under the Greenland margin by Hinz and Schlüter (1978).

Spreading on Kolbeinsey Ridge Since Anomaly-Five Time

Anomalies 5 and younger are well-developed on both flanks of the Kolbeinsey Ridge itself, north of the 1,000 m isobath bounding the Iceland platform (Fig. 2). However, numerous minor fracture zones and bends have formed at varying times subsequent to anomaly-5 time. The magnetic data show that fractures of small

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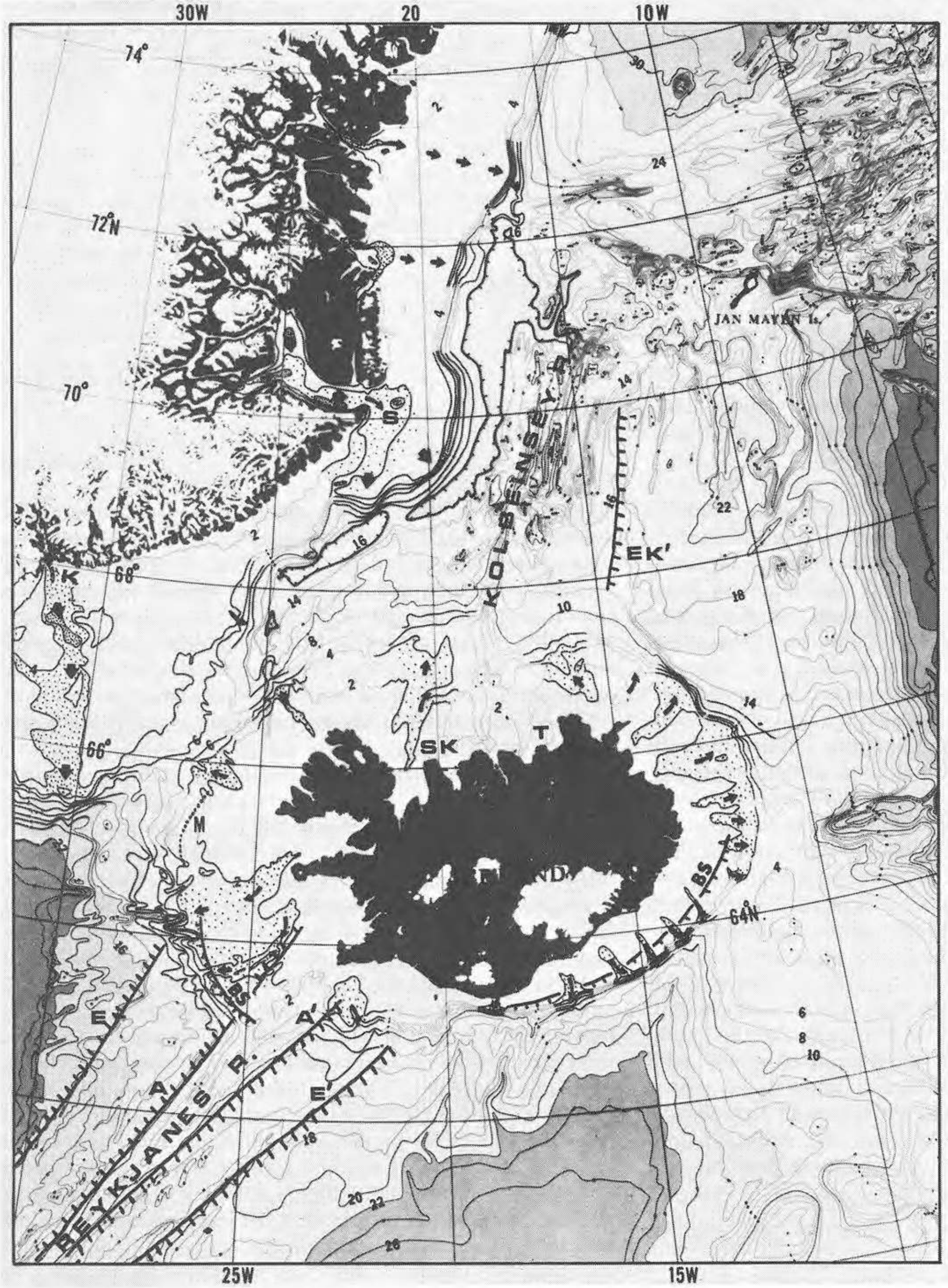

Fig. 1. Bathymetric chart (hundreds of meters) of Iceland area (adapted from Perry et al., 1977). *Stippled areas* show glacially incised troughs and associated shelf-edge deltas (Vogt and Perry, 1978). *Arrows* indicate direction of ice stream movement. Diachronous basement ridges/escarpments (*A, A', E, E'*) from Vogt (1971, 1974) and this paper (*EK'*). *M* is terminal moraine (Olafsdóttir, 1975). '*B.S.*' denotes basement step (southeast Iceland; Kristjansson, 1976a) or paleo-shelf edge (southwest Iceland, Egloff and Johnson, 1979). *SK*=Skagi; *T*=Tjörnes; *S*=Scoresby Sund; Kangerdlugssuaq

offset tend to be ephemeral features: They may form and disappear within a few million years or less. Whether the fractures formed by assymetrical spreading or by small jumps of the spreading axis is a question that awaits detailed analysis of these data (work in preparation) and will not be addressed here. The characteristic spacing between fractures is 30 to 50 km.

Most of the fractures formed subsequent to anomaly 4A time (7.7 Ma) and lie north of 68° N. Why did fractures begin to develop at that time, in an area where few or no such features had existed for the preceding 15 Ma? (In the next section (Figs. 3, 4) we argue that the Kolbeinsey axis actually dates from anomaly 6C time, or 24 Ma). Vogt and Johnson (1975) suggested that trans-

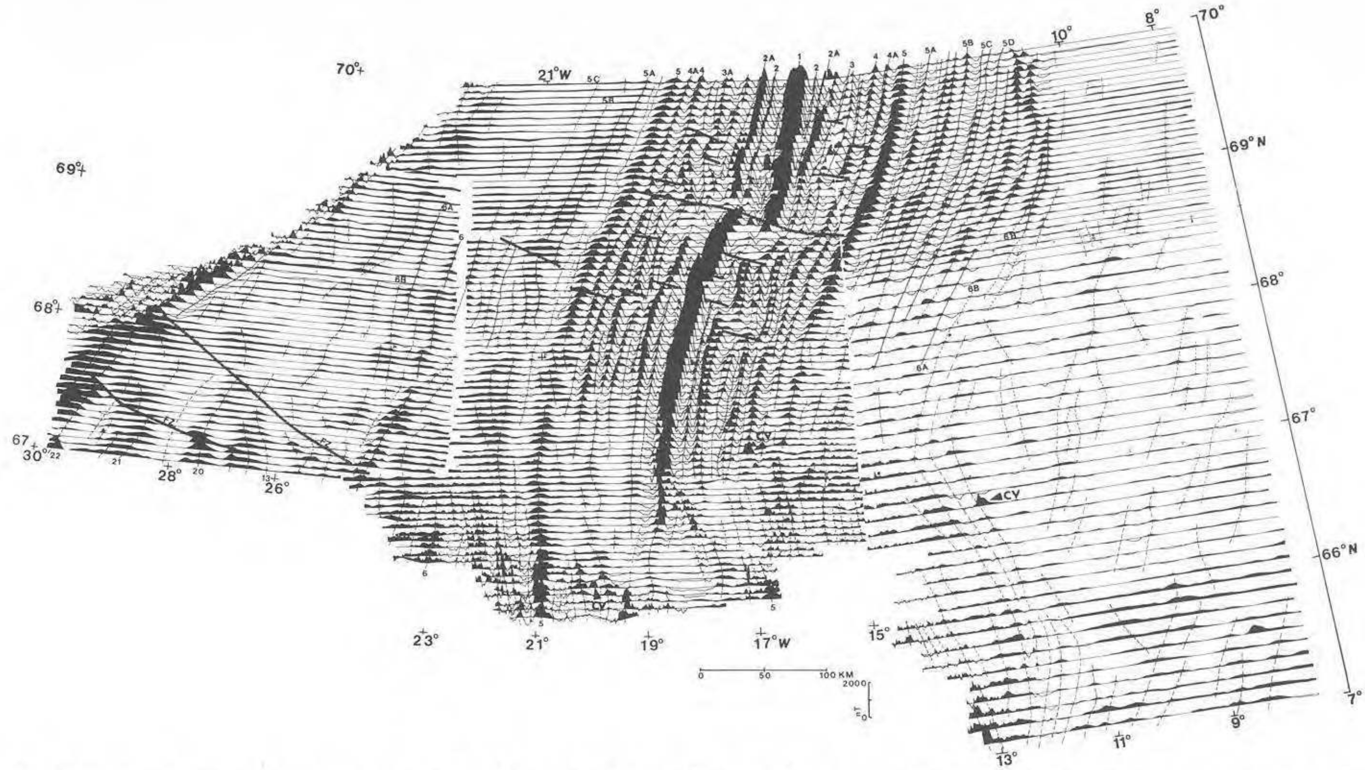

Fig. 2. Residual magnetic anomalies *(total field)* plotted along flight tracks. Anomaly identifications in small numbers; stippled bands, fracture zones (*F.Z.*); *thin solid lines*, convincing anomaly correlations; *dashed*, less certain

form faults disappeared along the Reykjanes Ridge around 20–30 Ma ago on account of increased asthenosphere flow from the Iceland plume. If their arguments are valid, the formation of fracture zones along Kolbeinsey Ridge north of 68° N after anomaly 4A time would mean a weakening of northward flow. Such an inference is independently suggested by morphologic features of Kolbeinsey Ridge, to be discussed in a later section.

The fracture zone of largest offset (30 km) is the Spar F.Z. at 69° N (Johnson et al., 1972; Meyer et al., 1972, Talwani and Eldholm, 1977). The offset terminations of the central anomaly appear to 'overshoot' the trace of relative plate motion, i.e., the theoretical transform trend ($\sim 105°$ *T*). Such *en echelon* spreading might account for the relatively smooth, confused magnetic signature in the vicinity of the Spar F.Z. (Fig. 2). Although the fracture zone came into existence by an eastward shift of the axis about 3 Ma ago (Meyer et al., 1972), anomaly bends or small offsets continue outward to Anomaly-5 (Fig. 2). Thus, a major transform fault may develop at a site 'preconditioned' in some way be the existence of earlier structural complexities.

South of the Spar F.Z., in the area 68.2° to 68.5° N, there exists a pattern of small offsets displaced progressively further northward with decreasing age (Fig. 2). The overall pattern of the fractures is that of an open *V* pointing northward. We think this might be a 'pseudo-transform' fault of the type proposed by Hey and Vogt (1977) on the basis of magnetic data in the area of the Galapagos hot spot.

In areas of unambiguous anomaly identification we measured separations between the same lineations on opposite flanks, in a 105° *T* direction of assumed plate separation. Figure 5 shows these distances plotted against time on the La Brecque et al. (1977) scale. A straight line (2 cm/a, or 1 cm/a half-rate) fits the data

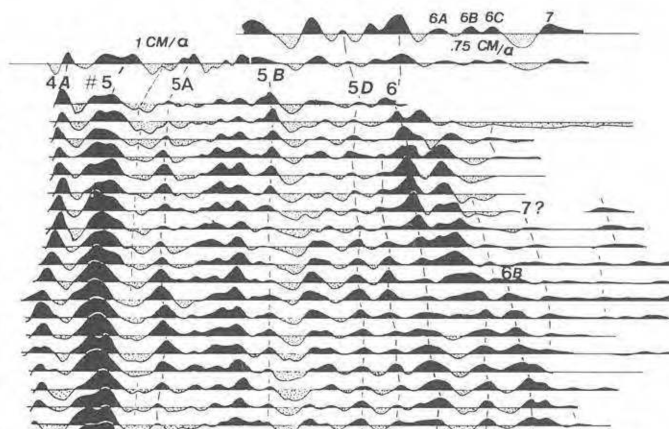

Fig. 3. Residual profiles east of Kolbeinsey Ridge, stacked on anomalies 4A and 5 at left. Models computed at 1 cm/a (after 5B) and 0.75 cm/a (5B to 7). Layer thickness: 0.5 km; magnetization, ± 0.0037 emu/cm^3 *(lower)* and ± 0.0075 emu/cm^3 *(top)*. Transition width: 2 km

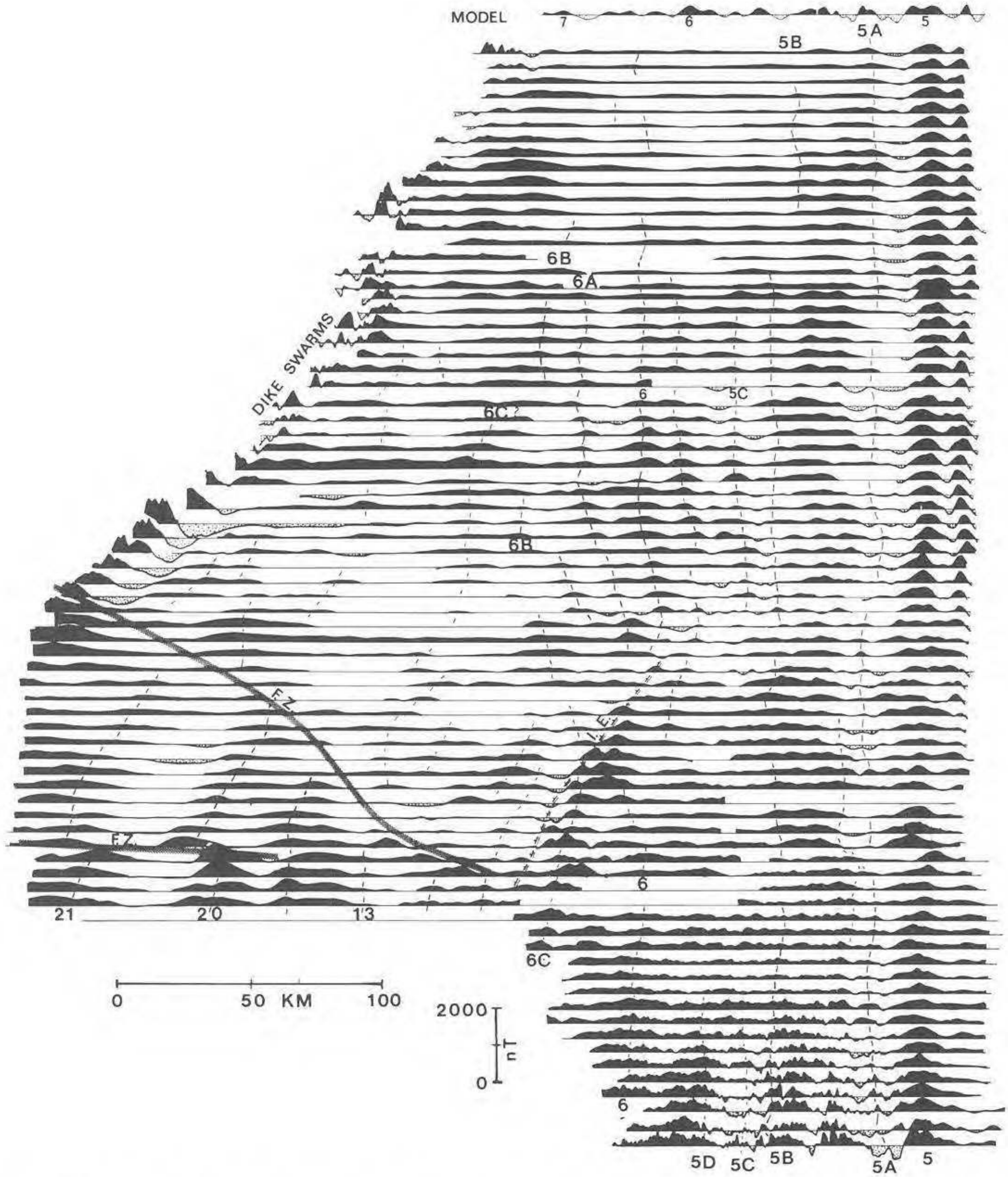

Fig. 4. Residual profiles and selected anomaly identifications west of Kolbeinsey Ridge, stacked on anomalies 4A and 5 (at right). North-northeast trending magnetic lineations labeled '*I.E.*' (Iceland Escarpment; see Hinz and Schlüter 1978) are probably of structural origin. High-frequency anomalies in the south and along Greenland margin (Larsen, 1978) probably reflect aggregations of dikes and perhaps (near Iceland) narrow fissure eruptions. Model profile is reverse of Fig. 3 model. '*F.Z.*' denotes fracture zones inferred from magnetic data only

out to anomaly 5A or 5B. (We discuss pre-anomaly 5 spreading in the next section.) There is a suggestion of slightly faster spreading from 3.2 to 5.2 Ma and slightly slower spreading 1.7 to 3.2 Ma (Fig. 5).

Effective spreading half-rates have been locally much more variable on account of small axis jumps and possibly asymmetric spreading. The 'average' rate since anomaly 5 time is only 0.65 cm/a on the east flank just north of the Spar F.Z., and 1.35 cm/a on the west flank. These values include the effects of axis jumps. At 70° N there has also been more crust added on the Greenland flank of Kolbeinsey Ridge. (Johnson et al., 1972, had suggested a higher *eastward* rate between 69° and 71° N. This conclusion was subsequently challenged on statistical grounds by Pálmason, 1973). Between 67.5° and 69° N it is the eastern flank that has acquired more crust. Between 67.5° N and Iceland the central anomaly lies roughly midway between the two anomaly 5's, although the latter anomaly is locally hard to identify on the east flank (Fig. 2). South of 67.3° N the central anomaly becomes progressively more subdued; the plate boundary is complex in this 'Tjörnes Fracture Zone' region, apparently composed of three *en echelon* rift zones which have developed in geologically recent time (McMaster et al., 1977).

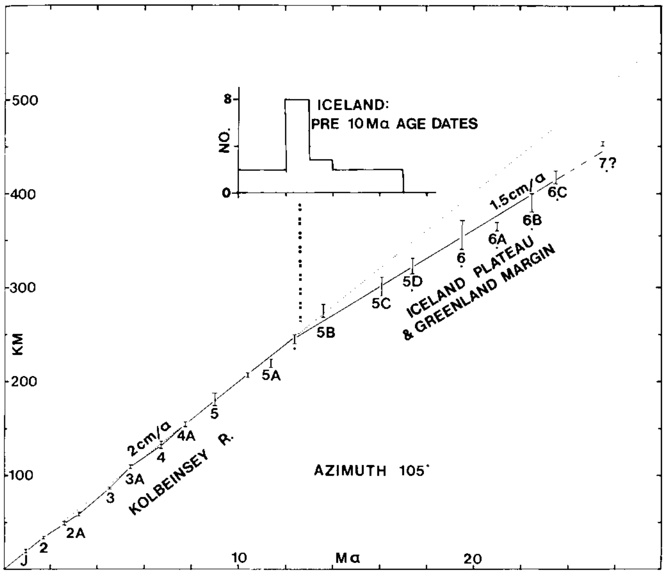

Fig. 5. Distances between corresponding lineations west and east of present spreading axis, plotted against age on the La Brecque et al. (1977) time scale. *Bars* show range of values. Anomalies with dots below them are based only on east-flank measurements, multiplied by two to give estimated total opening rate. *Dotted line* (2 cm/a fits data out to about 12–14 Ma age. Histogram of pre-10 Ma radiometric ages on Iceland (from Pálmason and Saemundsson, 1974) suggests first formation of present day Iceland somehow relates to plate acceleration (from 1.5 to 2.0 cm/a total opening rate) about 12–14 Ma ago. This assumes that coastal erosion has not exceeded a few tens of kilometers except in fjords

Sea-Floor Spreading From the Kolbeinsey Ridge Axis Prior to Anomaly-5: Intermediate Iceland Plateau Axis Does Not Exist

As first postulated by Johnson and Heezen (1967) and later elaborated by other authors (e.g. Vogt et al., 1970a; Talwani and Eldholm, 1977; Grønlie et al., 1979), sea-floor spreading between Iceland and the Jan Mayen F.Z. has not been restricted to a single axis – as it has for example along the Reykjanes and Mohns ridges. A prominent extinct axis (Aegir Ridge) lies in the Norway Basin. The plate boundary jumped westward from Aegir Ridge to the Greenland margin, splitting off a complex segment of continental crust which includes the Jan Mayen Ridge (Gairaud et al., 1978). According to Talwani and Eldholm (1977) the jump occurred at anomaly 7 time, at 25.5 Ma on the La Brecque et al. (1977) time scale.

Vogt et al. (1970a) first noticed that Kolbeinsey Ridge lies closer to the Greenland shelf break than to the postulated Jan Mayen Ridge 'microcontinent'. They postulated an additional region of spreading on the Iceland Plateau. The idea of such an Iceland Plateau Extinct Axis was pursued by Johnson et al. (1972) who tentatively identified a prominent negative anomaly, 50 km east-southeast of anomaly-5, as the axis of symmetry. Talwani and Eldholm (1977) and Grønlie et al. (1979) identified a positive anomaly about 85 km south-southeast of anomaly-5 as the axis of symmetry, which they proposed is anomaly 5D. The Intermediate Iceland Plateau Axis was proposed to have been active from 22.7 Ma to 17.3 Ma (anomaly 5D), whereas spreading on Kolbeinsey Ridge began just prior to anomaly-5. Talwani and Eldholm attribute the unaccounted for gaps in their model (25.5 to 22.7 and 17.3 to 10 Ma) to 'phenomena such as stretching of the crust prior to opening of each shifted center of spreading.' (The dates given here are those given by Grønlie et al., 1979, and are based on the reversal chronology of La Brecque et al., 1977).

According to our interpretation of the detailed Project MAGNET data (Figs. 2–4) all these previous speculations about an extinct intermediate spreading axis on the Iceland Plateau (from Vogt et al., 1970a to Grønlie et al., 1979) are wrong. We find that the Kolbeinsey Ridge lineation pattern simply continues eastward past anomaly-5. Anomalies 5A through 5D, 6, 6A, 6B, and 6C can be readily identified, at least from 68° N to 69.5° N (Fig. 3). This accounts for the gaps in the Talwani-Eldholm model, but is still consistent with a westward jump after anomaly-7 time as they have postulated. The non-existence of a spreading axis also explains the absence of a bathymetric or gravity signature over the supposed extinct axis (Grønlie et al., 1979). The main difference between the early and late (post-anomaly 5A-5B) spreading on Kolbeinsey Ridge is the relatively slower early half-rate (0.75 cm/a). The supposed symmetry axis of Talwani and Eldholm (1977) is actually anomaly 5E. Anomaly 'R' of Grønlie et al. (1979) is actually 5A. Anomaly 6B-6C is associated with an east-dipping basement and bathymetric escarpment (Fig. 6, see also Belousov and Udintsev 1977). We suggest this is the line of initial spreading from Kolbeinsey Ridge. Earlier spreading axes, if any, must lie between the 6D-6C step and the Jan Mayen Ridge.

Anomaly amplitudes are very low east of 6B-6C and a further eastward continuation of the sequence (e.g. to Anomaly-7) is conjectural (Figs. 2 and 3). However, what lineations there are tend to parallel those to the west and may represent some of the spreading between anomaly-20 and-7 time required to account for the fan-shaped lineation pattern in the Norway Basin (Talwani and Eldholm, 1977). In other words, a hypothetical extinct center east of the 6B-6C escarpment may have been active at the same time as Aegir Ridge after Anomaly-20 time. In order to explain the fan-shaped anomaly pattern in the Norway Basin, a complementary spreading axis on the eastern Iceland Plateau would also have had to produce a fan-shaped anomaly pattern, but with a northward convergence. No such pattern is apparent in the data (Fig. 2).

Many authors have overlooked the fact that even young, shallow oceanic crust may be associated with a magnetic smooth zone. Note that the southern Kolbeinsey Ridge has been generating such a smooth zone (Fig. 2). We analyze this problem in a later section. Whatever process or processes are responsible, they may also have operated east of anomaly 6C, and the lack of pronounced anomalies in that region (Fig. 2) is a very weak argument for the existence of continental crust. (Seismic reflection and refraction data are more convincing; Talwani and Eldholm, 1977).

The existence of anomalies 5A to 6C east of Kolbeinsey Ridge (Figs. 2 and 3) requires a similar set of lineations to the west. Indeed, we believe these anomalies do exist between Kolbeinsey Ridge and Greenland (Fig. 4). The anomalies are however reduced in amplitude relative to their eastern counterparts. This relative reduction begins on lineations as young as 4A and 5. We attribute the suppressed amplitudes of these lineations to (1) deep subsidence, caused by 1 to perhaps over 3 km terrestrial sediment (Grønlie and Talwani, 1978; Hinz and Schlüter, 1978) derived from Greenland and (2) erasure of primary magnetization caused by crustal heating made possible by relatively high heat flow and thick insulating sediments (Vogt et al., 1970b). The amplitudes

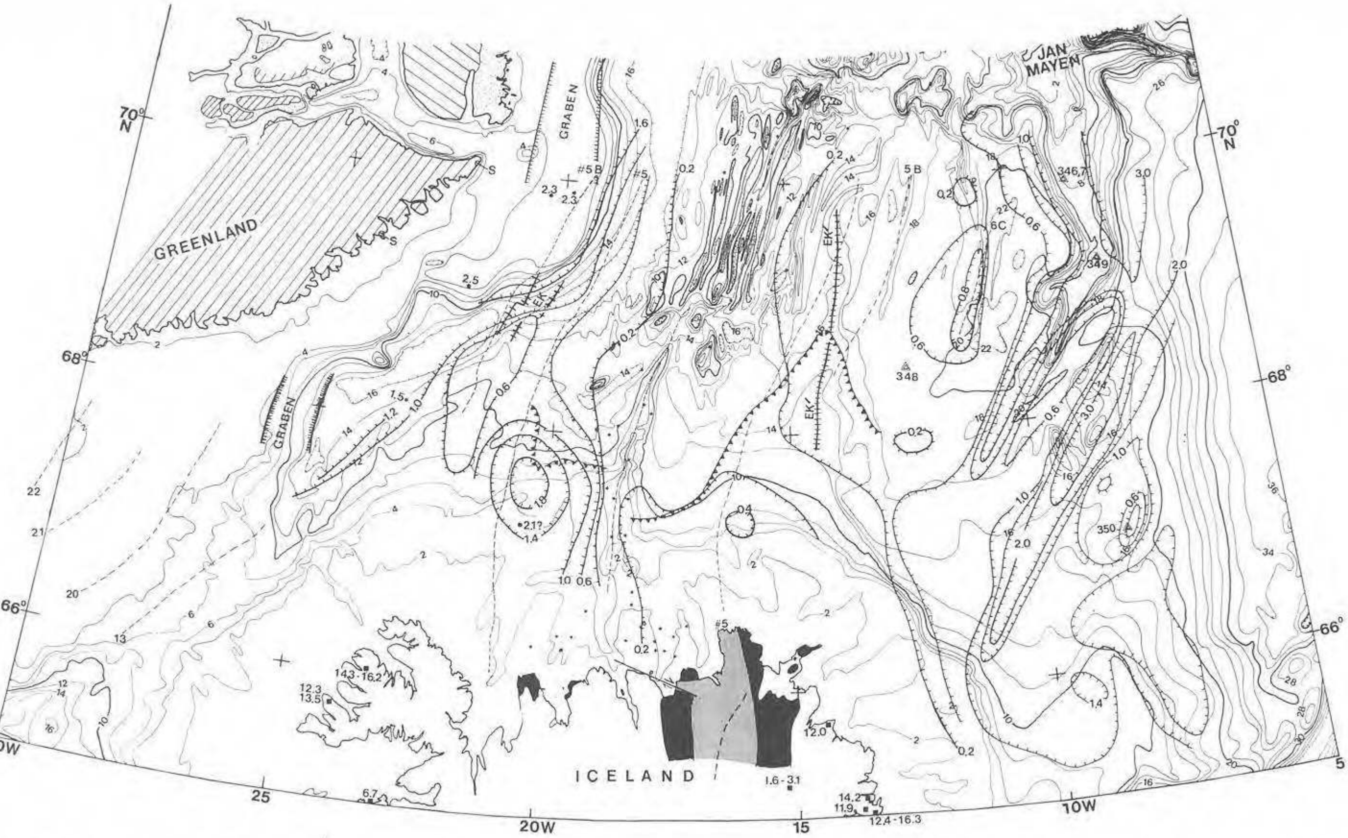

Fig. 6. Base chart: bathymetry in meters (Perry et al., 1977) with areas shallower than 1,000 m stippled on Kolbeinsey and Jan Mayen ridges. Small stars indicate earthquake epicenters. *Heavy contours* show sediment thickness in seconds of two way reflection time (Grønlie and Talwani, 1978). Spot values of sediment thickness based on sonobuoy stations (Grønlie and Talwani, 1978). *Double triangles*, DSDP drill sites on Leg 38 (Talwani et al., 1976). *Thin dashed lines*, principal magnetic lineations (from Fig. 2). Two grabens and homocline (*EK'*) under Greenland margin from Hinz and Schlüter (1978). *EK'*, time-transgressive bathymetric and basement lineament on Iceland Plateau (see also Fig. 7). *Heavy toothed line*, line of greatest southward decrease in anomaly amplitude. *Iceland* (after Pálmason, 1974): *Vertical ruling:* younger than 0.7 Ma; *solid:* 0.7 to 3 Ma; *squares*, older radiometric age determinations. *Greenland* (Anonymous, 1970): NE-SW hatched area, Tertiary igneous province with local Cretaceous to Lower Tertiary sediment outcrops (*S*); NW-SE hatching, Jurassic platform sediments; stippled, Pre-Cambrian

are most attenuated – even completely erased – under the thick sediments seaward of the mouth of Scoresby Sund. The conspicuous arcuate salient of the Greenland margin (Fig. 1) in this area is best explained as a deltaic sediment accumulation dating largely from the Plio-Pleistocene glacial ages (Vogt and Perry, 1978). We believe it is incorrect – particularly along glaciated shelves seaward of fjords or straths – to use the 500-fm bathymetric contour at the base of the continental slope to estimate the line of initial rifting, as Talwani and Eldholm (1977) have done. Instead, the ocean-continent crustal boundary must lie well landward of the shelf-break, perhaps even close to the Greenland coast between 69° and 70° N. In fact, our magnetic anomaly identifications *east* of Kolbeinsey Ridge *require* oceanic crust to continue under the Scoresby Sund salient. Neither the sonobuoy stations (Fig. 6; Grønlie and Talwani, 1978) nor the multi-channel profiles (Hinz and Schlüter, 1978) preclude such an interpretation. Furthermore, Hinz and Schlüter independently concluded that the thick sediment accumulations in the Scoresby Sund area post-date the (25 Ma?) separation of Jan Mayen Ridge from Greenland. This is in keeping with the proposal of Vogt and Perry (1978) that the arcuate shelf outbuilding occurred primarily during the Plio-Pleistocene glacial ages.

Oceanic Crust Older Than Anomaly 6C

We consider now the possibility of ocean crust predating anomaly 6C. In the Jan Mayen Ridge area the anomalies east of 6C are generally low in amplitude and tend to be lineated in a NE to NNE direction. Since similar low-amplitude areas of oceanic crust are found where Kolbeinsey Ridge enters Iceland and along the Greenland margin, we cannot adduce magnetic data as necessarily indicating continental crust in the Jan Mayen Ridge area. We suppose most of the area between anomaly 6C and 7.5° W (Fig. 2) is underlain by oceanic crust of anomaly 13 to 7 age. Continental fragments (Talwani and Eldholm, 1977) cannot be excluded, however.

What about anomaly-7 or older ocean crust along the Greenland margin? There is little or no room for such older crust in the Scoresby Sund area. Southwestwards towards the Denmark Straits there is progressively more room. The graben structure discovered by Hinz and Schlüter (1978) under the Greenland margin about 68° N may contain oceanic crust of anomaly 7 to 22 age even though the graben is associated with a magnetic smooth zone (Figs. 2 and 6).

Further south, we believe to have identified the sequence 13 to 22 in the Denmark Straits area (Figs. 4 and 6). These early to mid-Tertiary lineations appear to end at a major fracture zone, perhaps equivalent to the right lateral offset of the Faeroes block from the Faeroes-Shetland Escarpment (Talwani and Eldholm, 1977). Alternatively, this fracture formed when the spreading axis jumped westward from Aegir Ridge. Our identification of anomalies 13 to 22 in the Greenland-Iceland gap is contrary to the conclusions of Talwani and Eldholm (1977) who postulate spreading from an extinct Iceland-Faeroe Ridge axis until anomaly 13 time. Our interpretation does not conflict with Voppel ct al. (1979), who suggest abandonment of an Iceland-Faeroe Ridge center at anomaly 22 time. However, we cannot rule out the existence of anomaly 22 to 24 age crust under the wide Greenland shelf between 66° and 68° N. In fact, Larsen (1978) suggests that crustal extension during anomaly 24 time occurred solely by dike injection along the present Greenland coast from 63.5° N to 70° N. If this is true, we do not need to look for this lineation at sea.

The existence of anomaly 13 to 22 age crust – and possibly older – in the Denmark Straits means that the northwestern and southeastern edges of the Iceland Platform do not necessarily mark jumps in the spreading axis as postulated by Talwani and Eldholm (1977). We prefer to interpret these basement steps as reflecting abrupt increases in mantle-plume discharge and basalt magmatism (Vogt, 1974). The first such increase occurred ca. 25 Ma ago and the second – marked by Iceland's oldest rocks – about 13–17 Ma ago. The 25 Ma increase may also be marked by the initiation of volcanism at what is now the eastern and western extremities of the Iceland insular basement margin. The age of the second increase correlates with the oldest rocks of eastern and western Iceland, but this may also be a fortuitous effect of coastal erosion removing older rocks (e.g., Nilsen, 1978), and furthermore may be meaningless if the rocks at depth below eastern and western Iceland are more than 1 or 2 Ma older than the oldest surface exposures. The existence of old anomalies west of Iceland may remove the need to postulate oceanic crust under the Faeroe Islands. Finally, the identification of anomalies 20–22 and perhaps older in areas of present Greenland shelf implies the existence of oceanic crust at depth. This important conclusion should be testable by seismic refraction methods. Again, the area in question lies seaward of the Kangerdlugsuaq fjord system and probably experienced rapid outbuilding as a result of ice streams delivering continental detritus in great quantity to the edge of the continental shelf (Vogt and Perry, 1978).

Diachronous ('V-shaped') Structures North of Iceland: Implications for the Iceland Mantle Plume Hypothesis

Using the seismic reflection profiles published by Talwani et al. (1971), Vogt (1971) discovered 'V-shaped' (diachronous or time-transgressive) basement ridges and escarpments on the Reykjanes Ridge southwest of Iceland (Fig. 1). From the angle between these structures and the crustal isochrons – , i.e., magnetic lineations – Vogt calculated a southwestward propagation rate of the order of 10 to 20 cm/a. He proposed further that the V-shaped basement structures are generated at the spreading axis by wave-like magmatic irregularities traveling southwest in a conduit of low viscosity below the Reykjanes Ridge (Vogt, 1974; 1976; Vogt and Johnson, 1975). The source of this flow and of the irregularities entrained in it was proposed to be a plume of upwelling mantle (Morgan, 1972) located under south-eastern to central Iceland. The two most prominent V-shaped features on the Reykjanes Ridge are the A-A′ and E-E′ escarpments, proposed to reflect abrupt increases in discharge from the Iceland plume (Fig. 1). These escarpments dip towards older crust; upon approaching Iceland they increase in steepness and relief, tending toward asymmetrical ridges in cross-section. Extrapolation suggested the 'A' and 'E' events would have first influenced Iceland itself around 6–7 Ma and 13–17 Ma respectively. Watkins and Walker (1977) discovered a short-lived 7.3 Ma to 6.4 Ma pulse of increased lava production in eastern Iceland. They suggested this might be a manifestation of the 'A' event on Iceland. However, the increase in lava production may well be a local phenomenon or an artifact of miscorrelation; recent work by Harrison et al. (1979) does not confirm the 7 Ma ago event. Both Watkins and Walker (1977) and Vogt (1974) pointed out that the 17-13 Ma age corresponds to the oldest rocks on Iceland (Fig. 3) and may therefore represent the plume 'event' leading to construction of present-day Iceland. This correlation may be a fortuitous result of coastal erosion, as mentioned previously.

If the mantle-plume interpretation of Reykjanes Ridge basement structures (Vogt. 1971; 1974) has any merit, features similar to the AA′ and EE′ escarpments should exist on the Kolbeinsey Ridge north of Iceland. The 'V'-s should point northward, moreover, in the direction plume materials would be expected to travel under the Kolbeinsey Ridge, i.e., away from Iceland.

Comparing our magnetic isochrons (Fig. 2) with the bathymetric profiles of Meyer et al. (1972), we see both isochronous and 'V'-shaped trends north of Iceland (Fig. 7). The 'V'-shaped structures 'point' northward as predicted by the mantle plume hypothesis (Vogt, 1971, 1974). If interpreted as a measure of northward flow from the Iceland plume, the diachronous bathymetric trends younger than anomaly-5 would imply mantle flow of the order 1 to 5 cm/a, distinctly less than the southwestward flow under the Reykjanes Ridge (Vogt, 1971, 1974). The slower northward flow might reflect (1) competition with a separate Jan Mayen plume, (2) damming at fracture zones such as the Tjörnes or Spar (Vogt and Johnson, 1975), (3) northward motion of the plates over the Iceland plume (Minster et al., 1974) or (4) the northward decrease in spreading rate, hence pipe cross-section (Vogt, 1976). On the other hand, the tectonic complexities of the present plate boundary in the Tjörnes fracture zone area (McMaster et al., 1977) and the repeated formation and disappearance of transform faults on the Kolbeinsey Ridge (Fig. 2) by mechanisms not yet understood could have produced some of the trends in Fig. 7. Although we are not wholly convinced that the diachronous structures north of Iceland do reflect northward flow, the plume model (Morgan, 1972; Vogt, 1971) does explain their existence, at least qualitatively.

Furthermore, the 'E' escarpments, which previously were not thought to exist on Kolbeinsey Ridge (Vogt, 1974), do show up clearly on the east flank (EK′ in Fig. 7). The EK′ structure cuts lineations between 5A and 5B between 68° N and 69° N and on the bathymetric chart (Figs. 1 and 6) can be followed southward as a broad, low ridge which merges with Iceland's northeastern insular margin. The crest of the EK′ ridge has an age of 12.8 Ma at 69° N. Between 68° N and 69° N the implied propagation rate, along the crustal isochrons, is about 10 cm/a, of the same order as on the Reykjanes Ridge (Vogt, 1971, 1974). Crust of corresponding age west of Kolbeinsey Ridge is buried by 600 to 2,000 m sediment (Fig. 6); thus, no western equivalent to EK′ would be expected on bathymetric profiles. However, the reflection profiles of Hinz and Schlüter (1978) reveal a west-dipping basement escarpment ('homocline') 25 to 45 km WNW of anomaly 5 at 69.4° N and 40–50 km WNW at 68.8° N. We propose that this homocline is in fact EK, the western equivalent to the EK′ structure on

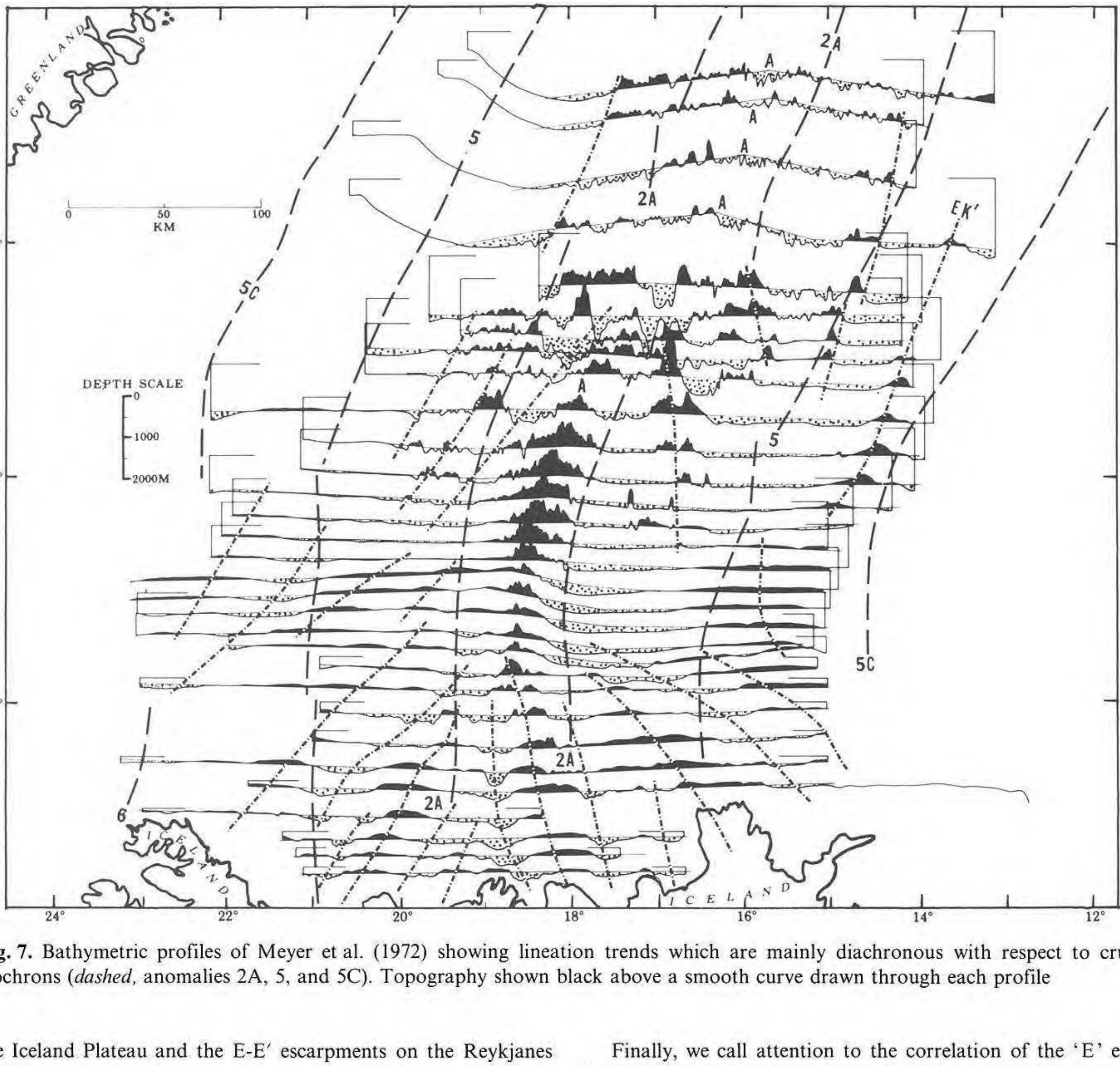

Fig. 7. Bathymetric profiles of Meyer et al. (1972) showing lineation trends which are mainly diachronous with respect to crustal isochrons (*dashed*, anomalies 2A, 5, and 5C). Topography shown black above a smooth curve drawn through each profile

the Iceland Plateau and the E-E′ escarpments on the Reykjanes Ridge.

We concluded earlier (Fig. 5) that spreading half-rates increased rather abruptly from 0.75 to 1.0 cm/a about 12.5 Ma ago (limits: 11 to 14 Ma). Although it has long been known that average spreading rates were lower during the interval anomaly 6 to 5 than subsequently (e.g., Vogt and Avery, 1974; Talwani and Eldholm, 1977), the time of the acceleration is here for the first time shown to be 12.5 ± 1 Ma ago, which is within dating uncertainties identical to the age range of the 'E-EK' event on the Kolbeinsey and Reykjanes ridges. Although this implied correlation of a 'plume'-generated feature with acceleration in plate motion does not prove plumes contribute to driving the plates, such an inference certainly becomes more attractive, particularly since the earliest appearance of the E-EK basement escarpments along the Kolbeinsey and Reykjanes Ridges nearest to Iceland actually occurred around 13–17 Ma ago, slightly prior to the plate acceleration. In other words, we suppose that an increase in plume discharge took a few million years to affect a volume of lithosphere/asthenosphere large enough to alter the parameters of plate motion.

Finally, we call attention to the correlation of the 'E' event in the Iceland area with the Gardner Pinnacles episode of increased basalt discharge by the Hawaii plume. Both events are part of an apparently global middle Miocene magmatic episode (Vogt, 1978).

Dike Swarms and Central Volcanoes

The magnetic field at 500 ft (166 m) altitude near the coasts of Greenland and Iceland is rich in short wavelength anomalies (1 to 5 km), typically 100 to several hundred *nT* in amplitude (Fig. 2). The short wavelength areas reflect shallow magnetic sources, according to a statistical treatment by Kristjansson (1976c) of shipborne measurements west of Iceland, but we have not completed depth to source processing of the present results.

On the Greenland margin, the observed magnetic anomalies probably reflect dikes or swarms of dikes as suggested by Vogt (1970) and Larsen (1977); this may aid offshore mapping of the East Greenland early Tertiary igneous province (see Noe-Nygaard, 1976; Deer, 1976). In low-level surveys over Iceland and the shelf, the major sources of magnetic anomalies so far recognized include thick series of lava flows of alternating polarity (see Piper, 1973), central volcanoes (see Kristjansson, 1976b and c) and arcuate structural anomalies associated with the edges of the Iceland platform (Figs. 1 and 2). None of the numerous elongated dike swarms in Iceland has to date been observed to coincide with elongated magnetic anomalies where data are available. This observation makes it doubtful whether the short-wavelength linear anomalies north of Iceland (Fig. 2) represent dike swarms.

Recent developments at the Krafla active central volcano in NE-Iceland (Björnsson et al., 1977; 1979) are of considerable interest in understanding the processes of spreading and anomaly generation. It appears that over intervals of hundreds of thousands of years, rifting on any 100-km ridge segment is accompanied by repeated subhorizontal injection of magma into a fissure system from shallow magma chambers below a central volcano. Material in the volcano, situated at the center of that fissure system, is periodically replenished from below until the volcano is disconnected from its mantle source and transported out of the active zone, even as new centers appear nearby. Similar processes, perhaps on a different scale, may well characterize the mid-oceanic ridge system in general; changes in the relative width and amplitude of small linear magnetic anomalies over the ocean floor (Figs. 2 and 3) would then reflect changes in the activity of individual intrusive centers or groups of these.

In this context it is noteworthy that magnetic anomalies over central volcanoes in SW- and W-Iceland (Sigurgeirsson, 1970; 1979) as well as on the shelf (Kristjansson, 1976c) are generally equidimensional and coincident with caldera structures and hypabyssal intrusions. Central-volcano anomalies are numerous on the shelf east and west of Iceland (Kristjansson et al., 1977) but rare or non-existent south of Iceland. They are also uncommon north of Iceland; only a few such features could be identified in our data ('cv' in Fig. 2). The areal density and degree of development of such volcanoes on any part of the ridge is likely to be strongly related to distance from the center of the mantle plume, through variables such as magma production and chemistry, melt percentage, heat flow, crustal and lithosphere thickness, or other effects. It does not appear that the trace of the Iceland mantle plume, as inferred by Kristjansson (1976b), passes anywhere through the region covered by the present survey.

Erosion and Sedimentation

Iceland represents a large area of anomalous ocean crust up to 16 Ma in age, exposed to erosion by water, and in the last 3 Ma also to ice. During glacial periods lowered eustatic sea level and grounded ice sheets probably exposed the entire Iceland platform above present 200–300 m depth to erosion. Although a mean denudation of 400 m has been estimated for Iceland itself (Einarson, 1963) the erosion was highly selective, concentrated wherever ice streams drained the insular ice shield. Much more spectacular ice streams carved out the east Greenland fjord topography, carrying large quantities of coarse sediment to the depocenters along shelf edges (Sommerhoff, 1973; Vogt and Perry, 1978).

In this section we consider the connection between the magnetic anomaly data (Fig. 2) and present morphology in terms of erosion and deposition.

Much of the present Iceland platform near the coast consists of an outcropping or thinly sedimented basaltic erosion surface (Johnson and Pálmason, 1980). Sediment was evidently carried across this region by the ice, but how far did the ice extend?

West of Iceland, a 20–30 m high, 100 km long moraine ('M' in Fig. 1) lies at present depths of 200–250 m (Olafsdóttir, 1975), near the shelf break. The moraine may represent the maximum advance of the Weichselian (Wisconsin) ice-sheet in this area and suggests the Iceland ice cap extended outward to a calving ice shelf located near the shelf edge. In Greenland (Weidick, 1976) as in most other areas, the Weichsel ice did not advance as far

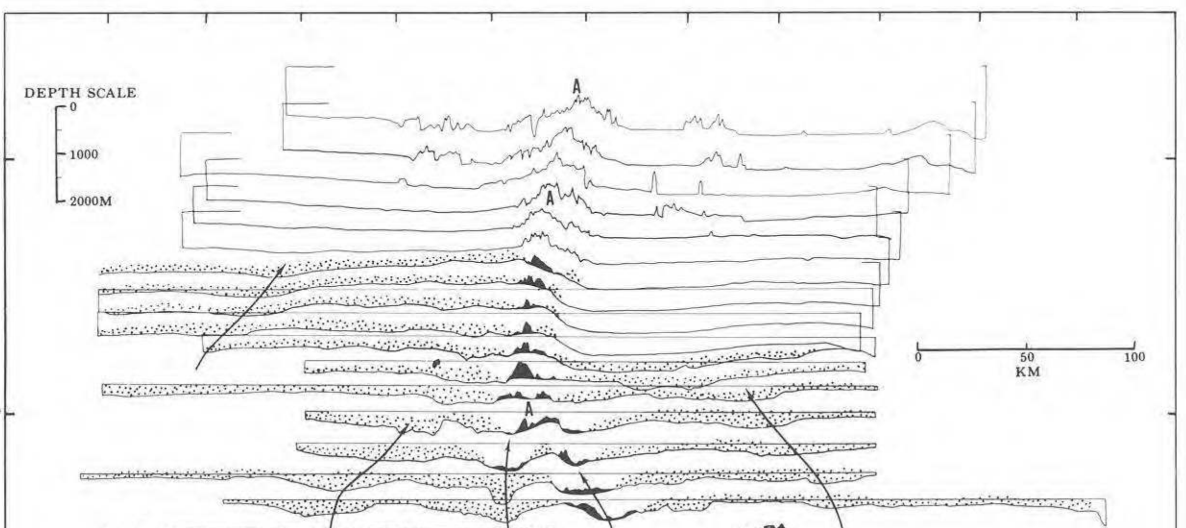

Fig. 8. Bathymetric profiles of Meyer et al. (1972) showing suggested outcropping basement *(black)*, submerged wave-eroded volcanic edifices (*G*), and suggested maximum extent of grounded Pleistocene ice streams *(stippled pattern over sea-floor)*. *Arrows* show direction of ice stream flow and submarine sediment transport along valley floors. (*A*) denotes axis of Kolbeinsey Ridge

as during earlier glaciations. Thus, the moraine reported by Olafsdóttir (1975) represents a minimum position for the seaward limit of grounded ice.

The Iceland platform is indented by numerous shallow U-shaped valleys, many of which appear to be submarine extensions of fjords and other embayments of the Iceland coastline (Perry et al., 1977; Fig. 1). It is most reasonable to explain these submarine valleys as the work of glacial erosion by grounded ice streams flowing radially outward from an ice dome culminating in central Iceland. The bathymetric chart shows recognizable arcuate salients of the shelf edge located at the mouths of the submarine valleys (Fig. 1). These salients most likely represent ice-front deltas composed of debris transported to the shelf edge by grounded ice streams. In most cases the 400 m isobath is deflected seaward where the 200 m isobath shows an embayment. This suggests the ice streams were grounded to depths between 200 and 400 m.

On the southwest and northeast Iceland shelf, even the 400 m isobath is indented landward, suggesting ice streams possibly were grounded below 400 m there. However, both areas are near the active spreading axis, and tectonic effects cannot be discounted. The bathymetry alone suggests extra shelf-building of the order 1 to 10 km seaward of the valleys (Vogt and Perry, 1978). These are minimum values for total shelf progradation, since sediment was also deposited along platform margins between the glacial valleys. Kristjansson (1976b) has used magnetic anomaly source depths to identify a buried basement step under the outer shelf off southeastern Iceland. The present shelf break has prograded by amounts ranging from 5 km (at 19° W) to 15 km (at 14° W) seaward from the step. The shelf itself is narrow, and prominent submarine canyons incise the insular slope (Johnson and Pálmason, 1980). The prograded sediment wedge is estimated to be about 2 km thick (Kristjansson, 1976b). Single-channel reflection profiles show at least 1 km sediment (Johnson and Pálmason, 1980). Based on seismic reflection profiles, Egloff and Johnson (1979) conclude that the shelf edge has prograded 10 to 35 km off southwest Iceland.

In the area north of Iceland examined in the present study, seismic reflection data (Grønlie and Talwani, 1978) show sediment thicknesses of at least 0.5 km on the insular slope north of Tjörnes peninsula, over 1 km east of northern Iceland, and an extensive lens at least 1.8 km thick lies west of the southern Kolbeinsey Ridge, north of the Skagi peninsula (Fig. 6). Clearly, greater sedimentation in the west explains why the 400 to 1,000 m isobaths extend farther northwards *west* of the present accretion axis, which has acted as an effective barrier to eastwest sediment transport. Based on these data (Fig. 6), we roughly estimate that the shelf break north of Iceland has prograded of the order of 50 km in the area north of Skagi, 10 km north of Tjörnes, and 0 to 30 km east of northern Iceland. Although we have not completed processing the magnetic data for depth to basement, the pattern of short-wavelength magnetic anomalies qualitatively confirms the conclusions from seismic profiling. Shallow magnetic sources extend outwards towards the shelf edge north of eastern and western Iceland (Fig. 2). Thus the northward projections of the Iceland platform in these two areas are basement arches, not the results of sedimentation. However, depressions in magnetic basement occur between the present spreading axis and the outer arches, and these depressions are occupied by sediments, at least near the shelf break. Possibly thick sediments continue southward towards the Iceland coast, but are seismically too reflective to be charted by single-channel techniques. The existence of low-density sediments is also suggested by *relatively* negative free-air gravity anomalies (Pálmason, 1974). Whereas the platform off the Skagi and Tjörnes peninsulas and the Kolbeinsey Ridge north of 66.5° exhibit anomalies of about +50 to +60 mgal, the region of possible sediment accumulation is typically +35 to +45 mgal. A more local free-air negative dips to below 0 mgal near the coast due south of the Kolbeinsey Ridge. This WNW trending anomaly parallels the Husavik faults and may be a deep, sediment-filled trough associated with the Tjörnes F.Z. (Saemundsson, 1974; Johnson, 1974).

Off the Greenland margin, locally extensive shelf prograding is directly implied by our magnetic anomaly identifications (Figs. 2–4 and 6). At 66°–67° N (Denmark Straits), the present shelf break at ~400 m lies well over 100 km southeast of anomalies 20–21 (Figs. 1, 2 and 6). We envision most of the prograding to have occurred in the last 3 Ma as a result of several coalescing ice streams emanating from the Kangerdlugssuaq Fjord complex. Another such 'ice-delta' forms a conspicuous arcuate salient seaward of Scoresby Sund. Prograding of as much of 100 km is suggested by the morphology and indeed required by our magnetic anomaly interpretations (Figs. 2–4). Sonobuoy stations (Grønlie and Talwani, 1978) and multi-channel profiling (Hinz and Schlüter, 1978) suggest sediment thicknesses of the order 2 to 4 km under these deltas. The data published by those authors are not inconsistent with our thesis that oceanic crust forms the basement in these two areas.

As noted by Vogt and Perry (1978), relatively rapid shelf prograding around Iceland (locally 20 km or more) and Greenland (locally 100 km or more) has been facilitated by (a) the young age and large positive depth anomalies, i.e., shallow crust, and (b) the efficient transport of coarse sediment to the shelf edges by ice streams.

Magnetic Smooth Zones Near Iceland

Magnetic smooth zones (or quiet zones) are oceanic areas characterized by magnetic anomalies of relatively low amplitude, generally less than ± 50 to $100\,nT$ (e.g. Vogt et al., 1970b; Poehls et al., 1973). Various processes could account for smooth zones, for example, high spreading rate compared to reversal frequency – resulting in broad strips of ocean crust magnetized with constant magnetic polarity. A magnetic smooth zone would then be generated provided that the lateral contrasts in induced and viscous magnetization are small. An accretion axis orthogonal to the equator also generates a magnetic smooth zone, for example the equatorial Mid-Atlantic and East-Pacific ridges. Inspection of Fig. 2 shows that a magnetic smooth zone is being generated where the Kolbeinsey Ridge approaches and crosses the Iceland platform (see also Figs. 4, 9, and 10; Meyer et al., 1972, Vogt and Johnson, 1973, 1974). The data published by Talwani et al. (1971) and Serson et al. (1968) reveal a similar effect where the Reykjanes Ridge enters Iceland (Fig. 10). Magnetic smooth zones are also found in the Jan Mayen Ridge area east of 6C and along the Greenland margin west of anomaly-5 and north of the Greenland-Iceland Ridge (Figs. 2 and 4). The processes responsible for these older smooth zones may resemble those at work at the Reykjanes Ridge-Iceland and Kolbeinsey Ridge-Iceland junctions.

What are those processes? Constant polarity and equatorial polarity can be immediately ruled out, but a number of possibilities remain to be examined. Relevant parameters and model profiles are shown in Figs. 9 and 10.

1. A large fraction of the magnetized layer has been removed by glacial, wave, or/and fluvial erosion. This process may have been significant on the shelf near Iceland, but would require the paleo-coastline to have lain 100 to 200 km north of northern Ice-

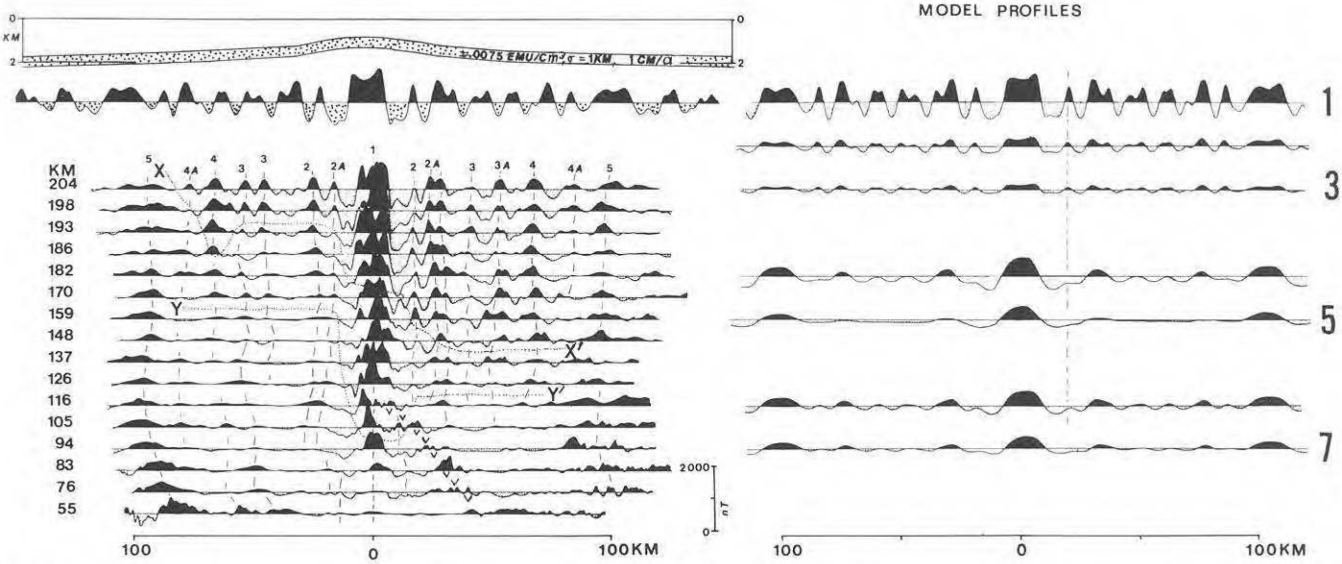

Fig. 9. *Left:* Profiles showing decrease of anomaly amplitude from Kolbeinsey Ridge southward to Iceland. Profiles indexed by distance (km) north of 66° N (Fig. 2). Dotted line XX' indicates amplitude reduction. South of YY' anomalies become smoother, more irregular, and still lower in amplitude. *Right:* Model profiles simulating three possible processes to explain amplitude decrease; magnetized layer is 0.5 km thick in all cases. Top profile (1) was starting point (depth D to top of layer: 1.24 km; magnetization M: ± 0.0075 emu/cm^3; transition width ($\sigma = 1$ km; Blakely, 1976). Profile 2 same, but $M = \pm 0.0025$ cgs; profile 3, same, but $M = \pm 0.0015$ cgs. Profiles 4 and 5 show effect of increasing σ to 3 km and 4 km (other parameters as in 1); profiles 6 and 7 show effect of increasing source depth to 3.84 and 4.84 km (other parameters as in 1)

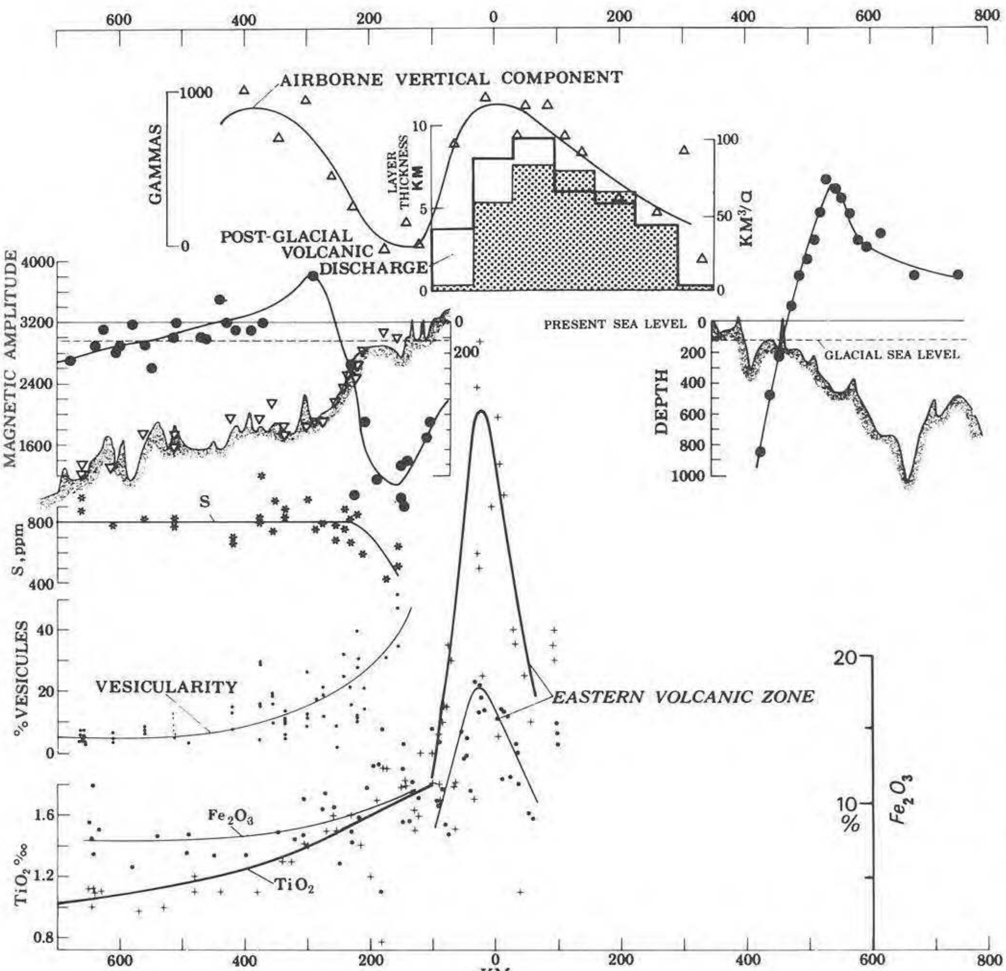

Fig. 10. Profiles of magnetic anomaly amplitude, volcanic discharge, water depth, sulfur concentrations, vesicularity, and Fe-Ti concentration along plate boundary from Reykjanes Ridge *(left)* through Iceland *(center)* to Kolbeinsey Ridge *(right)*. From Vogt and Johnson (1974), based on data from Talwani et al. (1971), Jakobsson (1972), Meyer et al. (1972), Serson et al. (1968), Schilling (1973), Moore and Schilling (1973), and Brooks and Jakobsson (1974)

land and subsided to depths of 1,500 to over 2,000 m. Furthermore, recent work suggests the magnetic layer is at least 1,000 m thick (Huestis and Parker, 1977); drilling in the FAMOUS area (Joint Oceanographic Institutions Deep Earth Sample, 1975) indicates only minor hydrothermal alteration and little effect on remanence at 582 m depth. In Iceland, Kristjansson and Watkins (1977) have suggested that some of the primary remanence in basalt lava flows will survive burial to 3 km (i.e., 200° C); the magnetic mineral in these flows will certainly survive 4 km burial (Pálmason et al., 1979).

2. The magnetization was acquired at shallow confining pressures, leading to degassing, high vesicularity, higher oxidation state, and therefore, perhaps reduced magnetization (Vogt and Johnson, 1974). As a related process the higher vesicularity would facilitate brecciation and subsequent low-temperature alteration, causing a loss of magnetization (Pálmason et al., 1979). In support of this process we note that the decline of magnetic amplitudes along the *present* spreading axis begins at about 400–600 m depth, where vesicularity begins its sharp increase and sulfur content (a measure of gas retention) its decrease (Moore and Schilling, 1973; Fig. 10). The line of magnetic amplitude change (Figs. 6 and 9) would then be a fossil $\sim$500 m isobath. Difficulties for this explanation are that the magnetic anomalies are not simply attentuated but also *smoothed* as Iceland is approached. This might be explained in terms of Blakely's (1976) two-layer model. The upper, pillow layer is less magnetized, leaving the lower layer with its more diffuse polarity boundaries (transition widths) to dominate the signal. A more serious problem is the strongly asymmetrical attenuation (Fig. 2; profiles km 126 to 193 in Fig. 9): How could the east and west flank basement be formed at two different depths?

3. Subsidence of the crust after it was formed would cause both attenuation and smoothing. However, the depths required, 3 to 5 km according to model profiles in lower right of Fig. 2, are unreasonably great. Reflection profiling suggests basement depths of 0 to 2 km (Fig. 6; Grønlie and Talwani, 1978). Gravity data hint at additional sediment in the Tjörnes F.Z. area, hidden by acoustically opaque materials on the platform (Saemundsson, 1974). More serious objections to the subsidence hypothesis is the large amount of it, greatly exceeding sinking of normal ocean crust of comparable age. Finally, subsidence does not account for the decline in central anomaly amplitude (Fig. 10) because the axis is not buried by sediments.

4. Since the extrusion zone is substantially wider on Iceland than along the normal mid-oceanic ridge, it would be reasonable to expect the magnetic transition width to increase as Iceland is approached. Increasing transition width from 2 to 3.5 km does result in a strongly attenuated, smoothed signature (model profiles in Fig. 9). However, it is hard to understand how dikes injected east of the axis are less spread than those on the west flank, as would be required to explain the unequal amplitudes. Furthermore, anomalies between XX′ and YY′ (Fig. 9) are simply attenuated, not smoothed.

5. Thick sediments rapidly deposited on very young crust (high heat flow) would insulate the magnetic layer and cause temperatures to rise, tending to destroy the magnetization. This mechanism is attractive because thick sediments occur predominately on the *west* flank of southern Kolbeinsey Ridge and correlate with the amplitude asymmetry (Fig. 9). Similarly the relatively low amplitudes of anomalies 4A to 6C on the Greenland margin (Figs. 2–4) correlate with thick sediment cover (Fig. 6). However, the mechanism fails to explain why even the axial anomaly declines dramatically toward Iceland. Furthermore, unless substantial thicknesses of sediments can be demonstrated on the Iceland shelf by seismic methods, low amplitudes in that region cannot be attributed to sedimentation.

6. The connection between the Iceland rift zones and Kolbeinsey Ridge may have consisted of complex, time-varying en echelon rift zones (McMaster et al., 1977). For example, the Quaternary volcanic zone crosses previous lineations on a northwest strike (Fig. 9). Such complexities would smooth and attenuate the lineations. However, such a process could not account for the simple amplitude reduction observed between YY′ and XX′ (Fig. 9).

At present, none of the six mechanisms by themselves explain all the observations. Nor can any of them be wholly discounted. We therefore infer that several processes are responsible: Near Iceland (south of YY′ in Fig. 9), 1, 2, 4, and 6 are likely to be most important. Farther north, 2 may be most important at the axis, and 5 for crust more than 1 Ma old.

Conclusions

In this paper we have presented new data which, if we have correctly interpreted them, call for some major revisions regarding the origin of the Iceland Plateau and the position of the continent-ocean crustal boundary.

Our most important conclusions was the 'disproof' of an extinct spreading axis on the Iceland Plateau. The magnetic anomalies previously attributed to the extinct axis actually form the *east* flank of Kolbeinsey Ridge. An important consequence is that the *west* flank anomalies, strongly attenuated in amplitude, and for this reason not previously recognized, occur over the Greenland margin. Even parts of the shelf up to 100 km inland from the shelf break must be underlain by Miocene oceanic crust. We are forced to conclude that the present continental slope (e.g., the 500 fm contour) is a poor guide to the oceanic-continental crustal transition. Our interpretation may explain many of the overlaps that occur when continents are reconstructed. However, conditions have been especially favorable to shelf prograding in the Greenland-Iceland area. Grounded ice streams deposited large sediment volumes at the shelf edge, which could prograde rapidly in the relatively shallow ocean in the Iceland area. Our interpretations may be tested by seismic reflection and refraction. Limited available data (Hinz and Schlüter, 1978; Grønlie and Talwani, 1978) are not inconsistent with oceanic crust underlying at least the outer Greenland shelves. Deep drilling is the only sure test, of course, but drilling in search for hydro-carbons certainly has minimal promise.

The Iceland Plateau has the best 'recording' of anomalies 5A to 6C that we have seen in the Atlantic. This record allowed us to pinpoint the late Tertiary plate acceleration 12–14 Ma ago. All that could be concluded previously was a relatively lower rate between anomaly 6 and 5 time compared to post-anomaly 5 (9.5 Ma). We find the 12–14 Ma time especially interesting because it correlates with the development of the 'E' escarpments around Iceland, perhaps a magmatic 'pulse' of global proportions (Vogt, 1978). The case for a causal connection between hot spot activity and plate dynamics is thus strengthened. Although we cannot disprove the alternative hypothesis, that the plate acceleration at 12–14 Ma caused the 'E' escarpments, we prefer to see both plate acceleration and the escarpments as manifestations of increased plume flow.

A magnetic smooth zone is being formed where the Reykjanes and Kolbeinsey ridges enter the Iceland platform. We could exclude some mechanisms postulated to produce smooth zones, but a lengthy list remains. At this time we prefer (a) degassing at low confining pressures at extrusion depths of 400–600 m and less, followed by (b) sediment loading of the young hot crust, causing reheating and loss of magnetization. Both these mechanisms can be tested – the first by measuring magnetic properties on a large dredge sample collection from the present axis, and the second by deep drilling through the 500–2,000 m thick sediment cover to determine the magnetic properties of the underlying crust.

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