Fine-scale sonar study of tectonics and volcanism on the Reykjanes Ridge

Reykjanes Ridge
Lateral sonar
Gloria
Tectonics
Ride de Reykjanes
Sonar latéral
Gloria
Tectonisme

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ABSTRACT

We describe a survey, using medium and long-range (Gloria) sidescan sonars of the Reykjanes Ridge crest between 58 and 61°N. The survey extended from the part of the ridge crest exhibiting a median valley to that with an axial high. An axial zone, about 13 km wide, is dominated by linear volcanic ridges striking 14° and believed to form over fissures running approximately normal to the spreading direction. Outside the axial zone the sea-floor morphology is dominated by inward-facing faults striking subparallel to the Reykjanes Ridge axis, and therefore oblique to the spreading direction. The strike of these faults is believed to be controlled by the way in which the strength of the lithosphere increases away from the ridge axis. The faults have an average spacing of 2.6 km and are about 10 km long. This pattern of faulting is essentially the same as that on "normal" slow-spreading and fast-spreading ridges. The major changes observed going from the SW (median valley) part to the NE (axial high) part of the ridge are decreases in fault throws, fault-block tilts, and heights of volcanic ridges. The origins of these features are discussed qualitatively in terms of a changing temperature structure of the lithosphere along the Ridge axis.

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RÉSUMÉ

Étude de détail au sonar latéral, de la tectonique et du volcanisme de la ride de Reykjanes.

Une étude détaillée de la tectonique et du volcanisme de la ride de Reykjanes a été effectuée au moyen du sonar latéral Gloria à longue et moyenne portée entre 58 et 61°N. La zone étudiée s'étend du sud-ouest de la ride, caractérisé par une vallée axiale, au nord-est où elle manque. La zone axiale, qui mesure environ 13 km de large, est dominée par des crêtes volcaniques linéaires orientées sur 14° et probablement formées à l'aplomb de fissures approximativement normales à la direction d'expansion. En dehors de la zone axiale, la morphologie du fond est caractérisée par un système de failles orientées vers l'intérieur et obliques par rapport à la direction d'expansion.
La direction de ces failles nous paraît elle-même contrôlée par la direction suivant laquelle augmente la résistance élastique de la lithosphère depuis l'axe de la ride.
Les failles sont espacées de 2,6 km en moyenne, et ont une longueur d'environ 10 km. Leur distribution est fondamentalement la même que sur une ride d'expansion rapide ou lente, mais dont la direction d'expansion est normale à l'axe. Les changements majeurs qu'on observe, du sud-ouest (vallée médiane) au nord-est (vallée non existante), sont les suivantes : diminution du rejet des failles ; décroissance du basculement des blocs faillés ; et baisse de la hauteur des rides volcaniques. Nous expliquons l'origine de ces caractéristiques de façon qualitative en termes de changements de structure thermique le long de la ride de Reykjanes.

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INTRODUCTION

In this paper we present new data concerning the fine-scale morphology of the Reykjanes Ridge, obtained principally with two side-scan sonars of the Institute of Oceanographic Sciences.

The long-range, 6 *k*Hz towed sonar, Gloria, is capable of rapid surveying of a swath up to 60 km wide, with down-range resolution of about 50 m and a beam-width of 2 1/2° giving cross-range resolution of 1.3 km or better. It is thus ideal for surveying patterns of faulting and volcanism on a regional scale. The medium-range, hull-mounted sonar, which uses a 36 *k*Hz acoustic pulse, has higher resolution (about 10 m down and cross-range) than Gloria, but a more limited maximum range of about 2.5 km. It can therefore only be employed in relatively shallow water, but there it is an ideal complement to Gloria, providing finer resolution of fault-scarps and volcanic land-forms. Enough energy is transmitted vertically so that there is continuous coverage across the record, from the side-scan portion to what is effectively a bathymetric profile vertically beneath the ship produced by an echosounder with a very narrow beam in the fore and aft direction.

There were three features of the Reykjanes Ridge which particularly interested us. First, although the ridge has a mean spreading half-rate of only about 10 mm.a^{-1} (Talwani *et al.*, 1971 ; Vogt, Avery, 1974 ; Minster, Jordan, 1978) the regional morphology at its northern end — subdued relief and median ridge rather than a median valley — is more akin to that of a fast spreading ridge. We wished to see if this was also true of the small-scale morphology and tectonics, and to examine how the transition from median high to median valley is accomplished.

Secondly, the Reykjanes Ridge is a region where highly oblique spreading with no obvious transform offsets seems to have been stable over a mid-ocean ridge segment some 1 000 km long for the past 20 Ma (Vogt, Avery, 1974). The regional trend of the axis is 36°, nearly 30° different from the spreading normal direction of 9° predicted by the RM2 pole of Minster and Jordan (1978). We wished to determine whether the spreading is truly oblique even at the smallest scale, and to examine the effect of this on the tectonic pattern.

Finally, we wanted to check the presence and possible nature of the V-shaped time-transgressive ridges postulated by Vogt (1971).

SURVEY

Our survey was carried out from R.R.S. Discovery during 6 1/2 days of June and July 1977. The survey area and ship's track are shown in Figure 1. This area was chosen because it straddles the transition from median valley to median ridge structure (the change is apparent from the 2 000 m isobath in the inset of Figure 1). A standard 10 *k*Hz echo-sounder, Askania GSS3 gravimeter and Varian proton magnetometer were run throughout the survey, and single-channel reflection profiling was carried out during the first 4 1/2 days, but was then terminated because of equipment failure in heavy seas.

Sonar data

Gloria data were processed via two channels before being analogue tape recorded and photographically displayed. Each channel provides correlation of the long output pulse

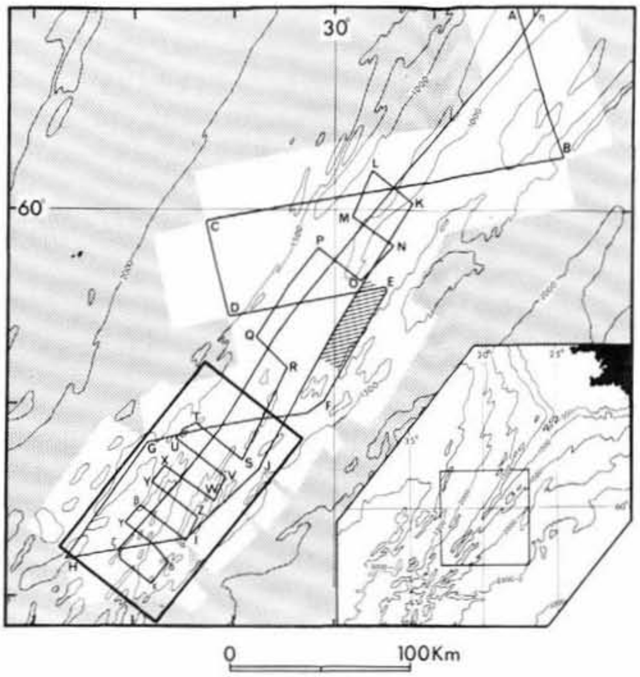

Figure 1
Track chart of Discovery 84 survey, with 500 m isobaths. Areas without Gloria coverage are stippled. Rectangular box outlines area of Figure 6. Hatched area indicated position of Figure 8. Inset : regional bathymetry (metres) and location of survey area.

and corrections for geometric spreading losses and attenuation. The one channel is recorded directly ("fixed gain"), and the other is recorded with automatic gain control (AGC). The latter allows very high and low-level signals to

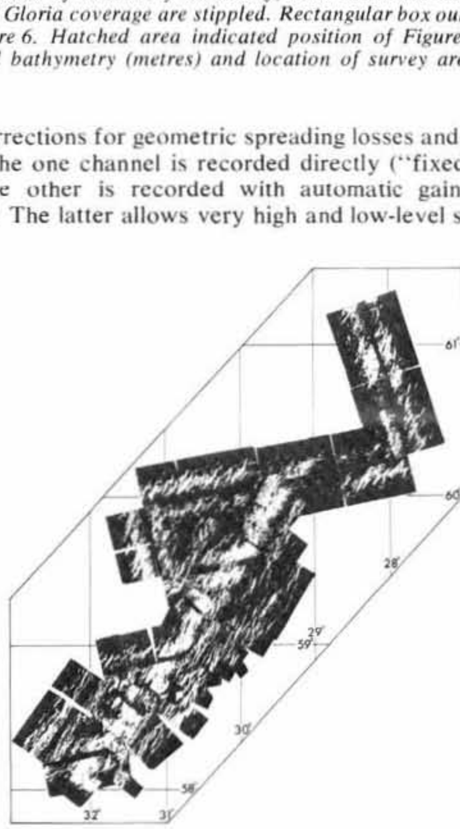

Figure 2
Montage of "fixed gain" Gloria records over the survey area. Records were anamorphosed to correct for variations in ship's speed, and scale to maximum range is equal to scale along track. However, since it is slant range, not horizontal range, that is displayed, the horizontal range scale is non-linear. Reflections are represented by light areas. Note that direction of insonification varies with ship's course.

be accommodated to the limited dynamic range of the tape-recorders, but distorts signal levels non-linearly.

A montage of the fixed-gain records is given in Figure 2. A typical record from the hull-mounted sonar is shown in Figure 3 for one of the oblique crossings, and a stack of records from the same sonar for some of the profiles normal to the ridge axis is given in Figure 4.

RESULTS

Volcanic features

The "fixed gain" Gloria montage reveals an axial zone, about 13 km wide, of very high acoustic backscatter (appearing as a broad, white band in Figure 2). This high level of backscatter is distributed fairly uniformly within the axial zone, and is interpreted as coming from the rough surfaces of basaltic lava flows which, in the young, axial crust, have not yet been covered by sediment (Laughton *et al.*, 1979). In this context, "rough" means rough compared with the sonar wavelength, which is about 25 cm for Gloria.

Records from the hull-mounted sonar also display high backscatter in a similar axial zone, but the higher resolution of this instrument allows some structure to be perceived within this zone. Most of the strong reflectors are seen to be lobate structures from about 10 to 100 m across, and they are interpreted as individual lava flows.

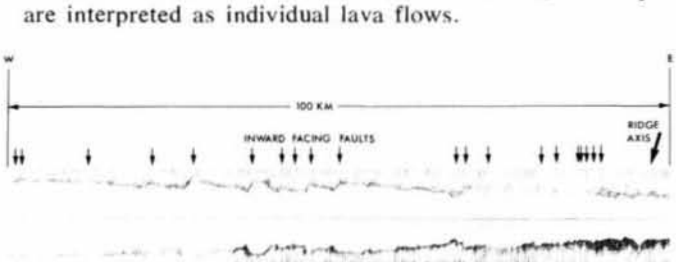

Figure 3
Record from the hull-mounted sonar for part of the oblique E-W crossing of the Reykjanes Ridge crest near 60°N. Note that on this record reflections are dark, shadows light. No correction has been made for variations in ship's speed or for slant-range distortion. The total width of the record represents 5.0 km and the along-track scale is compressed relative to the cross-track scale by a ratio of about 3 : 1.

A clear evolution of volcanic land-forms can be seen on the hull-mounted sonar records, as crust farther from the axis becomes progressively covered by sediment (Fig. 3, 4). Within the axial zone the sea-floor is essentially covered by overlapping flows. At the edges of this zone, which often appear to be fairly clearly demarcated by faults (although not necessarily the youngest faults), fairly flat, sedimented areas several kilometres across are seen, with outcrops of basalt between them, usually on higher ground. The level of backscatter from these outcrops is less than in the axial zone, however. The upper surfaces of lava flows appear covered by sediment here, but the lobate flow fronts can still be clearly seen. Going farther from the axis, the frequency and size of lava outcrops gradually decrease, although distinct flow fronts on isolated hills and especially at lips on the fault scarps (Macdonald, Luyendyk, 1977) can be recognised out to the limits of our survey, about 80 km from the axis.

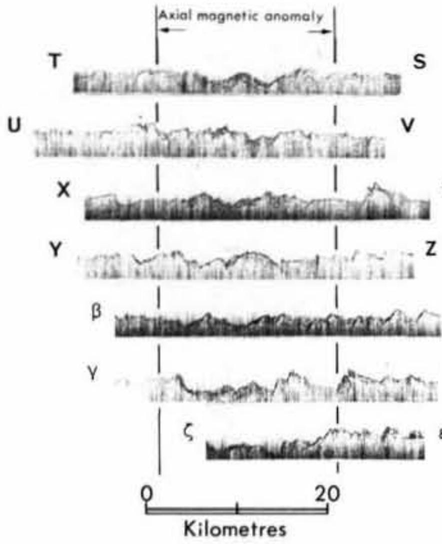

Figure 4
Stack of records (one side only) from hull-mounted sonar, of the southernmost profiles normal to the ridge axis. Reflections are dark, shadows light. Along-track scale compressed about 3 : 1 relative to cross-track scale.

The hull-mounted sonar records show distinct volcanic ridges in the axial zone. Laughton *et al.* (1979) concluded from a very preliminary look at the data that the hills had constant height. However, a more detailed study now reveals that they increase in height from NE to SW along

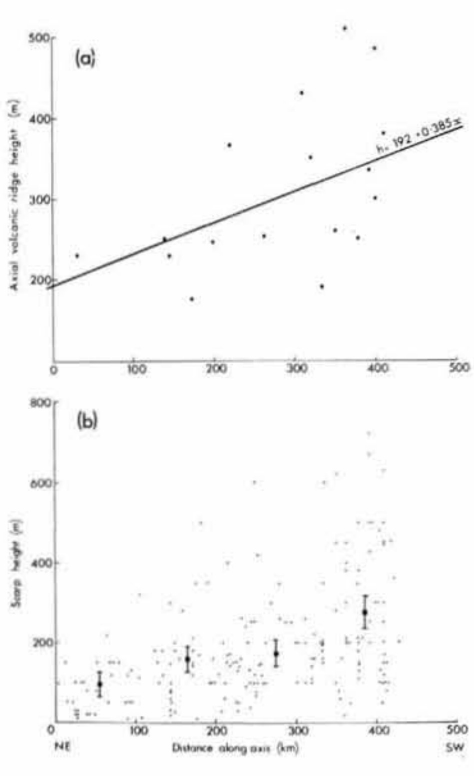

Figure 5
Variations of (a) heights of axial volcanic ridges and (b) heights of fault scarps with distance along the axis of the Reykjanes Ridge away from Iceland. Origin of distance scale is at 61°06′N, 27°48′W. Data were all taken from hull-mounted sonar records.

the Reykjanes Ridge axis, from a mean of about 240 m near 61°N to about 380 m near 58°N (Fig. 5 *a*). Their widths vary from about 3 to 6 km, and their crests are rounded or pointed. Similar ridges were seen with the hull-mounted sonar outside the axial zone, where they are often fault-bounded on the younger side. Some off-axis ridges have flat tops, suggesting they are capped by sediments or lava sheets.

These axial ridges were also seen by Gloria, which revealed fully their linear nature. They were most clearly seen from the long track run parallel to the axis, for which a higher pulse repetition rate of one per 20 seconds was used. Part of this record is shown in Figure 6. We have not been able to locate examples of similar ridges outside the axial zone with Gloria, presumably because their relatively low slopes, once they have accumulated enough sediment to cover the lava flows, do not backscatter very differently from the surrounding sea-floor.

The volcanic ridges are 20 to 30 km long and 3 to 6 km wide. Their trends range from about 8 to 20°, with a mean of about 14°. They overlap *en echelon*, with parts of up to three separate ridges sometimes crossing a single spreading flow-line. South of 59°N, the ends of the ridges often curve in a sigmoidal manner to parallel major SW-NE trending scarps at the edge of the axial zone, and in fact some ridges may join or even change continuously into such scarps (Fig. 6). The ridges in the south are more clearly defined, possibly because they are higher, and they have sharp crests which cast shadows.

Figure 6 *a* shows the detailed bathymetry of the southern part of the survey area, where we had sufficient soundings to recontour. The contouring was controlled by the Gloria data, and in particular shows the correct orientation of the axial volcanic ridges. Without the benefit of the sonar it would have been extremely difficult, if not impossible, to make the correct correlations between adjacent sounding lines, since the ridges run obliquely from one side of the axial zone to the other.

Many small circular volcanoes were also seen on the Gloria images (Fig. 7). Although large central volcanoes have been observed elsewhere by Gloria (unpublished data), those seen on the Reykjanes Ridge are all relatively small having

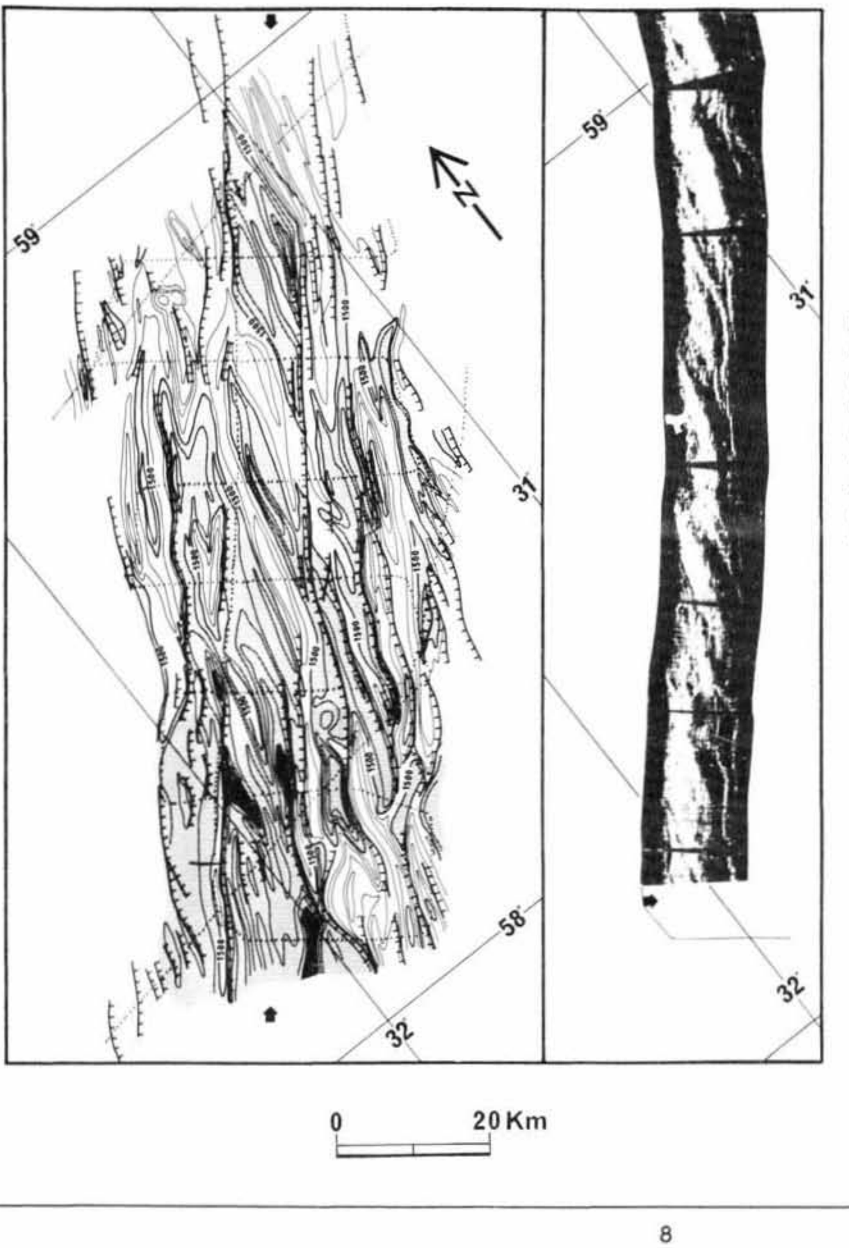

Figure 6
a) Detailed bathymetry of southern part of survey area, in metres corrected according to Matthews (1939). Fault scarps shown by heavy lines; ship's track by dotted lines. Areas deeper than 2 000 m in black; 1 500-2 000 m stippled. b) Gloria sonographs, at same scale as (a), taken looking to the southeast of the track running from bottom to top of part (a) at left of centre.

diameters of about 1 to 4 km. All have the appearance of a bright ring surrounding a central dark area thought to be a crater. More were seen near the ridge axis than elsewhere, presumably because older ones are covered by sediment or eroded by tectonic processes. Sometimes volcanoes (often very closely spaced) are aligned along the crest or flank of one of the linear volcanic ridges.

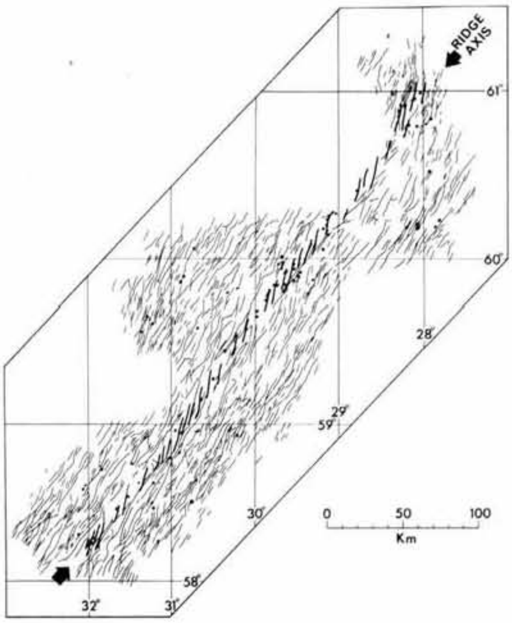

Figure 7
Summary of major faults (light lines), axial volcanic ridges (heavy lines) and central volcanoes (dots, drawn to scale) observed with Gloria.

Tectonic features

Outside the axial zone, the Gloria montages show large numbers of relatively straight, parallel reflectors, with an average length 10 km (and maximum of 30 km), spaced about 3 km apart. They backscatter strongly, and are only a few hundred metres or less in width. Similar features seen by Gloria in the Famous area and near Kurchatov Fracture Zone have been interpreted as fault scarps (Whitmarsh, Laughton, 1976 ; Searle, Laughton, 1977). Most of the reflected sound energy would appear to arise from backscattering by basalt or other hard rock exposed at the fault face, since in other areas steep scarps in sediments are recorded much less strongly. That these are scarps and not narrow ridges is confirmed by a pair of overlapping sonographs from near 59°30'N, 29°45'W (Fig. 8). The lineations clearly show up only when insonified from one side, that facing the scarp. Insonification from the opposite side produces long, linear shadows thrown by the scarps and scattered reflections from broad zones corresponding to the dip slopes. The latter reflections we believe are from outcropping lava flows.

This interpretation is confirmed by numerous crossings of the "Gloria" lineations with the hull-mounted sonar. The greater resolution of this instrument, combined with its narrow-beam echo-sounding capability, allow the steep scarps to be identified on the sub-ship trace and then followed out into the side-scan image. This instrument also

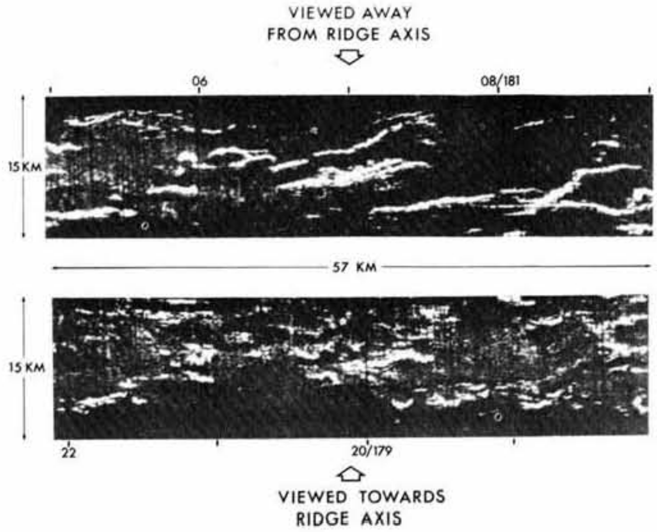

Figure 8
Pair of Gloria sonographs, each of which covers the hatched area of Figure 1 but with opposite directions of insonification.

shows that, within its resolution, the scarp faces are relatively smooth and featureless compared with the typically lobate volcanic terrain, from which they are readily distinguishable.

Few scarps were seen within the axial zone, the mean distance from the ridge axis to the first fault being 4.7 km (Laughton, Searle, 1979). Outside the axial zone, the faults are spaced on average 2.6 km apart, which is not significantly different from the spacing at other sites on the northern Mid-Atlantic Ridge (Laughton, Searle, *op. cit.*). The fault spacing does not vary significantly either with distance from the axis (providing thickly sedimented areas are excluded) or along the axis.

The mean strike of the faults is 28°, but with considerable variation (standard deviation about 13°). This mean direction is sub-parallel to the Reykjanes Ridge axis (36°), and significantly different from the 14° strike of the axial volcanic ridges. However, the Gloria echoes from which these mean trends were measured contain segments exhibiting a continuous spectrum of trends from about 10 to 40°. They therefore probably comprise 14° volcanic ridges (although these have not been explicitly observed outside the axial zone) and more oblique major scarps having a mean strike near 36°. Positions of the faults and the axial volcanic ridges are summarised in Figure 7.

Heights of the scarps were determined from the echo-sounder portions of the hull-mounted sonar records, for a total of 198 scarps throughout the survey area. In contrast to the fault spacing, we found here a very significant change as a function of distance along the axis : heights increased from a mean of 96 m in the NE to 275 m in the SW part of the survey area (Fig. 5 *b*). When this along-axis variation is taken account of, there is no significant variation of height with distance from the axis. Of all the faults examined, only 6 were seen to face outward (away from the ridge axis). Scarp slopes varied from 20 to 90° over 127 measured samples, with a mean of 49°. Macdonald and Luyendyk (1977) found a mean dip of 50° from Deeptow studies in the Famous area.

Because there are so few outward-facing faults and because, apart from the small median valley in the SW, the sea-floor regionally slopes down away from the ridge axis, there must be outward tilting of the fault blocks. From our knowledge of scarp heights (which we equate with fault throws) and the regional topographic slopes, we calculate that tilts ranging from 2° in the NE to 6.5° in the SW are needed. We estimated the tilts of 32 flat-topped fault blocks on the assumption that the (now sloping) tops were originally horizontal. Measured slopes ranged from 6 to 30°, with a mean of 11° (averaged over the whole survey area). This is nearly twice the average dip of tilted blocks found by Macdonald and Luyendyk (1977) in the Famous area. Although this mean dip is more than adequate to explain the regional slope, it is likely that our sample is biased since blocks with small or zero tilt have not been recognised.

DISCUSSION

Comparison with other work

Two other high-resolution surveys have been carried out on the Reykjanes Ridge. The first was the Deeptow survey of Shih *et al.* (1978). We have compared our data with the original Deeptow records in areas where they overlap, and most features seen on them can also be observed on our records. However, because of the differing scale of cover, we find that the relative significance of different features may be different on the Deeptow and Gloria records. For example, many strong NE-SW scarps observed by Deeptow are seen on the Gloria records to be relatively short, and may therefore not be given great significance by us, and may not all appear in diagrams such as Figure 7. Another example is given by the E-W scarps seen by Deeptow near the Ridge axis at 60°N. Close inspection shows that similar trends can be seen in that area on the Gloria records ; however they are very faint, and we would not normally have noticed them (this may partly be due to the fact that all the scarps face south in an area where none of the Gloria passes has a northward component of insonification). Other aspects of our results are in good agreement. Shih *et al.* (*op. cit.*) confirmed the presence of volcanic ridges trending about 15° in the axial zone, first suggested in the bathymetric chart of Johnson *et al.* (1971). They also found that fault scarps trend more easterly than the volcanic ridges, though their figure of 21° for the mean trend is less than ours of 28°. This is probably because their survey was more closely confined to the axis than ours, so that they sampled a relatively greater proportion of 14° trends within the axial zone itself.

The second high-resolution study was a small narrow-beam echo-sounder survey at 62°N by Jacoby (1980). This also showed a central rough zone, 15 km wide, containing *en echelon* volcanic ridges and bounded by fault scarps. The axial ridges were also found to be sub-parallel to the spreading normal and oblique to the Reykjanes Ridge axis, whereas the flanking scarps were found to be parallel to the axis. Jacoby reported a marked NW-SE asymmetry in his survey area, but our results suggest this is not a widespread feature of the Reykjanes Ridge.

The presence of V-shaped ridges

One objective of our survey was to check on the concept developed by Vogt (1971) that southwesterly flow of asthenosphere along the ridge axis from the Iceland hot spot has given rise to V-shaped ridges in the topography of the Reykjanes Ridge. A survey carried out by Vogt and Johnson (1972) to the west of the ridge appeared to give support to this idea in that a basement high trending obliquely to the axis was seen. Our data on both sides of the ridge show that the obliquity of faulting is not symmetrical about the ridge axis and thus cannot give rise to the V-shaped ridges predicted by the Vogt (1971) model. On the contrary the fault trend on both sides has been shown to be slightly more northerly than the axial trend. However, because Gloria does not give good indications of gentle slopes or small changes of depth, we are unable to rule out the presence of subdued V-shaped basement ridges (produced perhaps by excess volcanism). What is clear is that if such ridges have been produced, there was no accompanying disturbance to the tectonic fabric of the Reykjanes Ridge.

The transition from median valley to axial high

As one approaches Iceland, there is a gradual transition from a "normal" slow-spreading ridge with fully developed median valley, to the fully "anomalous" Reykjanes Ridge with well developed axial high. Jacoby (1980) emphazises the presence of a "rift valley" as far north as 62°N ; but we feel this is a misleading use of the term, since the sea-floor at the ridge axis is considerably shallower than the tops of the inward facing scarps which bound his "valley". We were unable to examine the axial high region very fully, but our survey did straddle the transition, covering the median valley regime in the south, an intermediate regime in the central to northern part, and the beginning of the axial high in the north.

In terms of the local sea bed morphology, this transition is accomplished principally by a decrease northwards of the throw of the major faults parallel to the ridge axis. Thus the median valley is gradually reduced in amplitude, until its sides become lower than the volcanic hills on the axis and it essentially disappears as a morphological feature. At least in the north this effect is emphasized by a slight arching of the sea-floor in the axial region, but in the south the topography is too rugged to be able to discern such a subtle feature.

The diminution in scarp heights is accompanied by a decrease in the outward tilt of the fault-blocks. If the sea-floor were regionally flat, then block tilts would have to match fault throws, for a constant fault spacing. In fact of course the regional slope is not zero, but is finite, producing a ridge. However, the regional slopes are still small compared with those needed to compensate the effect of faulting, so a decrease in fault throw must be accompanied by a decrease in block tilt if the regional slopes are not to change drastically. Apart from the axial zone, regional slopes vary by less than a degree throughout the survey area, compared with 6° of variation in average tilting.

A third change across the transition region is a diminution in height of volcanic ridges. However, unless the morphology of these ridges changes substantially with distance from the axis, which seems unlikely, this should have no overall effect on the regional bathymetric profiles across the ridge.

These changes in sea-floor morphology must reflect differing conditions in the underlying earth. We believe the ultimate cause of the changes is a higher temperature field under the northeastern part of the Reykjanes Ridge, as a result of the proximity of the Iceland hotspot. This idea receives some support from the discovery of extensive partial melting beneath Iceland itself (Gebrande *et al.*, 1980).

There appear to be four ways in which increased temperatures could affect the morphology, the final shape of the ridge depending on the net effect of all four. However, most of them do not directly control the detailed morphology of the seabed, but rather they affect the deep-seated forces to which the brittle lithosphere responds. The first effect is simply increased thermal expansion which would make a hotter ridge shallower, and its sides steeper. The next effect is a thinning of the lithosphere, which should result in smaller fault throws and block tilts (Vening-Meinesz, 1950). Third is the effect of a lowered viscosity. If the viscosity is high, upwelling and spreading will leave a depression at the axis, flanked by highs (Sleep, Rosendahl, 1979). Physically, this occurs because the viscosity causes a finite time lag between separation of the plates and upwelling of new material to fill the gap. However, if the viscosity is lowered sufficiently (to about 0.4×10^{14} $m^2.s^{-1}$) the depression will effectively disappear (Collette *et al.*, 1980). Finally, higher temperatures should lead to the existence of a broad magma chamber, which will isostatically raise the crust above it (Rosendahl, 1976).

Of these four factors, the most important in determining the presence or absence of a median valley are probably the viscosity and the presence or absence of a large magma chamber (Sleep, Rosendahl, 1979). There is no evidence of a large magma chamber under the part of the Reykjanes Ridge we have surveyed : a seismic refraction survey near 60°N (Bunch, Kennett, 1980) and our unpublished gravity data near 59°30'N both indicate that no large magma chamber can exist in that region. However, it is possible that one may be developed farther north, and we are investigating that possibility now.

Comparison with fast-spreading ridges

Several workers have suggested similarities between the Reykjanes Ridge and fast-spreading ridges (Rosendahl, 1976 ; Lonsdale, 1977 ; Sleep, Rosendahl, 1979), and our detailed observations tend to confirm this.

Fast spreading ridges have much less rugged topography than normal slow-spreading ones, and this is certainly characteristic also of the northeastern Reykjanes Ridge with its low fault scarps and volcanic ridges. Lister (1977) suggested the low relief on fast-spreading ridges was a result of broad sub-axial magma chambers decoupling the brittle crust from the underlying viscodynamic forces. As stated above there is no evidence of a broad magma chamber under the part of the Reykjanes we studied, so perhaps the effect is simply a result of a thinner lithosphere.

In the NE part of our survey area the axial volcanic zone is raised above the regional level, as is the one on the East Pacific Rise. However, the detailed morphology is somewhat different. The volcanic hills we observe within the axial zone might be considered analogues of the axial shield volcano of the East Pacific Rise ; although the latter is somewhat narrower, being only 2 km wide (Lonsdale, 1977). Also, the axial volcanoes of the Reykjanes Ridge form a series of overlapping *en echelon* ridges, compared with the straight, continuous East Pacific Rise axial volcano (however, we interpret this *en echelon* pattern as a consequence of oblique spreading — see next section). The East Pacific Rise axial volcano has a narrow crestal graben, which we have not observed on the Reykjanes Ridge volcanic hills.

On the Reykjanes Ridge most of the major faults face inwards, whereas Lonsdale (1977) interpreted deep-towed sidescan and echosounder data from the East Pacific Rise at 3.5°S to indicate equal numbers of inward and outward dipping faults. However, a recent (May 1980) Gloria survey of the same area on the East Pacific Rise suggests that, of the major faults viewed by Gloria, by far the greatest number dip inwards (Searle, unpublished data). Rea (1975) has also concluded that major normal faults on the East Pacific Rise are predominantly inward dipping. Predominantly inward dipping scarps are also found at the medium spreading Galapagos Rift (Klitgord, Mudie, 1974). They therefore seem to be characteristic of all spreading centres, irrespective of spreading rate.

Lonsdale (1977) describes a zone of almost zero vertical offset faulting over the East Pacific Rise axial volcano, with increased vertical movement of tens of metres beyond about 1.5 km from the axis, and another increase in fault throws to over a hundred metres at 10-15 km from the axis. He interpreted the increased vertical movement as a result of increasing crustal (lithospheric) thickness, with the sudden increase at 10-15 km occurring where the crust moves off the edge of a wide axial magma chamber. In contrast, on the Reykjanes Ridge we observe a fairly sudden increase in vertical offset of faults from less than tens of metres to over one hundred metres at about 5 km from the axis.

The azimuths of the volcanic ridges and normal faults

One of the most important results of our survey is the discovery that the volcanic ridges have a different trend from the major normal fault scarps. We think it unlikely that this represents a recent (ca. 0.6 Ma b.p.) change in tectonic style, and prefer to interpret the difference as arising from two separate aspects of a quasi-steady-state sea-floor spreading process. The 14° trend of the volcanic ridges is almost normal to the spreading direction (which is predicted to be 99° by the RM2 pole of Minster and Jordan, 1978). The trends of the volcanic ridges therefore follow the directions expected if they have accumulated from lavas erupted along fissures normal to the spreading direction. In other words, the axial fissures sense a horizontal tension imposed by and in the direction of the separation of plates at the ridges axis, and orient themselves normal to this direction. This same tensional field may also give rise to some minor faulting and open fissuring in the axial region. These ideas were first presented by Laughton (1978) ; recently Jacoby (1980) has published very similar conclusions.

The observation that the volcanic ridges are *en echelon* and that two or three can overlap along a flow line would lead to problems of geometry in the sea-floor spreading process if all of them were actively spreading simultaneously. However, as a fissure grows in response to tension, and propagates diagonally across the median valley, the stresses in neighbouring sections will be relieved and active fissures there will die. Thus there will be an episodic birth and death of the volcanic ridges cutting into young but not zero age crust, in a way similar to that described by Ballard and Van Andel (1977) in the Famous area.

We suggest that the 36° direction of the faulting outside the axial region comes about mainly as a result of the way the strength of the lithosphere changes in time (and therefore distance from the axis). The strength of the young lithosphere will increase away from the axis and should be mainly a function of temperature. We expect the broad elongation of the Reykjanes Ridge along 36° to reflect the lithospheric temperature distribution, and infer that for a given depth the

deep isotherms run roughly parallel to the ridge axis. We therefore expect the lines of equal strength will also tend to parallel the ridge axis.

The gradient of lithospheric strength is therefore oblique to the spreading direction. If one imagines a fissure or small fault formed in the axial zone and propagating outwards along the normal to the spreading direction, it will cross progressively older and stronger crust (Fig. 9). As it approaches lithosphere whose yield stress is greater than the local tensional stress, it will be unable to break that, and will tend to be deflected parallel to the lines of equal lithospheric strength (i.e. parallel to the ridge axis), giving rise to the sigmoidal structures of the axial zone (Fig. 9 *a*). Similarly, faults formed near the edges of the axial region will tend to run perpendicular to the gradient and therefore parallel to the ridge axis.

Since volcanic and tectonic lineations in the axial zone are nearly normal to the spreading direction, an oblique lithospheric strength gradient does not seem to exert a strong influence there. This could be either because the gradient in the axial zone is not oblique (because there the isotherm distribution is strongly influenced by the intrusion process to be parallel to the fissures rather than ridge axis), or because the gradient in the axial region, though oblique, is not very steep. This case is represented in Figure 9 *b* by showing the lithosphere with almost constant thickness throughout the axial region. A possible explanation for this is that the local intrusion centre (under one axial volcano) can jump about throughout the axial region, so that over a long time the time-averaged intrusion zone is quite broad. An abrupt thickening of the lithosphere might occur at the edge of the axial zone because there major faulting first allows cooling water to penetrate deep into the crust.

The origin and onset of major faulting

Given that faulting outside the axial region will tend to run parallel to the ridge axis and not perpendicular to the spreading direction, it remains to consider why major normal faulting of this trend should begin, fairly abruptly, some 5 km from the axis, while the fissures and any minor faults in the axial zone have only small vertical offsets. The answer must be intimately bound up with the origin of the faults themselves, and the observation that similar patterns of inward-facing normal faults occur at all spreading axes, regardless of spreading rate, suggests we should look for a common mechanism to explain it. Clearly the faulting mechanism can depend neither on spreading rate (at least, there is no strong dependence) nor on ridge morphology (presence or absence of a median valley).

Normal faults can be produced by horizontal tension (maximum and minimum principal compressive stresses vertical and horizontal, respectively ; shear planes dipping approximately 60°) or vertical shear (extremal principal stresses dipping approximately 45° ; shear plane near vertical). Horizontal tension was invoked by Rea (1975) and Lonsdale (1977) to explain normal faulting on the East Pacific Rise, and Tapponier and Francheteau (1978) have stressed its importance at slow-spreading ridge axes. The main difficulty with the tensional hypothesis is that it does not predict the dominance of inward-dipping faults : both inward and outward dipping ones should be equally likely (Vening-Meinesz, 1950). It also fails to explain the sudden onset of normal faulting, unless one assumes that this corresponds in position to a sudden increase in lithospheric thickness (since fault throw would be proportional to this thickness).

Vertical shear has been proposed by several authors including Deffeyes (1970), Osmaston (1971), Francis (1974), Whitmarsh and Laughton (1976), Ballard and Van Andel (1977) and Laughton and Searle (1979), to account for large-scale normal faulting on slow-spreading ridges with median valleys. In the version of Laughton and Searle, uplift under the rift mountains resulting from visco-dynamic forces in the mantle also raises the newly-formed lithosphere of the rift floor until its unsupported weight is sufficient to fracture it, allowing it to drop down along a new fault.

The main difficulty with vertical shear is that in the case of a fast-spreading ridge (or a hot-spot ridge with a large magma chamber), it is difficult to see how the stress can be transmitted to the brittle crust in the axial region ; it cannot be transmitted via the thick lithosphere at the edge of the magma chamber, since we know the lithosphere is broken

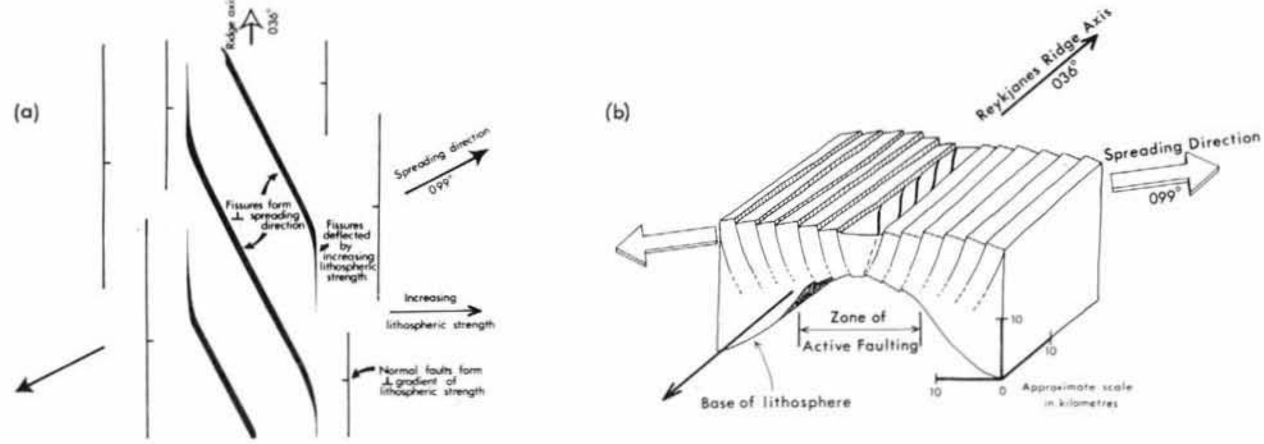

Figure 9

a) Diagram of plan view of axial region of Reykjanes Ridge, showing development of axial fissures perpendicular to spreading direction. Toward the edge of the axial zone the fissures are deflected parallel to the axis of the Ridge, and at the edge of this zone normal faults form also parallel to the axis, i.e. perpendicular to the gradient of increasing lithospheric strength. b) Block diagram, approximately to scale, showing same process. Linear volcanic ridges form above the fissures, but are omitted from the figure for clarity.

by active faulting between there and the axial region where the first faults form. On the other hand this mechanism does explain the consistent inward dip of the normal faults, since the shear induced is always in the sense that will tend to uplift older lithosphere relative to younger. The shear mechanism also offers an explanation for the sudden onset of normal faulting. The lithosphere is uplifted faster than the axial upwelling magma, so is supported by its own shear strength, not by pressure from below (Laughton, Searle, 1979). Its strength will increase from some finite value and the shear stress within it will increase from zero with distance from the axis, and it will break at the point where the stress just exceeds its strength.

Our observations on Reykjanes Ridge tend to favour vertical shear. If horizontal tension produced the major faults, then the interplay of tension along the spreading direction and a strength gradient oblique to it would be expected to give rise to faults of some intermediate trend ; whereas in the case of vertical shear we would expect the stress gradient to be parallel to the strength gradient and therefore faults to form parallel to the ridge axis. We do observe lineaments whose mean trend is intermediate, but as explained above this appears to be a result of individual lineaments comprising a 14° trend inherited from the axial zone together with a 36° trend resulting from faulting parallel to the ridge axis.

In summary, we favour the vertical shear hypothesis, but we are forced to recognise the difficulty of transmitting shear to the brittle crust above a broad magma chamber.

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