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Morphology of the Reykjanes Ridge Crest Near 62° N

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Abstract. During the RRISP 1977 experiment FS METEOR conducted a detailed bathymetric survery of a 45 × 50 km^2 quadrangle of the Reykjanes Ridge crest near 62° N with a narrow-beam echosounder. On the basis of the profiles and a contour chart we recognize a central zone of oblique en echelon volcanic ridges filling a <30-km-wide rift valley nearly to the brim. Thus, at least in the survey area, Reykjanes Ridge does not differ from other slow spreading ridges in having no median rift at all, but only in the valley fill. The orientation of the volcanic fissures tends to be normal to the spreading direction, while the main rift faults rather follow the general ridge morphology. At 61°55′ N the sea floor features are disrupted and depressed and the physiographic character changes from north to south; this suggests a fracture zone though not a clear-cut transform fault. The preferred model is one in which the axial tensile stress leading to fissuring and volcanism is normal to the direction of plate separation (N 095°); the stress field off the axis leading to normal faulting and rift valley formation, on the other hand, is governed by the thermal boundary conditions and is thus rotated into that of the average ridge orientation.

Key words: Bathymetry – Median valley – Mid-Atlantic Ridge – Oceanic volcanism – Rifting – Transform fault.

Introduction

A detailed narrow-beam echosounder survey of the crestal region of Reykjanes Ridge near 62° N was conducted by FS METEOR with the aim to see whether features as volcanic ridges and a median valley could be resolved. Reykjanes Ridge is unusual: oblique spreading and slow spreading but with no apparent rift valley; instead, its known crestal morphology north of 61° N is rather that of a block, about 45 to 55 km wide and standing nearly 1 km above the neighbouring sea floor near Iceland (Dietrich, 1959; Ulrich 1966; Talwani et al., 1971, Vogt, 1974). The block structure is superimposed on the regional subsidence with age (e.g. Sclater and Francheteau, 1970). Between 61° N and 58° N the block gradually disappears and gives way to a well defined rift valley (Laughton et al., 1979). Between Iceland and about 57° N Reykjanes Ridge is remarkably straight, striking N 036°, i.e., about 30° oblique to the direction normal to spreading (N 005°) whose rate is about 2 cm/a (e.g. Vogt and Avery, 1974). A summary of these and other geophysical data on Reykjanes Ridge is given by Fleischer (1974).

Some of the questions we ask are: What is the style of rifting in the crestal block of Reykjanes Ridge? Is there any indication of a rift valley or major normal faults? Can we distinguish volcanic features and faults? The oblique spreading may provide a chance to separate effects of volcanism and faulting or of plate kinematics and cooling.

Data

As part of the Reykjanes Ridge Iceland Seismic Project (RRISP 1977), FS METEOR during cruise No. 45 collected 660 km of echosounder track in 4.5 km spaced profiles perpendicular to the morphological axis of Reykjanes Ridge within a 45 × 50 km^2 quadrangle centered at 62° N. 26°30′ W (Fig. 1). The survey area is just north of the region studied by Shih et al. (1978) with a deep-tow instrument package. The ELAC echosounder has a half-power beam width of 2.8° and uses signal frequencies of 15 and 30 kHz. Navigation was by the integrated INDAS IV system (PRAKLA-SEISMOS 1972) using LORAN (chains SL7W-SL7X) and updated automatically by satellite fixes. The relative position accuracy during the survey is estimated to be only a few hundred meters at most.

In Fig. 1 the original echosounder recordings are reproduced for the first four crest crossings. The direction of Profiles 1 and 3 has been reversed to permit easier visual comparison of topographic features. For reference to age of the seafloor, a generalized magnetic anomaly profile (after Talwani et al., 1971) has been superimposed on the top bathymetric record. Figure 2 shows the locations of the ship's tracks discussed, it is also a composite of simplified bathymetric profiles, corrected for ship speed to give true distance. Simplification was done by picking only the prominent high and low points and conspicuous changes in slope (I owe the readings to captain H. Feldmann who did them aboard the ship during the cruise). A comparison of Figs. 1 and 2 demonstrates the amount of simplification, features of 0.5 km extent or less are generally neglected.

A few attempts to contour the depths shown in Fig. 2 by several expedition members lead to rather similar results. Figure 3 presents as an example the contour chart of the area combining the various efforts; it is preliminary. The correlation of small features from profile to profile is, of course, ambiguous if not impossible in some cases. It is also influenced by the plausible though unproven hypothesis that the topographic features are elongated grossly parallel to the ridge axis. Some confidence in the results can be gained from the fact that several independent contouring attempts yielded similar maps. Our interpretation is also supported by observations further southwest on Reykjanes

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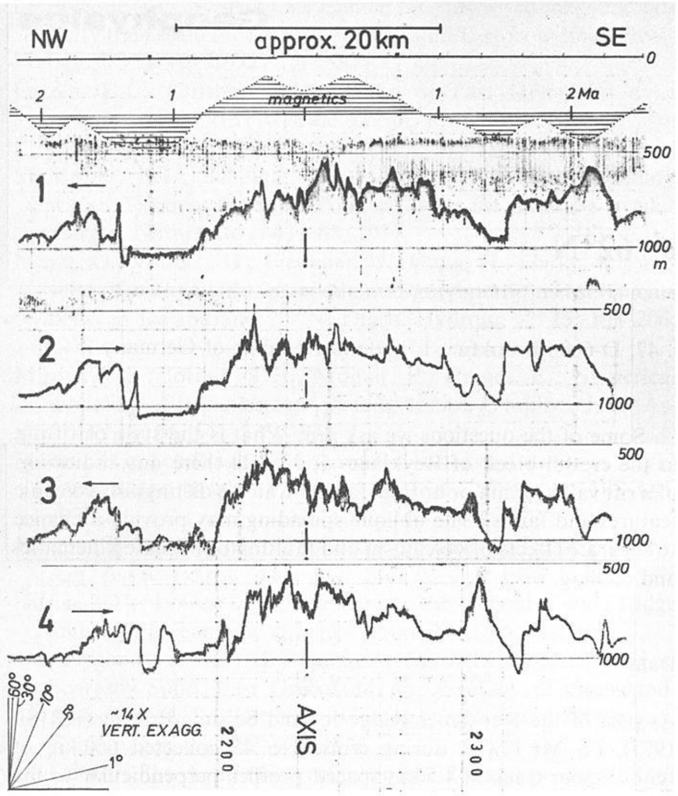

Fig. 1. ELAC narrow-beam echosounder recordings during the four northeasternmost ridge crossings. *Profiles 2 and 4* as recorded, *1 and 3* reversed for better visual correlation of features (*arrows* indicate ship's heading). *Uncorrected depths; horizontal scale:* time along ship's track (*thin vertical lines* in 10 min intervals); approximate length scale (in km) on top; vertically exaggerated slopes in left lower corner. Generalized magnetic anomaly (arbitrary scale, Profile 2 of Talwani et al., 1971) and approximate crustal age in Ma shown on top bathymetric profile

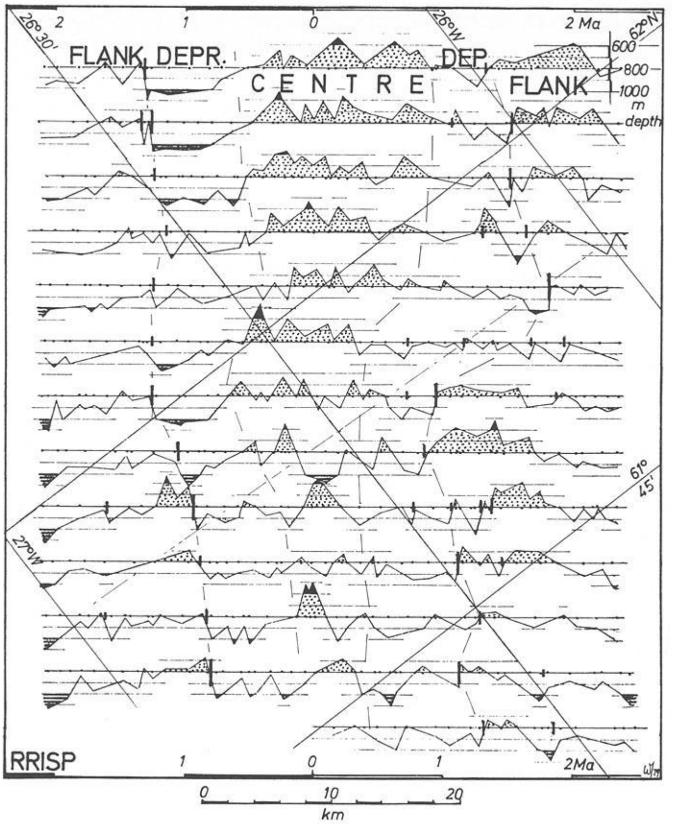

Fig. 2. Simplified echosounder profiles across Reykjanes Ridge crest. Vertical exaggeration about 9; vertical scale in upper right corner. Ship's tracks along 800 m depth lines. *Bold ticks* indicate steep slopes suggestive of normal faults (lengths qualitatively symbolize throw). Morphological provinces 'Center', 'Depression', 'Flank' separated by *thin dashed lines*. Approximate location of proposed minor fracture zone near 61°55′ N shown by *thin dash-dotted line*. Approximate crustal ages indicated at top and bottom frame

Ridge crest by Shih et al. (1978), Laughton et al. (1979), and Laughton and Searle (1979) who used side-scanning sonar. Since it 'sees' parts of the morphology in continuity, the elongated ridges and scarps are unquestionably recognized. Their results and ours are very similar, indeed.

Discussion and Interpretation of Data

With the uncertainties in mind, we shall now discuss some of the features of Figs. 1–3. We can tentatively distinguish three morphological provinces crudely symmetrical about the ridge axis. (1) A central province, about 15 km wide (in the NE), with many narrow oblique en echelon ridges often many hundreds of meters high, is bounded by (2) a series of depressions on either side; their outer borders are about 27 km apart in the NE and about 20 km in the SW where, however, the depressions are poorly defined. (3) A series of outer rises follows; generally they have steep inward facing scarps toward Province 2 (Figs. 1 and 2). The drop in topography at the margins of the survey area marks the sides of the crestal block. The three morphological provinces are tentatively marked on Fig. 2; their boundaries are indicated by thin dashed lines.

I interpret these features to represent a rift valley of normal width between the inward facing fault scarps; the valley floor is, however, abnormal in that it rises in the central region above the elevation of the rift shoulders. The en echelon ridges in this central region are interpreted to be of volcanic origin. Volcanism thus appears to be much more vigorous than in more normal median valleys. It is not clear whether this records temporal variations of volcanicity during the past 2 Ma or whether it represents a quasi-steady state process of crustal generation. The median valley is about half as wide as the so-called crestal block or horst of Reykjanes Ridge and splits it about symmetrically. The crestal block does thus not simply replace the crestal rift of more normal ridges.

The rift valley is perhaps the most conspicuous feature of the northeastern part of the survey area, but it could have been overlooked with less data density and resolution, particularly in the southwest. Very steep slopes mark the sides of the rift on all profiles and sometimes they are near vertical; they have been indicated by vertical ticks at the profiles of Fig 2 (throw and steepness are symbolized by length of the ticks). At places the faults appear to be repeated at short distance on a profile, suggesting staircase or en echelon structures. Small local grabens of a few hundred meters to a kilometer width and with elevated shoul-

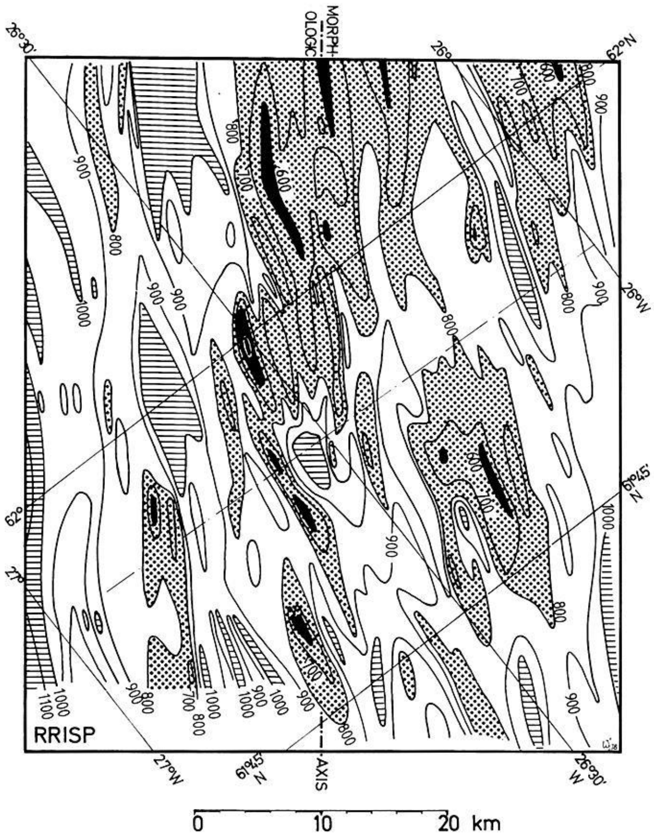

Fig. 3. Tentative depth contours of Reykjanes Ridge crestal region, on the basis of the profiles of Fig. 2. Depths in meter

ders appear to accompany some of the faults at their foot (e.g., at NW side of Profile 1, Fig. 1). This reminds us of similar features in Iceland, such as at Thingvellir.

The central region is mostly characterized by very rough, short-wavelength topography with amplitudes of tens of meters and more. Wavelengths are often less than 100 m perpendicular to the ridge (Fig. 1). This supports the interpretation that the region is of young active volcanic nature. The widths of the topographic features shown in the simplified profiles (Fig. 2) vary from a few hundred meters to several kilometers; note, however, that short wavelengths have been suppressed by the simplification. Figure 4 presents normalized frequency distributions of distances between neighbouring topographic maxima and minima ('half-wavelengths') irrespective of amplitude along all profiles in 0.2 mile or 0.36 km intervals. The left diagram covers the whole area, the others are for each morphological province separately; for depressions and flanks three diagrams are superimposed (NW, SE side, and both sides together). The dominant half-wavelength is less than 0.7 km; values between 1 and 1.5 km are half as frequent. The histograms do not differ very much from province to province, but a trend to more frequent short half-wavelengths and to very long ones can be recognized. This suggests break-up of volcanic forms by progressive fracturing and burrial of low ridges by sediments.

The en echelon ridges in the central zone typically trend between N010° and N030° and are often sub-parallel to the direction normal to spreading (N005°) but oblique to the general ridge morphology (N036°). In contrast, the scarps which are interpreted to be flanking the rift valley mostly trend N020° to N040°, sub-parallel to the ridge at large. There is distinct asymmetry in the ridge morphology. The depressions and the outer rises are more clearly developed on the NW flank than on the SE one. In the NW the inward facing escarpment of the outer rise can be followed through the whole survey area, but in the SE it is split up and irregular. There is generally a trend of topography rising toward SE; this is related to two prominent culminations on the SE side, one near 62° N, 25°55′ W, the other near 61°50′ N, 26°20′ W, with approximate dimensions of 8×20 km^2. On the NW side there is a smaller (3×10 km^2) topographic culmination near 61°55′ N, 26°48′ W. In size and shape these features are reminiscent of the volcanic centres of Iceland.

There are marked changes along the ridge axis, too. Mean water depth increases toward SW from <800 m to >800 m. NE of about 61°55′ N, 26°30′ W the central province is composed of a fairly regular series of volcanic ridges; to the SW its topography is more irregular with one dominant central high ridge. The change is rather abrupt and is marked by a hole about 1,100 m deep; near latitude 61°55′ N there is, in fact, a rather clear dividing line along which the topography is generally depressed indicated in Figs. 2 and 3. The presumed rift valley seems to narrow at this line abruptly (Fig. 2) and the morphological character changes. I interpret the dividing line to represent a poorly developed fracture zone along which some features seem to be offset by up to 15 km right-laterally, while other features as the central volcanic zone change more gradually. This is not unexpected for small fracture zones or transform faults (Courtillot et al., 1974; Macdonald, 1977; Macdonald and Luyendyk, 1977).

Support for the transform may come from the magnetic anomaly map of Heirtzler et al. (1966) which at its NE border contains our survey area. The anomalies are somewhat disturbed along 61°55′ N to the west from the axis out to anomaly 5, i.e., to about 10 Ma age. Other similar disturbances on Heirtzler's map seem to come and go on a somewhat shorter time scale and quite irregularly. The map does not resolve details as 10 km transforms (and corresponding normal spreading segments, some 20 km

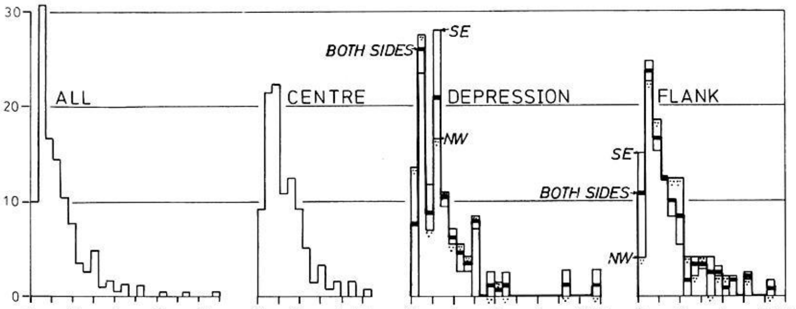

Fig. 4. Frequency distributions of horizontal distances between neighbouring topographic maxima and minima of all profiles of Fig. 2, for whole region and for the three morphological provinces (Fig. 2), separately; for 'Depression' and 'Flank' histograms for either side and both sides combined, superimposed with different symbols. The histograms are normalized to same area. 'Half-wavelengths' in 0.2 mile or 0.36 km intervals

long), but there is an indication of similar disturbances of the straight-axis oblique spreading (Shih et al., 1978).

For a discussion of the tectonics of the area it would be interesting to relate seismicity to morphology by plotting the epicenters of earthquakes on Figs. 2 or 3. Unfortunately the published data are not sufficiently accurate for a meaningful comparison with features of a few kilometers extent. A study with an array of ocean bottom seismometers would be most useful.

Model of Reykjanes Ridge

The most important results are summarized as follows. (1) As other slow-spreading ridges, Reykjanes Ridge, at least near 62° N, has a median rift of normal width. (2) The rift valley is about half as wide as the crestal block or horst of Reykjanes Ridge at 62° N. (3) The valley is largely filled with a great quantity of volcanics, the floor thus rising near the center above the rift shoulders. (4) As on the Reykjanes Peninsula of Iceland, the volcanic ridges in the rift valley and the feeder dykes are arranged en echelon and have the tendency of striking normal to the spreading direction or at least at directions intermediate between the spreading normal and the morphological Reykjanes Ridge axis. (5) In contrast, the normal faults bounding the rift valley have the tendency (or at least a stronger tendency) of striking subparallel to the ridge axis. (6) A small fracture zone has been recognized near 61°55′N. (7) As in Iceland volcanic centers may occur on Reykjanes Ridge.

We can take advantage of the oblique spreading and try to separate the sources of stress causing the fissuring and the normal faulting and rifting. An intuitive model is suggested by Fig. 5. If the stress field in the volcanic zone is tensile normal to plate separation, we should expect here a relatively broad region of very thin lithosphere above a magma chamber or a series of magma chambers. In this zone the stress field would essentially be in reaction to plate kinematics; principally this agrees with Tapponnier and Francheteau's (1978) necking model. The least principal stress would be actually directed outward in the direction of plate divergence. As we go outward we get to a region where cooling becomes the dominant process with rapid thickening of the lithosphere. Since cooling is governed by the boundary conditions, i.e., the geometry of the 0° C isotherm at the sea floor and the axial inflow of hot magma, it is plausible that the principal stresses are rotated from the spreading direction into that of the broad ridge morphology. Still near the culmination of topography, the minimum principal stress is directed normal to the ridge axis, but it need not be negative, i.e., truly tensile; over the depth range of faulting the maximum principal stress is vertical. As a result normal faults form, striking parallel to the ridge axis. Normal faulting with the axial side down is furthered by the volcanics loaded onto that side (Pálmason, 1973; 1980; Cann, 1974). Farther from the axis, down-hill compression in the lithosphere will build up with the topographic gradient, but that is outside the scope of this paper.

Figure 5 addresses itself also to the question why Reykjanes Ridge changes along its axis. In a gross sense this will be related to the balance of tectonic (with sources outside), gravitational, and viscous forces acting on the lithosphere and asthenosphere of the ridge (Sleep, 1969; Lachenbruch, 1973; 1976; Collette et al., 1980). Higher asthenospheric temperatures and melt contents or smaller viscosity would allow the asthenosphere to rise with less restriction than large viscosity would. The change in viscosity and temperature along Reykjanes Ridge may be related to the closeness to Iceland and to horizontal flow (e.g., Vogt, 1974). Vigorous volcanism corresponds to high temperatures and melt contents; at the same time it leads to fast loading of the crust and to subsidence of the rift valley floor (Pálmason, 1973; 1980; Cann, 1974). Detailed studies of slow spreading ridges with less vigorous volcanism and hence a more pronounced rift valley (mainly in the FAMOUS area of the Mid-Atlantic Ridge at 37° N: Ballard and van Andel, 1977; Ramberg and van Andel, 1977; Ramberg et al., 1977; Luyendyk and Macdonald, 1977) support the present model.

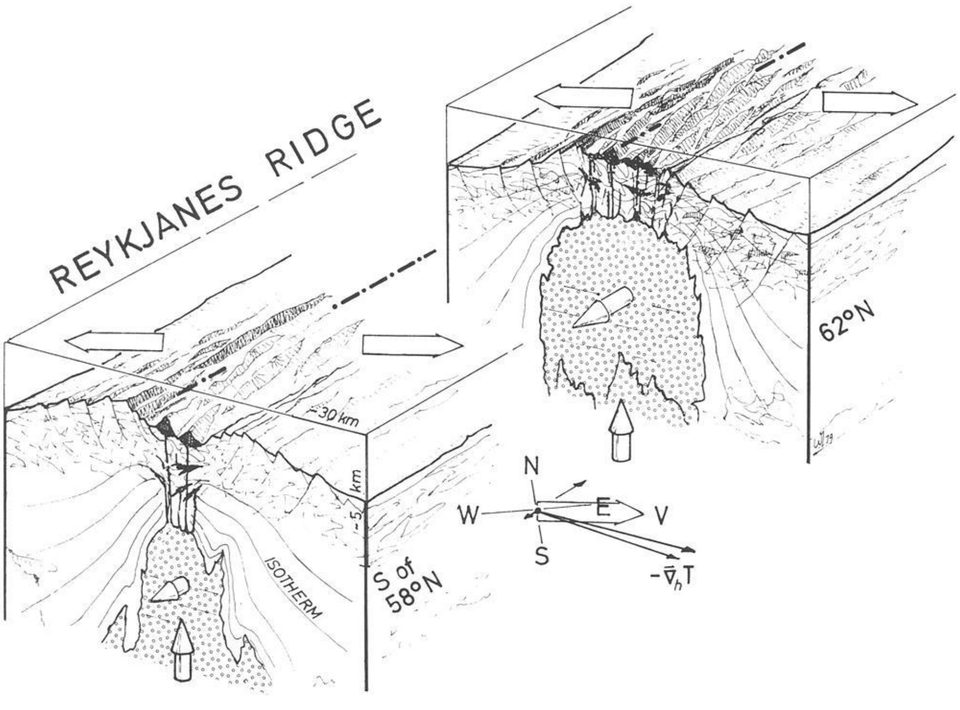

Fig. 5. Cartoon of Reykjanes Ridge model (approximate length scale at 'front corner'): solidified lithosphere, fissures, volcanic ridges, normal faults, isotherms, magma chamber or volume of crystal mush, flow (*round arrows*) partly upward, partly southwestward away from Iceland, oblique spreading direction (N095°, *flat arrows*); horizontal temperature gradient, $\nabla_h T$: shown in wind rose, nearly perpendicular to ridge axis. Righthand block depicts situation near 62° N; lefthand block further south (e.g. south of 58° N). For discussion see text

The crestal horst of Reykjanes Ridge has sometimes been looked upon as replacing the crestal rift usually found on slow-spreading ridges. From our data this appears to be wrong. The existence of a normally wide rift on top of the wider horst block suggests that they are two fundamentally different things, not only different in shape and mutually exclusive. As pointed out by Vogt (1971, 1974) the block is in plan view V-shaped and diachronous or time-transgressive. It is thus believed not to be steady-state (although it might be, if conditions change along the ridge), but rather to record time-varying discharge from the Iceland plume. We shall not discuss Vogt's hypothesis which we cannot prove or disprove, but we note the difficulty of interpreting features as the ones presented if we do not know their history.

Conclusions

The narrow-beam echosounder has proven very useful in studying the morphology and tectonics of the Reykjanes Ridge. It must be noted, however, that we have used only a small part of the information available from the echosounder records. More of the information should be used in the future and a more detailed and thorough interpretation is postponed till then. The combination with other data will also be helpful.

The 4.5 km spacing of the profiles has turned out to be not sufficient to achieve an unambiguous mapping of the topography of the ridge. Future work has to take this into account. In spite of the shortcomings, however, the present preliminary interpretation seems safe enough to present it to the critical reader.

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