Some properties of basalt lava sequences and volcanic centres in a plate-boundary environment

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SUMMARY: This paper discusses the implications that two current studies in Iceland may have in the interpretation of results from marine deep drilling and geophysical surveys in marginal volcanic areas of the N Atlantic. One study, concerning the magnetic remanence of lava flows, shows that the rate of geomagnetic reversals in the Tertiary is higher than is generally expected, and that caution must be exercised in tracing magnetic lineations between coeval submarine and subaerial formations. The other study, which deals with the distribution of major volcanic complexes within the Icelandic lava pile, demonstrates that this distribution is dependent upon various tectonic factors, especially any lateral shifts or direction changes of the active plate boundary that may have occurred.

During recent years, much evidence of marginal volcanism dating from the initial stages of opening of the N Atlantic has been found in the submarine areas off Europe and Greenland. This evidence is mostly derived from geophysical surveys and deep drilling, including Legs 81 and 104 of the Deep Sea Drilling Project/Ocean Drilling Program (DSDP/ODP). Either method yields valuable but rather incomplete information on the geological processes taking place during the initial rifting.

Observations of the accessible early Tertiary areas in Britain, the Faeroes and Greenland are likely to provide important constraints on the interpretation of the offshore results. Further constraints and analogies have emerged from research in Iceland, where a fairly continuous history of events at a divergent plate boundary during the last 15 My can be examined in surface exposures. Early models of crustal rifting in Iceland (Bödvarsson & Walker 1964; Pálsson 1980) were applied by Mutter et al. (1982) and by the Leg 81 Scientific Party (1982) to the generation of subaerial volcanics at the Norwegian and Rockall Plateau margins, respectively. A subsequent model (Helgason 1984) is being used by Skogseid & Eldholm (1987) in their description of volcanism and subsidence occurring during the formation of the Voring Plateau.

For those interested in comparisons of various geological and geophysical observations between Iceland and marginal volcanic areas, we refer to symposium volumes and review articles available on Icelandic geology (Fridleifsson et al. 1982; Björnsson 1983; Steinthorson & Jacoby 1985; Saemundsson 1986). It should be kept in mind, however, that the geological history, as observed in Iceland, results from an interplay of hot-spot and rift-zone influences, and is only to a limited extent analogous to the marginal volcanism. The geological environment in Iceland has also been influenced by a glacial climate during the past 3 My.

In this paper we shall concentrate on the description of two related features of the geology of Iceland which are currently being studied and evaluated in the light of the crustal generation model of Helgason (1984). These features are: (1) the palaeomagnetism of lava series and their associated aeromagnetic anomalies; and (2) the distribution of major volcanic centres. The study of these features in Iceland has far-reaching implications for the interpretation of oceanic magnetic survey results, and it may also help in establishing correct stratigraphic and structural relationships in marginal ocean areas.

Magnetic observations in Iceland

The linear magnetic anomalies observed over the submarine ridges SW and N of Iceland are well developed, allowing in many cases definite identification of individual lineations out to an inferred seafloor age of 10 Ma and a more tentative correlation to 20 Ma (Nunns et al. 1983; Vogt 1986). The sources of these anomalies are produced by the combined effects of seafloor-spreading processes and geomagnetic polarity reversals. The reversals will also be recorded as polarity zones in a lava pile emplaced in a subaerial rift-zone environment of the same age range. The resulting remanence contrasts giving rise to magnetic anomalies above these lavas.

At the present stage of research on aeromagnetic anomalies in Iceland, difficulties are being encountered in correlating individual polarity zones or anomaly lineations older than 5–6 Ma between the ocean floor and Iceland. This is due
to the following reasons, some of which will also apply to the Atlantic marginal volcanism:

1. Inadequacy of the 'geomagnetic polarity time scale'. Palaeomagnetic results have been obtained in several long composite K-Ar dated lava profiles in Iceland, involving magnetic measurements on samples from some 4000 lava flows. From a statistical study of reliably determined palaeofield directions in these surveys, Kristjansson & McDougall (1982) concluded that the rate of geomagnetic reversals in the last 15 Ma was at least eight per million years on average. In contrast, most versions of the polarity time scale (e.g. Harland et al. 1982; Lowrie & Kent 1983) indicate that the average reversal rate in this period was only four to five per million years. The discrepancy is most likely to originate from short (<50 000 years) geomagnetic subchrons whose magnetic field signal is attenuated by the distance between the ocean floor and the survey magnetometer. This fact will account for the presence of 'unexpected' polarity zones in cored deep-ocean sequences (Hall & Robinson 1979; Leg 81 Scientific Party 1982).

2. The low tilt angle of the lava pile. The average thickness of a polarity zone in the lava pile of Iceland is about 200 metres, and the pile has generally been tilted by less than 10°. Immediately above a level surface of the lava pile, magnetic anomalies may be expected to alternate from positive to negative at the boundaries of these zones. However, at an altitude of even only a few hundred metres, the magnetic signal has been smoothed to reflect long-wavelength variations in the magnetization of the lavas rather than individual polarity zones. In that context it is significant that the thickness of magnetized crust in Iceland is likely to exceed 3 km (Kristjansson & Watkins 1977).

A good example of such interpretation problems is seen in the 8–15 Ma lava pile of the northwestern peninsula of Iceland (Fig. 1) whose remanence polarity structure has been studied extensively by McDougall et al. (1984). Their sampling was carried out in locations indicated with closed circles, giving rise to the polarity columns shown in Fig. 1. Comparison with aeromagnetic profiles flown at 900 m above seal-level and 3 km spacing by Sigurgeirsson (1984) over the area reveals only a faint correspondence with the expected anomaly pattern. For example, a relatively thick sequence of normally magnetized lava flows outcropping in the eastern part of the peninsula has been assigned by McDougall et al. (1984) to the interval of generally normal geomagnetic polarity at about 10 Ma which causes the marine lineation known as 'Anomaly 5'. Although this anomaly is very prominent in all ocean-ridge magnetic surveys, the corresponding lava series does not give rise to a recognizable signature in the aeromagnetics. Conversely, a prominent positive anomaly occurs over the enclosed area marked with a plus sign in Fig. 1, without having an apparent relation to the polarity zone pattern in the nearby sampled profiles.

3. Effects of topography. When the tilt of the lava pile is only a few degrees, topographic features may influence the anomaly field, especially if these are elongated erosion features or scarp. Thus, N of point C in Fig. 1 a fjord carved out of mostly normally magnetized lava series is found to cause a small negative aeromagnetic anomaly aligned along a direction which is unrelated to the local tectonic strike. The relative effect of topography will increase with the age and progressive alteration of the lavas, as the alteration of basalts causes a decay of their primary remanence (Wood & Gibson 1976) along with an increase in their induced and viscous magnetization (Kristjansson & Watkins 1977).

4. The lenticular structure of the lava pile. There is evidence that during the lifetime (around 0.5 My) of each major volcanic centre (see the section on volcanic complexes below), and its associated dyke swarm, relatively rapid accumulation of lava flows will occur in an area having dimensions of the order of 10–20 km by 50 km. Inferred thicknesses of polarity zones in these areas, if crossed by a composite sampling section or an aeromagnetic profile, will then not be in proportion to the corresponding chron lengths in the magnetic polarity time-scale. In agreement with this, Johannesson & Kristjansson (in prep.) have found that similarities between the polarity zone pattern of section A'B and that of A'C in Fig. 1 become progressively smaller with increasing distance between coeval parts of these sections. The problem of stratigraphic correlation between such sections, either by direct mapping or by anomaly tracing, is further compounded by the presence of hiatuses and unconformities (see Fig. 1) caused by frequent migration of the volcanic zone (Helgason 1984). Normal faulting, on the other hand, appears from experience in Iceland to be a less serious problem in such correlations.

5. Localized magnetic anomalies occur at some of the volcanic centres in Iceland and offshore (Sigurgeirsson 1970; Kristjansson 1976a), particularly in the central regions of western Iceland. Their main characteristics are quite similar to those described for British Lower Tertiary vol-
Basalt lavas, volcanic centres in a plate boundary

Fig. 1. The northwestern peninsula of Iceland. Palaeomagnetic sampling localities of McDougall et al. (1984) and Johannesson & Kristjansson (in prep.) are shown as closed and open circles respectively. Mean dip and strike of the lava pile are indicated. Primary remanence polarity column for the section A–B is on the left, and the corresponding column for D–E is on the right. Dark corresponds to normal magnetization. The cumulative thickness of each column where sampled is 3–4 km. Arrows show positions of unconformities. The ages inferred for column end-points from K-Ar measurements are A: 14.0 Ma, B: 11.9 Ma, D: 12.7 Ma, E: 8.0 Ma. The enclosed region marked + has the most prominent magnetic anomaly of the peninsula.

Canic centres (Hall & Dagley 1970; Bott & Tantrigoda 1987). These anomalies may be due to cone sheets, caldera-filling materials (Fridleifsson & Kristjansson 1972), coarse-grained mafic intrusions, or even andesitic rocks (Kristjansson et al. 1977); they are generally positive and less than 10 km in size.

(6) Possible lateral offset between magnetic anomaly lineations from typical oceanic crust and magnetic anomalies from coeval lava series. A proportion of outcropping Tertiary lava flows in Iceland must have flowed from feeder dykes now covered by younger lavas a considerable distance down dip (Helgason 1984). It is evident that magnetic anomalies observed over these lavas will be offset, possibly by several km, from a direct onshore continuation of anomalies caused by contemporaneous submarine volcanism on the same spreading axis. In Iceland, it has been found that dykes are not a major contributing cause of aeromagnetic anomalies (Kristjansson 1985).

In summary, it does not seem to be a straightforward matter to trace magnetic anomalies in detail from areas of typical ocean crust through a shelf or transitional region in order to connect them with anomaly lineations originating in subaerial volcanics. In southwestern Iceland, however, anomaly lineations younger than the latest major reorganization of volcanic zones at 5–6 Ma (Johannesson 1980) are reasonably well developed. Survey work, ground mapping, and modelling studies now in progress may make it possible to follow some of these anomalies, as well as anomaly 5, across the shelf and even across the entire island.
The distribution of volcanic complexes

Volcanic complexes in the Iceland hot-spot frame

The main topographic high of the Iceland region has an inferred lower age boundary coinciding roughly with the onset of the Miocene (25 Ma) and/or seafloor anomaly 6 (Vogt et al. 1980). Within the subsaerial Iceland segment there are numerous volcanic complexes, which are in many respects similar to the Tertiary complexes of Britain and E Greenland (e.g. Walker 1963; Roberts et al. 1983) but smaller in size (<10 km); this may be a reflection of the crustal thickness being less in Iceland than in the continental areas. Their main characteristics include the presence of differentiated rocks, a caldera at the centre of a dyke swarm, high-temperature alteration, intrusive activity, and various geophysical anomalies (Kristjansson 1976a; Saemundsson 1986). Few if any complexes of this type occur on the ocean ridges to the N and SW, i.e. on the Kolbeinsey and Reykjanes Ridges.

Several authors have used volcano spacing in Iceland to model long-term crustal construction processes or to infer hot-spot migration (Vogt 1974; Walker 1974). However, available compilations of volcanic complexes (e.g. Sigurdsson 1967) are by now somewhat outdated. We present a new map (Fig. 2) of the sites of over 150 volcanic complexes in Iceland and its vicinity, based on various published and unpublished sources. Our main aims are to:

1. Analyse to what extent these complexes conform to a regional and temporal pattern.
2. Attempt to use the present distribution pattern to infer large-scale evolution of crustal properties within the Iceland hot-spot frame over the last 25 My, including shifts of the plate boundary, crustal thickness, and linear magnetic anomalies.
3. Apply the temporal variation in the distribution of volcanic complexes to infer variations in the production of acidic tuff layers in the N Atlantic.

Classification and compilation of volcanic complexes in the Iceland area

The systematic work of G. P. L. Walker and his colleagues in eastern Iceland proved fundamental to an understanding of the interrelationships between plutonic, hypabyssal, and extrusive rocks both of mafic, intermediate and felsic compositions (e.g. Walker 1963, 1966). The local occurrence of rhyolitic intrusions and sheets is a first order criterion to detect a partly buried volcanic chamber in an unmapped area. Felsic bodies normally indicate that a magma chamber was present at a shallow crustal level. Exposures of rhyolitic rocks in Iceland similarly indicate that a late-stage volcanic centre had developed, but notable exceptions include the monogenetic Sandfell laccolith in Faskrudsfjordur, eastern Iceland (Hawkes & Hawkes 1933). In other regions mafic intrusions are more conspicuous (Fridleifsson 1977), and some centres in the volcanic zones are recognized by the presence of fissure swarms and geothermal activity.

It is evident that various different aspects may be used in the classification of the volcanic centres, including their tectonic environment, structure, and geochemistry. Only the first of these will be dealt with below, as it is probably both the simplest and best documented aspect.

Interpretation

We studied the distribution or density of volcanic complexes in eight regions (see Fig. 2). In our approach we considered both the tectonic environment, the number of crustal complexes, the average area available for each complex, their distribution within each region and the degree of erosion as well as the available data on age boundaries for the regions. We have not taken into consideration the actual size of each complex: it is in most cases poorly known, and it is also not clear what measure of volcano size should be chosen for comparison between these, e.g. the area of a caldera or a dyke swarm, or a volume based on geophysical observations. Some of our results are presented in Table 1.

Regions 1, 2 and 4 are located at the accreting plate boundary. The mean area available for each complex is only 300–400 km². For all the other regions the density of complexes was smaller than this, in particular when it is taken into account that regions 1, 2 and 4 were formed during a relatively short period.

Region 3 is here regarded as a zone dividing northern and southern Iceland (N–S boundary zone) where a change in main tectonic trend from

Fig. 2. A compilation map for known volcanic complexes in the Iceland area (solid dots). The map is divided into eight regions of distinct tectonic character—regions 1, 2 and 4: active volcanism and crustal accretion; region 3: ‘N–S boundary zone’ with active volcanism and some crustal accretion; region 5: southern Iceland propagating volcanism; regions 6 and 7: Tertiary lava terrains of eastern and northwestern Iceland; region 8: early Miocene terrain off northwestern Iceland.
Table 1. Compilation of crustal complexes in the Iceland region

<table>
<thead>
<tr>
<th>Region</th>
<th>Complexes</th>
<th>Area km²</th>
<th>Area/Compl. km²</th>
<th>Approximate duration (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>2036</td>
<td>407</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1690</td>
<td>422</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>33670</td>
<td>481</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>4218</td>
<td>301</td>
<td>0.7</td>
</tr>
<tr>
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<td>7</td>
<td>5518</td>
<td>790</td>
<td>0.7</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
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</tr>
<tr>
<td>8</td>
<td>4</td>
<td>22675</td>
<td>5669</td>
<td>14-24</td>
</tr>
</tbody>
</table>

For locations of regions 1–8 see Figure 2

a northeasterly to a northerly direction is taking place. It is therefore transverse in comparison to the main active tectonic belts of Iceland, and includes a large time transgression (from the Miocene to the present) with regard to its volcanic centres. Seventy out of the 150 complexes of Figure 2 fall within this boundary zone. Broadly speaking, this region includes much of the highest topography and the thickest crust in Iceland. We also note that this zone differs from the other regions of Figure 2 in that the number and density of its crustal complexes has a tendency to increase with age. We attribute this increase in part to greater erosion and thus exposure to deeper crustal levels, but in part also to the passive nature of this tectonic environment. Thus, due to lack of crustal accretion in the boundary zone, its E-W orientation, and its extreme width (650 km) volcanism and formation of complexes has persistently been concentrated in this region. When compared to other regions in Iceland it would indeed seem that crustal accretion will lead to burial and ‘disappearance’ of volcanic complexes. On the other hand we attribute the large amount of time-transgression in region 3 to the long-term existence of separate tectonic trends in the northern and southern volcanic belts.

Region 5 in southern Iceland is highly active volcanically although its crustal accretion is small so far. Here the apparent density of volcanic complexes is low, with the average area per complex being about 800 km², but it should be kept in mind that the complexes of this region are generally quite large. We also note that there is a wide area between regions 5 and 3 where no volcanic complexes are present. Although volcanic fissures extend into this intermediate area they are all connected with complexes in either region 3 or 5.

Regions 6 and 7 are Upper Tertiary basalt lava terrains of eastern and western Iceland that formed roughly between 6 and 14 Ma. Here the area available for each complex is around 1000 km², i.e. twice as much as at the accreting plate boundary. A few of the complexes in Figure 2 were not included with any of the eight regions; they lie within crust of Tertiary age and have a similar distribution pattern as complexes within regions 6 and 7.

Region 8 is the submarine extension of northwestern Iceland. Only four localized complexes were found in a fairly detailed geophysical survey in this region (Kristjansson 1976b), resulting in an estimated area of 5550 km² per volcanic complex. However, this estimate is an upper bound as in the adjacent northwestern peninsula (region 7) most of the exposed volcanic complexes (see Fig. 2) are without prominent localized gravity or aeromagnetic anomalies (Einarsson 1954; Sigurgeirsson 1984). This may be due to less intrusive activity being associated with the complexes here than in other parts of Iceland, or it may be due to geochemical reasons.

Discussion

Except for region 3 (see Fig. 2), crustal complexes clearly tend to decrease in number with age. This raises the question of whether the generation of volcanic centres has increased in the Iceland area between the Upper Miocene and the present day, or whether there is a process that obliterates the centres formed in the volcanic zone when crustal rifting brings these away from the plate boundary. To answer this question it is necessary to bring into focus available models for the long-term crustal construction process in Iceland. Several such models have been proposed, assuming either: (1) that the plate boundary has been stationary for the past 15 Ma (Pálsson 1980); or (2) that the plate boundary has repeatedly shifted and that these shifts strongly affect the long-term crustal construction process, including the subsidence history and thus the temporal and spatial distribution of volcanic complexes in the Iceland crust (Helgason 1984, 1985).

We note in Figure 2 that no volcanic complexes have been detected in the 0.7–3.1 Ma areas flanking the neovolcanic zones (region 2) in northeastern Iceland. These are the distal areas of the plate boundary to which lavas have flowed, i.e. a depositional environment outside the areas of lava eruption. If the plate boundary had remained stationary for the entire period since 10 or 15 Ma, deep burial of volcanic complexes by distal-type lavas would probably have resulted. It has, however, been suggested (Helgason 1984) that the numerous complexes which have been...
exposed by the erosion of only approximately 500 m of lava from eastern Iceland, represent palaeo-rift zones. This circumstance is explained by frequent shifting of the plate boundary since the mid-Miocene, so that the rifting and extrusion process does not persist in one location long enough for deep burial of volcanic complexes formed at the rift axis. As an example, the eroded Thingmuli, Breiddalur and Alftafjördur volcanic centres of eastern Iceland were penecontemporaneously active on a common rift zone during the late Miocene.

We regard the low complex density in region 8 as a special feature which may be accounted for in several ways apart from the above explanations based on lack of geophysical signatures. Shifting of the plate boundary may have been infrequent during crustal construction in this region leading to deep burial of volcanic complexes. Another possibility is that it took many millions of years for the crust to develop sufficient thickness or other properties favouring the growth of volcanic complexes. In this context it is significant that Sigurdsson & Loebner (1981), on the basis of acidic tephra layers in marine sediments, show some evidence for a gradual increase in explosive volcanism in the Iceland area from the onset of the Miocene.

Conclusions

In all geological work it is appropriate to extrapolate not only from the present to the past, but also from the exposed to the unexposed. Iceland is certainly quite different from the Vøring Plateau and other marginal volcanic areas of the N Atlantic in key parameters such as age and crustal thickness. However, in Iceland good exposures provide direct observational control on geological properties such as lava accumulation rates, distribution of volcanic complexes, and tectonic patterns. The interrelations of these properties provide clues to processes having general applicability to a variety of geological, geophysical and geochemical studies of subaerial volcanism in marginal areas.

One aspect of the lava pile in Iceland which we have dealt with in the present paper is its remanent magnetization, which is the basis of a very useful means of stratigraphic correlation over short distances (up to tens of kilometres) in the field. Along with K-Ar dating, this property also furnishes an empirical measure of build-up rates in the lava pile, and it provides a way of estimating certain characteristics of the time-scale for world-wide geomagnetic polarity reversals more reliably than by indirect methods such as anomaly lineation inversions. Ideally, the magnetization of an inaccessible tilted lava pile should also allow tectonic directions, ages and other important features to be deduced through an analysis of magnetic survey results. We demonstrate, however, that several sources of error may occur in magnetic anomaly interpretation over lava series, affecting its usefulness in correlation with ocean-floor anomalies. One of these is due to volcanic complexes which cause enhanced production of lava flows during randomly selected periods, and which also give rise to localized (< 10 km) geomagnetic anomalies.

The second aspect concerns our compilation of crustal complexes of volcanic origin within Iceland and the submarine shelf. It shows that their distribution is dependent on crustal age and tectonic setting. In central Iceland an E-W-trending zone separates the volcanic belts of northern and southern Iceland. Time-transgression is continuous from Recent to Miocene strata in this N-S boundary zone, with a high density of crustal complexes, 480 km² per complex. In the Tertiary regions of eastern and northwestern Iceland (6–14 Ma age) the complex density is much lower, with approximately one complex every 1000 km². Within the neovolcanic zone (0–0.7 Ma) the density of complexes is highest, about 350 km² per complex. A very low density is recorded off the NW coast of Iceland. Similarly, large areas of Quaternary age that flank the neovolcanic zone have a very low density of complexes due to severe blanketing effects by more recent distal-type lavas. By analogy, it may be anticipated that the older volcanic segments of the N Atlantic are heterogeneous with regard to the distribution of crustal complexes and that the local tectonic environment during the first 10 My of ocean formation is mainly responsible for this heterogeneity.

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