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ICELAND IN RELATION TO THE MID-ATLANTIC RIDGE

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Introduction

The location of Iceland astride the axis of the Mid-Atlantic Ridge gives to it in many ways a unique role in the study of processes taking place at the mid-ocean ridge crests. If ocean-floor spreading is taking place in the way envisaged by plate tectonics then Iceland must be splitting apart also. The geological evidence for such a process is suggestive but opinions are still divided on whether it is conclusive or not, as far as Iceland is concerned. In any case the process would probably be more complicated there than in the adjoining submarine segments to the north and to the southwest of Iceland. This is clearly indicated by the prominent topographic high of Iceland as well as by the belt of earthquake epicenters (Fig. 1) which follows the crests of the Reykjanes and Iceland-Jan Mayen Ridges but takes a detour on crossing Iceland.

Iceland has traditionally been described as a part of the Brito-Arctic or Thulean basalt province, of which the basalt areas in Greenland, the Faeroes and Scotland were also a part. With the knowledge gained in the last one or two decades about the basaltic nature of the oceanic crust it appears more natural to consider Iceland as a part of the oceanic basalt province, a part which by virtue of the nature of the underlying crust and mantle is elevated to its subaerial position. The two prominent neighboring topographic features, the seismically and volcanically active Mid-Atlantic Ridge crest and the aseismic Greenland-Iceland-Faeroes Ridge, must enter into any hypothesis to explain the elevation of Iceland relative to the deeper basins to the south and northeast.

The hypothesis of ocean-floor spreading and plate tectonics has in recent years given a great impetus to geonomic studies of Iceland and the surrounding ocean areas. Bathymetric, magnetic, gravity and seismic reflection surveys have been carried out on the Reykjanes, Iceland-Jan Mayen and Iceland-Faeroes Ridges (3,19,35,45,49,56,57,68,105,118,120) and such surveys are in progress on the insular shelf surrounding Iceland. Seismic refraction studies have been made on the Reykjanes and Iceland-Faeroes Ridges (19,34,105) and on parts of the insular shelf (77). Aeromagnetic surveys have also been carried out over large parts of the ocean between Greenland and Europe (6). Heat flow measurements (53,105) and rock dredgings (23,62) have been made on the Reykjanes Ridge and the chemistry of the rock samples studied (87). On land various lines of research have been followed. Some of the earlier work has been summarized by Thorarinsson (108), Sigurgeirsson (94) and in Björnsson (12). Geological studies comprise mapping in the active zones of rifting and volcanism as well as mapping of the older rocks in various parts of the country (13,27,32,44,58,60,81,84,85,91,92,122,123,127).

Central volcanic complexes are being studied in both environments - in the active zones particularly in relation to geothermal areas, which are energy sources of potential economic importance (2,14,21,39,46,47,81,84,91, 109,124). Petrological and geochemical studies of basalts and acid rocks are in progress (54,55,74,96,97,110). Regional heat flow has been mapped (76,78). Crustal structure and thickness has been mapped by refraction seismology (7,75,77). Aeromagnetic surveys are in progress (89,95). A new systematic gravity survey has been completed (unpublished). Crustal and upper mantle electrical conductivity has been mapped (50). Studies of magnetic properties of basalts are in progress (63,64). Absolute age determinations are accumulating (22,33,40,48,67,70,73,93,106). Four different groups are attempting to measure directly crustal movements in the active zones (24,42,115,116). Studies of microearthquakes have been carried out on an increasing scale in recent years (61,129,131). The above studies are carried on by both Icelandic and other scientists, sometimes as cooperative projects.

The purpose of this paper is to review the present state of knowledge pertaining to geological processes at the crest of the Mid-Atlantic Ridge in Iceland. The presentation will be problem-oriented rather than by diciplines.

The surface geology will be discussed first, then evidence on the nature of the crust and thereafter on the mantle. Finally the problem of crustal drift in Iceland will be discussed.

Surface geology.

Iceland is composed almost entirely of subaerial Cenozoic basalts with some 10% of acid and intermediate rocks. The active zone of rifting and volcanism (Fig.2), also loosely called the Neovolcanic zone or the median zone, crosses the country in a complex pattern from southwest, where it connects with the Reykjanes Ridge axis, to the northeast, where it connects along an oblique offshore zone with the Iceland-Jan Mayen Ridge (also called the Kolbeinsey Ridge). The median zone is flanked by strips of Quaternary flood basalts followed by Tertiary flood basalts which often have gentle dips towards the active zone. The presently available K/Ar age determinations (Fig.3) indicate a trend of increasing age with distance from the active zone of rifting and volcanism, the oldest rocks dated at 16 m.y. being found in northwestern Iceland and in eastern Iceland.

The zone of rifting and volcanism displays a great variety of volcanic forms, cut by numerous faults and open fissures running mainly NE-SW in southern Iceland with a more northerly trend in northern Iceland. The predominant type of volcano is the monogenetic eruptive fissure which may reach a length of several kilometers or even a few tens of kilometers. The products of the fissure eruptions are usually basaltic lavas which may flow over distances of tens of kilometers. Shield volcanoes are also fairly common (58) and are probably closely related to the eruptive fissures (128). The other main type is the central volcano which in contrast to the eruptive fissure is a site of repeated eruptions in a relatively small area, sometimes distinctly grouped around a central vent. The life span of a central volcano has been estimated 0.5 - 1.0 m.y. (73,79). Most of the acidic rocks in Iceland are associated with the central volcanoes. However those located in the SW and NE appear to have less acidic rocks associated with them than those located farther inland. The Reykjanes peninsula lacks well defined central volcanoes and the acidic rocks altogether. This might reflect changes taking place along the Mid Atlantic Ridge leading to the presumabl purely basaltic volcanism of the ridge crest farther south and north. During the glacial periods the changed external conditions have modified the volcanic forms, giving rise to table mountains and hyaloclastite ridges which have formed over central vents and fissures respectively.

Eruptions in historical times (about 1100 years) are relatively well documented (e.g. 107,109). It is estimated that about 30 volcanoes have been active in historical times, and about 200 during Postglacial time (108). The most recent eruption is on Heimaey just off the south coast (55,110). At the time of writing it has been going on for two months. The rate of production of eruptives and its variation along the active zone has been studied by Jakobsson (54), who estimates that about 480 km^3 have been erupted during Postglacial time or on the average 0.048 km^3/yr. Most of this volume was erupted within the eastern zone with a maximum productivity just south of central Iceland where it may be 4-5 times higher than at the southwestern and northeastern ends of the zone. The average productivity per unit length of the zone is about 1.4×10^{-4} km^3/yr km. The relatively high productivity near central Iceland correlates well with the relatively great crustal thickness on the Iceland-Faeroes Ridge which was deduced by Bott et al (19).

Studies of the northeastern zone of rifting and volcanism have shown that the central volcanoes are located in the middle of NNE-SSW trending swarms of faults and eruptive fissures which have their highest intensity near the center but diminish in both directions away from the central volcano (83,85). Several such swarms have been identified in other areas such as Reykjanes and in the eastern zone as well. This distribution is in good agreement with the swarm distribution of dikes passing through central volcanoes as observed in the eastern Iceland Tertiary basalts by Walker (123)

A lenticular structure of the lava pile has been pointed out by Gibson (43) and Gibson and Piper (44). The controlling mechanism of this structure is seen in the grouping of central volcanoes and dike swarms into units which would produce a lenticular shield-like pile of lavas in a given period of time. The structural pattern of the active zones with their central-volcano fissure-swarm couples rather emphasizes the significance of this observation.

The zone of rifting and volcanism is a locus of high heat flow as evidenced by the 15-20 high-temperature[1] geothermal areas distributed more or less uniformly along the zone (Fig. 2). Many, but not all, the high-temperature areas are associated with central volcanoes, the Reykjanes peninsula being a notable exception. The heat source is probably the general long-term heating of the crust by dikes and other intrusions associated with the volcanism.

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[1] A high-temperature geothermal area is here defined as a hydrothermal circulation system with a subsurface temperature over 200°C at less than 1000 meters depth.

The conductive heat flow within the zone can usually not be deduced directly from geothermal gradients in shallow holes because the subsurface temperature field is disturbed by water movement in the relatively permeable zone of rifting. Meteoric water may flow for distances of the order of 50 km (4), driven mainly by a hydrostatic pressure difference due to elevation variations.

Of particular significance with respect to mid-ocean ridge processes is the Reykjanes high-temperature thermal area, located in the axial zone at the tip of the Reykjanes peninsula (13,112). Exploration by drilling to 1750 meters, where a temperature of about 290°C has been measured, has shown that sea-water percolates to a depth of a few kilometers. This process will modify the temperatures in the upper part of the crust, and it may be responsible for the relatively large scatter in heat flow values at the mid-ocean ridges, as was suggested by Pálmason (76).

Rough estimates of the total heat output of the high-temperature areas in Iceland (15) indicates that per unit length of the volcanic zone it amounts on the average to 15 MW/km. The average heat output of extrusive volcanism is about 20 MW/km.

The most detailed studies of the deeply incised older flood basalts have been made in eastern Iceland by Walker and his collaborators and a similar survey by the second author of this paper is in progress in SW -Iceland. The basalt lavas have a regional dip towards the volcanic zone increasing from near-zero at the top of the pile to 5-10° at sea level (Fig. 4). This was interpreted by Walker (122,123) as being due to a gradual sagging down of the pile by the accumulation of volcanics in an active zone. The basalt lavas are cut by numerous dikes distributed unevenly in swarms and decreasing in number upwards in the pile. From a study of secondary mineral zoning and an upwards extrapolation of the dike intensity to a zero value, Walker (123) deduced the original top of the lava pile to have been at an elevation of about 1500 meters in the area studied by him.

Tr. Einarsson (27) has studied the structure of the Tertiary lava pile in some other parts of Iceland. In many respects his results are similar to those of Walker for eastern Iceland. The dips are usually smallest in the uppermost part of the pile, increasing downwards, sometimes jumpwise across discordances. The directions of the dips do not however show as clear a relationship to the presently active volcanic zones as do the dips in most of southwestern and eastern Iceland (cf Fig. 2). Different from Walker, Einarsson (31) concludes that the relatively steep dips in the lower part of the Tertiary basalt pile were caused by a major tectonic phase after the main bulk of the pile had been formed. There are certain difficulties associated with this interpretation as will be discussed later.

It appears likely that the volcanism has been continuous from the Tertiary through Pleistocene and Postglacial times (108), although the pattern of the active zones may have changed. A prominent flexure of the Tertiary flood basalts in eastern Iceland (125), traceable all along the western border of the Tertiary outcrops, has been identified with a major discontinuity of the stratigraphic succession in this area (85). Stratigraphic correlations, age determinations and evidence from detailed studies in northeastern Iceland across this area suggest that the eastern volcanic zone is a relatively young feature formed perhaps 4 m.y. ago. Low heat flow values in eastern Iceland also support this conclusion. They indicate, when interpreted in terms of a cooling lithospheric plate moving away from a zone of crustal accretion, that the eastern Iceland lava pile is older than corresponds to its distance from the present eastern zone (78). The general pattern of dips of the Tertiary flood basalts (Fig.2) shows a certain synclinal symmetry about two or perhaps three zones. This points to a more complicated history of crustal accretion than indicated on the Reykjanes Ridge. A similar shifting of the spreading axis in the area between Iceland and Jan Mayen is indicated by bathymetric and magnetic data in that area (57,68).

The Snaefellsnes volcanic zone in western Iceland is somewhat of an anomaly with regard to the main zones of rifting and volcanism. The Recent and Pleistocene volcanics form an east-west lenticular pile resting unconformably on tilted Tertiary basalts (92). Volcanic activity has been confined mainly to three lines arranged en echelon with a WNW-ESE direction. Tensional open fissures which are common in the main SW-NE zones of rifting, are scarce or non-existent, but numerous dip-slip faults occur. The

Snaefellsnes zone is aseismic and heat flow is low as evidenced by drillhole measurements (78) and lack of major geothermal areas. The alkalic and transitional basalt volcanism (54,91) in contrast to the tholeiitic basalts of the main zones also points to a different state of the upper mantle.

Sigurdsson (92) has suggested that the Snaefellsnes zone is a transcurrent fault-zone generated by differential spreading rate in north and south Iceland. So far, however, the evidence given by magnetic anomaly patterns southwest and north of Iceland does not indicate greater changes in spreading rate with latitude than expected on the basis of the assumed pole position for the movement of the North-American-European plates (57). It is likely nevertheless that the Snaefellsnes zone is in some way related to the prominent change in strike of tectonic features taking place at about 65° N latitude. A major change in crustal thickness across this zone is indicated by the available seismic refraction data (77).

Several active fracture zones have been suggested in Iceland (86,103,129,130), mainly on the basis of earthquake epicenter distribution and changes in the tectonic pattern and strike of the volcanic zones. Of these the Tjörnes fracture zone near the north coast appears to be the best founded. Its existence is supported by earthquake distribution, submarine topography, strike-slip faults on land, and offset of the volcanic zone (85).

Crustal structure.

Evidence for the deeper structure of the crust comes mainly from geophysical data which must be interpreted with due regard to surface geology. The geology of Iceland suggests that the crust is basaltic, although the relative abundance of acidic rocks and the elevation relative to the surrounding ocean floor has led to suggestions that the visible basalt pile might be underlain by a continental sialic fragment (9,10,52,117).

Relatively detailed seismic refraction measurements have been carried out in the last 15 years to study the seismic velocity structure of the crust and its thickness (7,77). A characteristic layering has been found, resembling the oceanic crust in velocity values, but thicker (cf Fig. 6). The lowest seismic velocities, 2.0 - 3.3 km/sec , are found in the active zone of rifting and volcanism for near-surface rocks apparently consisting of a mixture of recent lava flows, hyaloclastic tuffs and breccia. This formation, termed layer 0, reaches a maximum thickness of about 1000 meters. Drillholes to a maximum depth of 1750 meters in the Reykjanes thermal area show that this formation, seismically determined to be about 900 meters thick, consists there mainly of hyaloclastic tuffs and breccias and tuffaceous sediments, with basalt lavas as a minor component (13,112). These rocks are believed to have been erupted under subaerial conditions or at shallow water depth.

The Tertiary and Quaternary surface basalts on both sides of the active zone have a distinctively higher velocity values, averaging about 4.1 km/sec (layer 1).

This velocity group is also found beneath the low-velocity surface layer in the active zone. Surface geology indicates that it consists mainly of basalt lavas with relatively minor intercalated sedimentary and tuff layers. Drillholes on the Reykjanes peninsula indicate that it may contain an appreciable amount, perhaps up to 50%, of tuffaceous rocks. The thickness of this layer is usually 0.5 - 2.0 km with an average value about 1.0 km.

At greater depth the velocity increases to about 5.2 km/sec on the average (layer 2). This group is exposed only in a small area in southeastern Iceland where it consists of basaltic lavas mixed with basic and acid intrusions. From its relatively shallow depth in many of the old flood basalt areas it appears likely that it is composed mainly of flood basalts. Its thickness is usually in the range 1-3 km with an average value close to 2.1 km.

The three seismic layers discussed above can apparently be correlated with known surface or near-surface rock formations. The underlying layer 3 with a P-wave velocity of about 6.5 km/sec is found beneath the whole of Iceland but nowhere at the surface. The depth to its upper boundary has been mapped in some detail (Fig. 5) and found to be quite variable, usually in the range 1-5 km but in one area reaching 10 km. No simple relationship to the active volcanic zones is evident, but in several cases a shallow depth to layer 3 coincides with major central volcanoes.

Layer 3 in Iceland is probably to be equated to the oceanic layer although the average P-wave velocity in the oceanic layer is commonly given as 6.7 - 6.8 km/sec. The lower velocity in the Icelandic crust can not be explained wholly by higher temperatures. On the Reykjanes Ridge Talwani et al (105) showed the existence of layer 3 with a velocity close to 6.5 km/sec in agreement with the Icelandic results. The thickness of layer 3 in Iceland is usually in the range 4-5 km, but from a limited amount of data a larger thickness is indicated in northern Iceland (77).

There seems little doubt that layer 3 in Iceland is essentially basaltic in nature. Earlier ideas about a sialic substratum receive no support from recent geophysical and geochemical evidence, rather the contrary. Poisson's ratio of layer 3 (75,77), Sr isotope ratios of basic and acid rocks (69,74,90) and Pb isotope ratios (132) all argue against a sialic substratum beneath Iceland. The acid component of central volcanism appears best explained by fractionation from a basaltic parent, either by fractional crystallization (21,91) or by fractional melting of the lower crust (46,97). All these results support the decision of Bullard et al (20) to omit Iceland when fitting together the continents across the northern Atlantic.

The cause of the higher velocity in layer 3 in Iceland relative to the overlying rocks is not well understood. From a comparison of the depth to the upper boundary of layer 3 with crustal temperatures as inferred from borehole data, Pálmason (77) suggested that a temperature-dependent process, perhaps metamorphism of the basaltic rocks, might be responsible for the increase in velocity in layer 3. A similar view had earlier been expressed by Einarsson (28) who pointed out that the seismic boundaries, which in many places are nearly horizontal, cut across the stratigraphic horizons given by the surface lavas dipping 5-10°.

Another possibility is that layer 3 in Iceland is largely composed of intrusives associated with the volcanism (16,43,44). There is little doubt that the volume fraction of intrusives, mainly in the form of dikes, increases downwards in the crust. Model calculations of crustal growth by dike injection and surface lavas show that the lower crust in Iceland should consist almost entirely of intrusives (78) (cf Fig.8). The steady-state model, however, requires the intrusives fraction to be elevated in the zone of volcanism relative to the adjacent lithospheric plates. No such elevation in the upper boundary of layer 3 in the active zone in Iceland is indicated by the available seismic data. This throws some doubt on the hypothesis that the intrusives as such are causing the increase in seismic velocity.

Perhaps the correct geological interpretation of layer 3 is to be sought in a combined effect of intrusives and some temperature-dependent effect, such as metamorphism or filling of pore space in the surface lava formations as they subside under the load of new lavas erupted in the active zone. It may be significant that with many central volcanoes, both Tertiary and younger ones, is associated a positive gravity anomaly and a relatively shallow depth to layer 3. The density difference between layer 3 and the overlying flood basalts has been estimated to be about 0.2 g/cm^3 (77). It is well known that the intrusives fraction beneath central volcanoes is relatively high and the strong metamorphism associated with them (123,125) also indicates rising of the isothermal surfaces in the crust during their period of activity.

It should be remarked here that the hypothesis of Hess (51) that layer 3 (the oceanic layer) consists of serpentinized peridotite is contradicted by the available evidence on crustal temperatures in Iceland. According to Hess the serpentinization can not take place at temperatures above about 500°C. The lower part of layer 3 is in many parts of Iceland inferred to be at a temperature of 500-1000°C on the basis of extrapolated borehole temperatures (77,78).

Magnetic surveys have played a key role in the development of ideas of sea-floor spreading and plate tectonics. Iceland might offer a clue to what geological structures may possibly be causing the anomaly patterns commonly found. The well-known Reykjanes Ridge magnetic pattern (49,105) continues towards the SW-corner of Iceland, and the strong positive central anomaly can be followed continuously along the volcanic rift zone on the Reykjanes peninsula towards Langjökull (cf. Fig. 6). This continuity has been shown clearly by the aeromagnetic surveys of Sigurgeirsson (95). Strong linear anomalies are also observed over the eastern volcanic zone (Sigurgeirsson, unpublished).It should be noted also that on both sides of the active zone northeast of the Reykjanes peninsula Matuyama and Gauss epoch rocks (79) correlate fairly well with the corresponding magnetic anomalies on Sigurgeirsson´s map (95). Correlations of linear anomalies with magnetic stratigraphy attempted by Piper (80) for northeastern Iceland on the basis of Serson et al (89) are dubious in the light of recent studies in that area (85).

Magnetic surveys over the Iceland-Jan Mayen Ridge (68, 119,120) show that a magnetic pattern with a strong central anomaly exists there also. The continuation of the axial anomaly into Iceland (68,89) is not as clear as in southwest Iceland. South of about 67°N two or three strong positive linear anomalies appear to be present (68).

Talwani et al (105) concluded on the basis of correlations of magnetic field variations with topography on the Reykjanes Ridge that the magnetization responsible for the anomalies resides mainly in the top 400 meters of the basalt layer. To explain the strength of the central anomaly it is then necessary to assume a stronger magnetization in the axial zone. Some evidence in support of this is available from dredged rock samples (23). Observations in Iceland do not appear to support the assumption that such a thin, highly magnetized layer is responsible for the magnetic anomalies. Kristjánsson (64) studied the magnetic properties of drill chips from up to 2000 meters deep boreholes in southwest Iceland. The magnetic properties reside primarily in magnetite, and a lack of a downward trend in magnetite content indicates that a 2 km thick layer at least may be responsible for the magnetic anomalies in Iceland, including the Reykjanes peninsula. The two results, however, may not be incompatible, because a different upper crustal structure may be expected in the two areas, due in part to the larger production rate of extrusives in the Iceland area.

Strong isolated magnetic anomalies are often found associated with major central volcanoes in Iceland. The best known of these is the Stardalur magnetic anomaly in southwest Iceland (38,95,101). A study of chips from a 200 m deep borehole revealed the presence of highly magnetic tholeiitic lava flows. A combination of a high magnetite content and a high paleofield strength is considered to be responsible for the 10-20 times higher magnetization than found on the average in Icelandic basalts of a similar age.

The upper mantle.

In revealing the state and structure of the upper mantle beneath Iceland, seismic, gravity, heat flow and magnetotelluric data are significant as well as geographical variations in the chemical composition of extrusive rocks. This evidence will be reviewed below.

The anomalously low seismic velocities in the upper mantle beneath much of the North Atlantic between Greenland and Europe were already evident in the early refraction measurements of Ewing and Ewing (34). Between 56°N and 72°N 6 profiles gave velocities in the range 6.9 - 7.7 km/sec and only one profile, located in the Norwegian basin, yielded a value over 8.0 km/sec. The thickness of the overlying crust was in the range 3-5 km. None of these profiles was close to Iceland or the Iceland-Faeroes Ridge. Relatively detailed refraction measurements in Iceland and on the insular shelf off the south and west coasts (7,77) have shown that the P-wave velocity in the uppermost mantle is close to 7.2 km/sec , and the crustal thickness, i.e. the depth to the 7.2 km/sec velocity, varies from 8-9 km in southwest Iceland to 14-15 km in southeast Iceland (Fig. 6) and possibly also in northern Iceland. A single reversed profile about 200 km southeast of Iceland south of the Iceland-Faeroes Ridge gave an upper mantle velocity of 7.1 km/sec and a crustal thickness of only 4.6 km (19). On the Reykjanes Ridge upper mantle wave velocities of 7.3 - 7.4 km/sec are found below a 3-5 km thick crust (105).

Francis (36) used the travel times of body waves from earthquakes to the north and southwest of Iceland to deduce the velocity distribution beneath the ridge axis through Iceland. He deduced a linearly increasing velocity from just over 7.0 km/sec in the uppermost mantle to about 8.0 km/sec at about 250 km depth. From velocity variations along different paths he also estimated the width of the deep anomalous zone to be 300 km. This is significantly narrower than Tryggvason´s (113) estimate of 1000 km, which was based on a study of only four earthquakes.

The residuals of arrival times of distant earthquakes to receiving stations in Iceland, as compared with standard travel-time tables, have been used by Tryggvason (114) and Long & Mitchell (65) to study the upper mantle structure. A time delay of at least 1 sec is found to be associated with the upper mantle. This can be explained by a low upper mantle velocity of about 7.4 km/sec extending to a depth of 200-250 km. The study by Long & Mitchell (65) which is based on four receiving stations indicates that there are no major variations in the time delay over Iceland itself.

The ratio of P to S velocities may be an indicator of the state of the upper mantle. No detailed studies of this ratio have been made, but the work of Francis (36) indicates a ratio of about 1.89, a value which is considered typical for the low-velocity zone beneath the lithosphere. A normal value for the oceanic upper mantle is about 1.76. The crust beneath Iceland has a P to S velocity ratio of 1.78-1.80 with no significant variation between the crustal seismic layers (75,77). The higher value which is indicated in the upper mantle beneath Iceland suggests a state of partial fusion.

The regional gravity field in Iceland and the surrounding ocean gives significant information regarding the upper mantle. Both satellite data and terrestrial gravimetry show that the free-air anomalies are positive over much of the ocean between Greenland and Europe and over Greenland as well (59,104,105). The free-air anomalies average about 50-60 mgals on the ridge segments south and north of Iceland (35,68,105), and 40-50 mgals on the Iceland-Faeroes Ridge (19,35). From the available data the free-air anomalies appear to decrease somewhat over the basins south and northeast of Iceland. Over Iceland they are similar or somewhat higher than on the adjoining ridges, indicating that Iceland may be at the center of the regional positive gravity anomaly located in the northern part of the North Atlantic.

The Bouguer anomalies are essentially reflected in the topography since isostatic equilibrium prevails for large scale topographic features. The lowest Bouguer values are found in central Iceland, about -30 milligals (26). Towards the coast of Iceland the values increase to +40 to 50 mgals. At the crest of the Reykjanes Ridge the Bouguer anomaly increases southwards reaching 180 mgal at 54°N (35,105). North of Iceland the Bouguer anomaly is about 120-140 mgal between 68° and 70°N (68). On the Iceland-Faeroes Ridge the Bouguer anomaly rises gently to a value of about 110 mgal towards the Faeroe Islands (19). In the deeper basins south and northeast of Iceland the Bouguer values are still higher, in the range 150-200 mgals.

The available seismic refraction measurements indicate that only a minor part of the Bouguer variation can be attributed to variations in crustal thickness. The major part is then most likely caused by inhomogeneities in the density of the upper mantle. The outward increase from central Iceland appears to be relatively smooth, judging from the Iceland-Faeroes profile (19) which does not indicate a deep seated structure associated with the present coastline of Iceland or the edge of the surrounding insular shelf.

To explain the Bouguer minimum Bott (17,18) suggested that it could be caused by partial fusion in the upper mantle resulting from a decrease in confining pressure in a rising mantle limb. A 10% partial fusion would lead to a density reduction of about 0.03 g/cm^3. If the density contrast extends over a depth range of 200 km, the corresponding Bouguer anomaly could reach about -250 mgal which is of the same order as the Bouguer minimum in Iceland relative to the surrounding ocean areas.

An estimate of the viscosity of the upper mantle may be obtained by studying the rate of glacio-isostatic rebound of Iceland at the end of the ice age. From a comparative study of Iceland and Scandinavia Tr. Einarsson (29) concluded that the viscosity of the upper mantle beneath Iceland was an order of magnitude lower than beneath Scandinavia.

The regional heat flow in Iceland gives direct indications as to the state of the upper mantle. Although the surface heat flow is often disturbed by the movement of water giving rise to the geothermal areas, it appears nevertheless possible to discern a certain pattern of conductive heat flow with high values (up to 7 HFU[1]) near the volcanic zones (cf Fig. 6) and lower values (down to 1.7 HFU) at greater distance from them. On the basis of the available regional heat flow data and model calculations of crustal heating by dike intrusions in the volcanic rift

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[1] 1HFU = 1 microcal/cm^2 sec ≈ 42 mW/m^2

zone, Pálmason (77,78) concluded that the solidus of basalts was reached at a depth of 10 km or less beneath the volcanic zone in SW-Iceland. This implies that the uppermost mantle as defined by the 6.5/7.2 km/sec boundary, located at a depth of 8-9 km, is at a temperature close to the solidus of basalts. It will be noted that the thermal gradient inferred for the active zones in Iceland is very similar to the gradient deduced by Gass & Smewing (41) for the Troodos Massif on the basis of secondary mineral zoning. A similar or slightly lower gradient was inferred by Ade-Hall et al (1) for the eastern Iceland lava pile, also on the basis of secondary mineral zoning.

Magnetotelluric measurements (50) in the rift zone in SW-Iceland indicate resistivities of 10-20 Ωm at 10-15 km depth. A comparison of these values with laboratory data for basalt and peridotite leads to the conclusion that crustal temperatures at that depth are in the range of 800-1100°C.

The geophysical data which have been discussed above lead to a remarkably coherent picture of the state and structure of the upper mantle beneath Iceland and the surrounding ocean. The high heat flow, low seismic velocity and low density, together with a high P to S velocity ratio all show that the upper mantle beneath

Iceland is in a state of partial fusion. The gravity anomaly and the teleseismic P-wave delays indicate that this state of partial fusion may extend to a depth of the order of 200 km. The anomalous mantle appears to become thinner away from Iceland. The Reykjanes Ridge appears to be underlain by an anomalous mantle intermediate in thickness between that beneath Iceland and the deeper parts of the Mid-Atlantic Ridge (105).

Studies of Postglacial lavas in Iceland have revealed a certain geographical pattern of composition and also of discharge rate (54) as has been discussed earlier. Tholeiitic basalts are characteristic of the active zones of rifting. Alkali olivine basalts and transitional alkali basalts are found on the flanks at Snaefellsnes and in the southern part of the eastern zone (Fig. 7). This pattern appears to correlate with crustal structure and regional heat flow, such that the alkali basalts occur in areas of relatively low heat flow and relatively great depth to the upper mantle. This is in agreement with the models of Aumento (5) and McBirney and Gass (66) for magma generation at mid-ocean ridges.

According to Jakobsson (54) all the main basalt types of Iceland have now been found on the ocean ridges. There remains, however, a certain difference between the Icelandic basalts and those described from the Mid-Atlantic

Ridge (96). The Icelandic basalts are usually higher in iron, titanium and potassium, but lower in alumina and magnesia.

Schilling (87) has studied rare earth and minor element contents of the tholeiitic basalts from the Reykjanes Ridge and the Reykjanes peninsula. He found a systematic decrease southwards in the contents of K,La, Ti and P. He investigated several mantle source models that would explain the observed geochemical variation and concluded that two separate mantle sources were necessary. One would be a primordial mantle plume rising beneath Iceland, the other would be the globally existing low-velocity layer assumed to be the source of magma for crustal accretion at the normal oceanic segments of the mid-ocean ridges. The two sources would mix along the Reykjanes Ridge to produce the observed gradient in the chemistry. The mixing process, however, is not well understood.

This model appears compatible with the longitudinal variation of seismicity along the Reykjanes Ridge discussed by Vogt & Johnson (121) and Francis (37).

Crustal drift in Iceland.

It is now over 40 years since the opinion was expressed that Iceland was being split apart by tensional forces of a regional character and that this process was responsible for the fissural volcanism and the associated linear tectonic features. Nielsen (72) concluded after a study of the zone of rifting and volcanism west of the Vatnajökull ice sheet that subsidence was a dominating tectonic feature and that it was closely associated with the volcanism. Nielsen appears to have been inspired by Wegener´s ideas about the drifting of continents.

In 1964 Bodvarsson & Walker (16) proposed a process of crustal drift in Iceland by dike injection in a stationary volcanic zone. The geological evidence for this hypothesis came from Walker´s detailed mapping of the structure of the Tertiary flood basalts in eastern Iceland (122,123,124,125). The geophysical evidence came mainly from early heat flow observations and theoretical studies attempting to explain them (15). Gravity and seismic refraction data were also used, but their interpretation was critizised by Tr. Einarsson (28) and has later been modified in the way discussed earlier. Einarsson also pointed out that the regional dips of the flood basalts in northern and western Iceland do not bear as clear a relationship to the presently active volcanic zones as the eastern Iceland dips do, and one should therefore not extrapolate the eastern Iceland structure to the rest of Iceland. As has been discussed earlier however recent geological and geophysical evidence indicates that the active volcanic zones have during the geological history of Iceland shifted between 2 or 3 zones (78,82,85,130).

Tr. Einarsson has been the chief contender against crustal drift in Iceland (e.g. 28,31). Many of his arguments are no doubt valid in that one should not extrapolate to Iceland the relatively simple models of crustal spreading usually assumed for the submarine parts of the ridges. There are more constraints imposed by geological observations on the spreading process in Iceland than elsewhere and these have to be taken into account. But it appears also that many of his arguments are not necessarily incompatible with drift if one takes into account the possibility of shifting of the active zones.

An important point in Tr. Einarsson´s argumements is the pattern of regional dips of the Tertiary flood basalts (cf Fig. 2). The apparent symmetry of the dips about three zones is interpreted by him as the result of folding (cf also 25) and breaking up of the pile of more or less horizontal lavas, followed by peneplanation. However it is difficult to accept this interpretation. The dips are sometimes 5-10° over areas of a few tens of kilometers measured perpendicularly to the strike of the lavas which necessitates that a thickness of several km has been eroded away in the stratigraphically lowest parts in a few million years. This difficulty has been pointed out by Walker (123) and by Tr. Einarsson (31,32). Furthermore one would expect alteration to increase towards the older tilted strata (82), and the dike intensity to increase also. Neither of these is confirmed by observations.

It appears that Walker's interpretation of the regional dips (16,123) as being due to a sagging down resulting from a stacking of lavas in an active zone is better in agreement with available observations if one accepts the shifting of volcanic activity between two or more zones.

Hast (48) has made direct stress measurements in shallow boreholes in rocks outside and adjacent to the active volcanic zones in Iceland. He concluded that horizontal compressive stresses prevailed everywhere. This does not appear to be compatible with ocean-floor spreading processes. The stress field to be expected in the crust adjacent to and within a zone of rifting and volcanism is, however, little known and it appears that further studies are required before a definite conclusion can be drawn from the available stress measurements.

The numerous faults and open fissures in the Icelandic zone of rifting and volcanism are by most workers considered as evidence of tensional movement (e.g. 71), although Tr. Einarsson (30,31) considered them to be largely surface expressions of deeper faults with a strike-slip movement. Estimates based on the total integrated width of open fissures in Postglacial lava fields together with the estimated age of the fissured lavas give a double drift rate from a few millimeters to two centimeters per year in certain parts of the zone of rifting and volcanism (11,16,108,126). The results of direct measurements of horizontal movements across some conspicuous zones of rifting (24,42) indicate small extensional movements but further measurements over a longer time interval are needed to obtain significant results.

Vertical displacements in the active zones relative to their margins may prove to be as strong an evidence for crustal drift as horizontal movements. According to the models of Bodvarsson & Walker (16) and Pálmason (78) elevation changes as a result of sagging down of the lava pile in the active zone may be expected to reach 1-2 mm/yr on the average. Measurements by Tryggvason (115,116) on selected profiles in SW-Iceland indicate that subsidence of this order is taking place. Schleusener & Torge (88) have made repeated precise gravity measurements along a 100 km long profile which includes crossing of the volcanic zone in NE-Iceland. Over a five year period, 1965-1970, they found the measured gravity values within the active zone to increase 0.005 - 0.01 mgal/yr with respect to the Tertiary basalt area to the west. It appears possible to interpret this as a subsidence of the surface amounting to a few mm/yr, depending on how the underlying masses are rearranged.

In addition to direct measurements of the subsidence there is supporting geological evidence also. Drillholes extending 1000-2000 meters below sea level at the very tip of the Reykjanes peninsula penetrate rocks which are typical of land or shallow water eruptions (13,112).

A similar result is deduced from a 1565 m deep hole in Heimaey at the southern end of the eastern zone (111). And last but not least, the regional dips of often 5° - 10° at sea level in subaerial basalt lava piles adjacent to the volcanic zones show that the subaerial lavas plunge to a depth of several kilometers below sea level beneath the active zones.

Pálmason (78) has made calculations on a model of crustal accretion, similar to that of Bodvarsson & Walker (16), by dike injection and surface lava flows in a single volcanic zone. Using model parameters based on estimates from Iceland, it is possible to reproduce fairly well the regional structure of the eastern Iceland lava pile as described by Walker, the regional dips as well as the average dike volume relationships, without however taking the swarm distribution or the central volcanoes into account. Fig. 8 shows schematically the model. Dike injection takes place mainly in a column of a certain width, with minor eruptive activity outside this zone. The surface lavas flow over a wider zone, in which subsidence takes place, equivalent to the build-up by lavas, thus keeping the surface at a more or less constant level on the average. The rate of increase of dike volume with depth in the uppermost part of the adjacent plate of the model depends on the relative distributions of dike injection activity and surface lava flows. For a narrow dike injection distribution the dike fraction in the uppermost part of the plate will be small.

This is an important property of the model which makes it applicable not only to the eastern Iceland pile, but also to western and northern Iceland, where dike intensity appears to be smaller than in eastern Iceland. The trend of downward increase of the dips in the basalt pile is a generally observed phenomenon in the eroded lava pile, although the absolute dips vary from one area to another.

A study of microearthquakes in the active zone may lead to a better understanding of the dynamic processes taking place. Several such surveys have been made (61,129,131) and an extensive survey of the Reykjanes peninsula is being undertaken at present (Björnsson, pers. comm.). The microearthquake activity appears to be largely confined to certain areas within the active zone, and the intensity varies with time, sometimes reaching over 1000 events/day. The focal depth range appears to be mainly confined to the upper part of the seismic layer 3. Focal mechanism solutions from the Reykjanes peninsula show both strike-slip and dip-slip movements (61), with the axis of maximum tension more or less perpendicular to the main direction of the ridge axis through Iceland. Larger earthquakes of magnitude 6 or more are known to occur only in an east-west zone in southern Iceland from

Reykjanes to Hekla, and in a broad east-west zone off the north coast(100). The depth of focus is unknown. Focal mechanism solutions (99,103,130) are still few but they indicate strike-slip movements.

Discussion and conclusions.

The central question to be answered concerning Iceland and its relationship to the Mid-Atlantic Ridge is whether Iceland fits into the framework of ocean-floor spreading or not. The presently available evidence rather favors a process of drift. This process, however, appears to be more complicated than usually envisaged for the submarine parts of the Mid-Atlantic Ridge.

There is increasing evidence that the active zones of rifting and volcanism have not been stationary during the period involved in building up the Icelandic basalt pile. The evidence for a shifting of the active zones comes from stratigraphic and structural studies and from heat flow data. This has a number of implications for the interpretation of data from Iceland in terms of ocean-floor spreading.

The magnetic anomaly pattern which according to ocean-floor spreading theories originates at the accreting plate margins would be affected and one would not find undisturbed the symmetrical pattern observed,e.g. on the Reykjanes Ridge. Therefore a correlation of the Reykjanes Ridge pattern with the pattern in Iceland does not provide a proof or a disproof of ocean-floor spreading in Iceland. The Icelandic anomaly pattern has to be interpreted independently of the neighboring ocean patterns and with due regard to the history of the volcanic zones on land.

The pattern of regional dips of the flood basalts may be viewed as reflecting the position of not only the presently active zones of rifting and volcanism but also of previously active zones. This invalidates the argument against drift in Iceland that the regional dips do not in general conform to the pattern of dip towards the active zone that is exhibited in the eastern Iceland basalt pile.

The crustal structure of Iceland does not appear to contradict ocean-floor spreading. The evidence provided by seismic velocities, P to S velocity ratios, Sr isotope ratios, lead isotope ratios, as well as petrogenetic considerations, points to a basaltic crust down to the upper mantle. The continuity of layer 3 as observed across the active zones is also in agreement with ocean-floor spreading, whether the layer 3 seismic velocity is attributed to an increased intrusives fraction, or to metamorphism or a combination of both.

The regional pattern of conductive heat flow as revealed by about 20 boreholes appears to be compatible with crustal accretion in accordance with plate tectonics. The heat flow is high near the Reykjanes-Langjökull zone, which is the landward continuation of the Reykjanes Ridge crest. It decreases away from this zone in southwest Iceland. The lowest heat flow values which are found in eastern Iceland appear compatible with a cooling lithospheric plate moving away from a zone of plate accretion. The apparent absence of a widespread conductive heat flow anomaly associated with the eastern zone is in agreement with other evidence for its relative youthfulness.

The hypothesis of ocean-floor spreading appears to provide a good working hypothesis for interpreting data of Icelandic geology, geophysics and geochemistry. Most of the available evidence appears consistent with it. Various arguments which have been presented as contradicting drift in Iceland (e.g. 8) do not appear to be valid in the light of what has been discussed in this paper.

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Figure captions.

Fig. 1. The earthquake epicenter belt through Iceland Earthquakes of magnitude greater than about 4 in the period Jan. 1955 to March 1972 are shown. Based on Sykes (102) , U.S.C.G.S. and N.O.A.A. determinations of epicenters. Bathymetry from Johnson et al (57). Depths are in nominal fathoms (1/400 sec travel time).

Fig. 2. Geological map showing the main tectonic and volcanic features of Iceland. The line $A-A^1$ shows the location of the profile in Fig. 6.

Fig. 3. A compilation of presently available K/Ar age determinations from Iceland. From ref. 22, 40, 48, 67, 70, 73, 93, 98, and unpublished work (Jakobsson ; Krasnov).

Fig. 4. Sections from west (left) to east through the Tertiary basalt pile in eastern Iceland according to Walker (16).

Fig. 5. Depth to layer 3 in Iceland, based on about 80 refraction profiles (77).

Fig. 6. Profiles along line A-A^1 in Fig. 2 showing seismic structure (77), geological cross section, heat flow (78), Bouguer anomaly (from (26) and later unpublished work) and magnetic field (Th. Sigurgeirsson and L. Kristjánsson). The central axial magnetic anomaly is denoted by A.

Fig. 7. Petrological division of the volcanic zones in Iceland, based on postglacial lavas (54).

Fig. 8. Schematic model of crustal accretion in Iceland by dike intrusions and surface lavas in a single volcanic zone. (1) distribution of dike injection activity, (2) distribution of lava flows. Modified from Pálmason (78).

FIG. 1

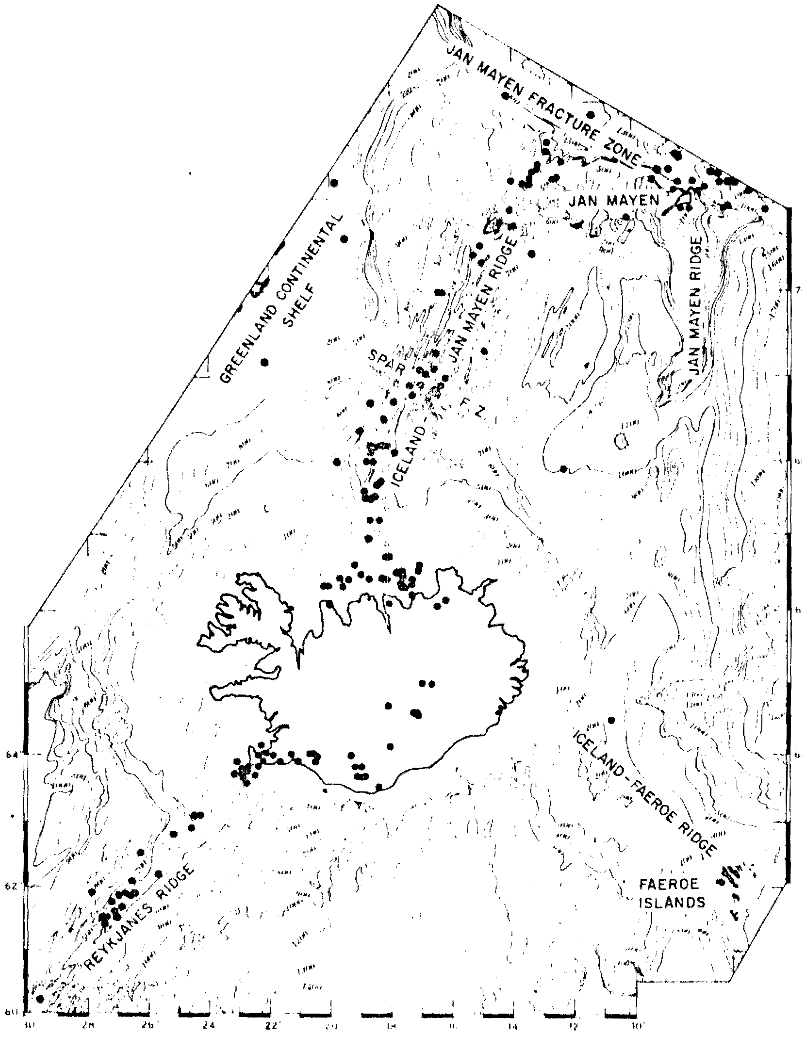
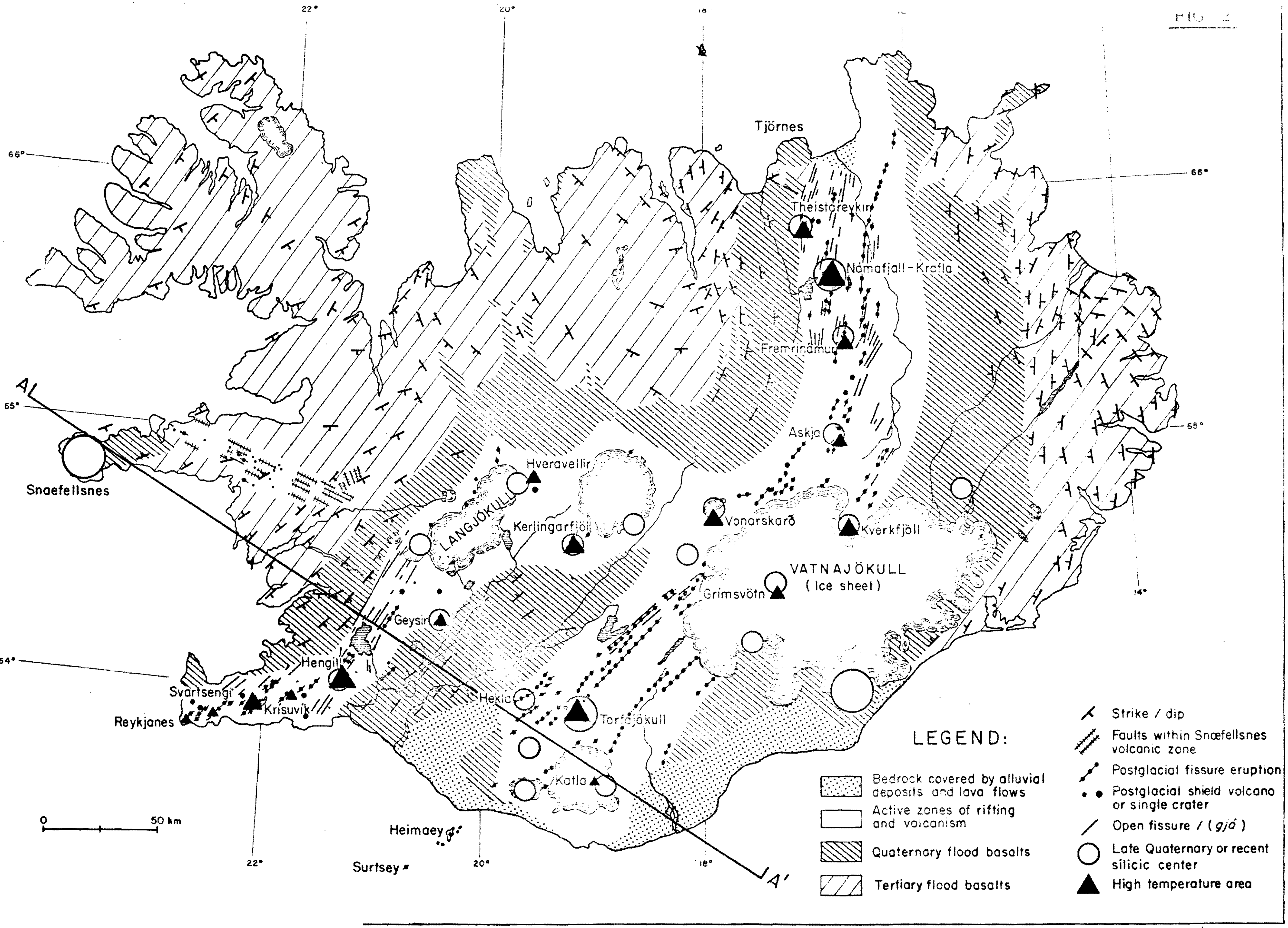
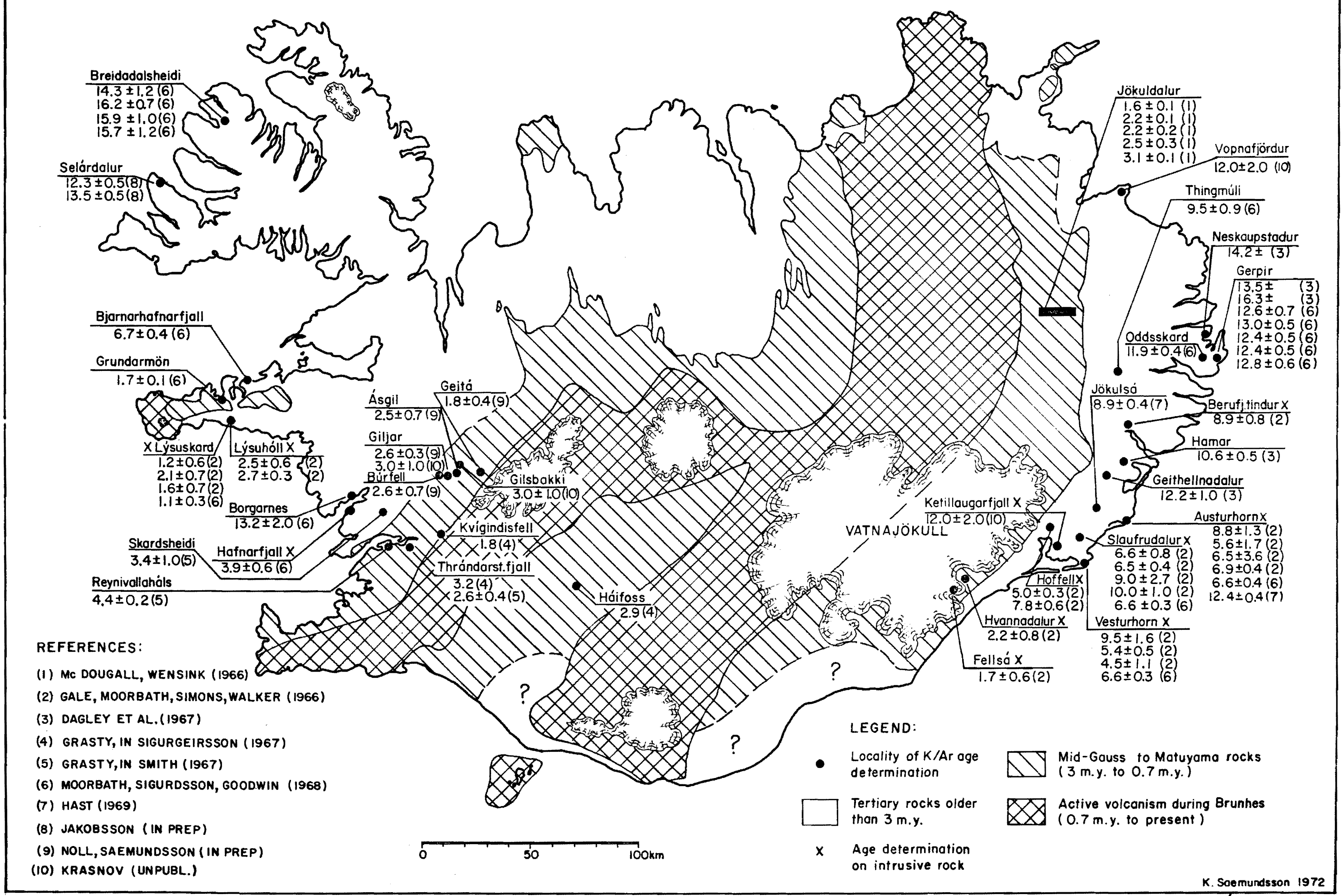

JAN MAYEN FRACTURE ZONE
JAN MAYEN
JAN MAYEN RIDGE
GREENLAND CONTINENTAL SHELF
SPAR F. Z.
ICELAND - JAN MAYEN RIDGE
ICELAND-FAEROE RIDGE
FAEROE ISLANDS
REYKJANES RIDGE
70°
68°
66
64°
64°
62
60
30
28
26
24
22
20
18
16
14
12
10°

FIG. 2



Tor. 185. J.Ým. Far. 8651

FIG. 3



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(5) GRASTY, IN SMITH (1967)
(6) MOORBATH, SIGURDSSON, GOODWIN (1968)
(7) HAST (1969)
(8) JAKOBSSON (IN PREP)
(9) NOLL, SAEMUNDSSON (IN PREP)
(10) KRASNOV (UNPUBL.)

29.2.1972 KS/Gyða J-Ým Tnr. 302 Fnr. 10435

FIG. 4

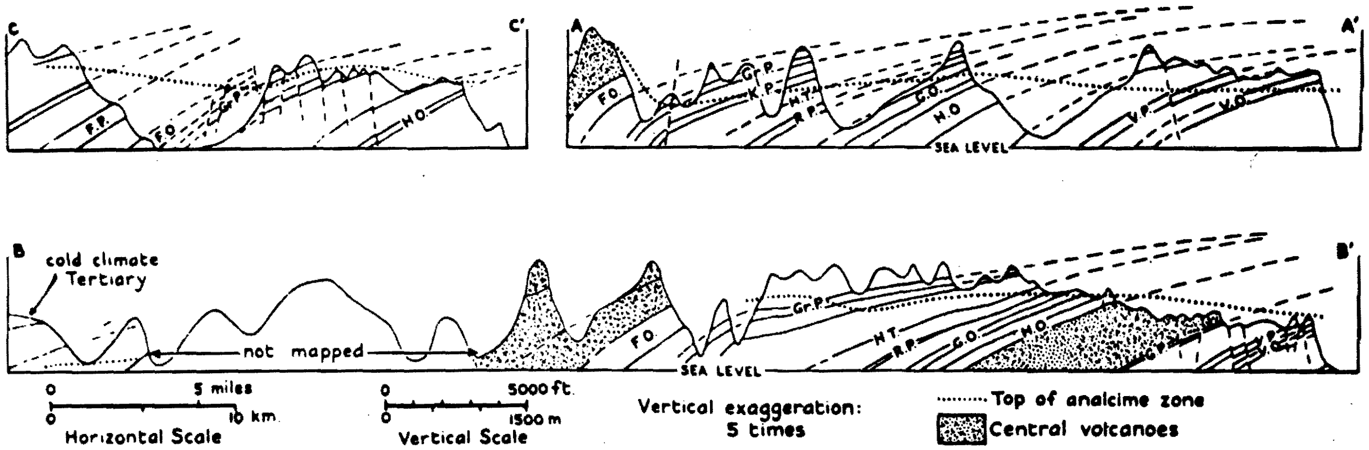

C
C'
A
A'
B
B'
F.O.
R.P.
Gr.P.
H.O.
K.P.
H.Y.
G.O.
N.O
V.P.
V.O.
SEA LEVEL
cold climate Tertiary
not mapped
H.T.
0 5 miles
0 10 km
Horizontal Scale
0 5000 ft.
0 1500 m
Vertical Scale
Vertical exaggeration: 5 times
Top of analcime zone
Central volcanoes

FIG. 5

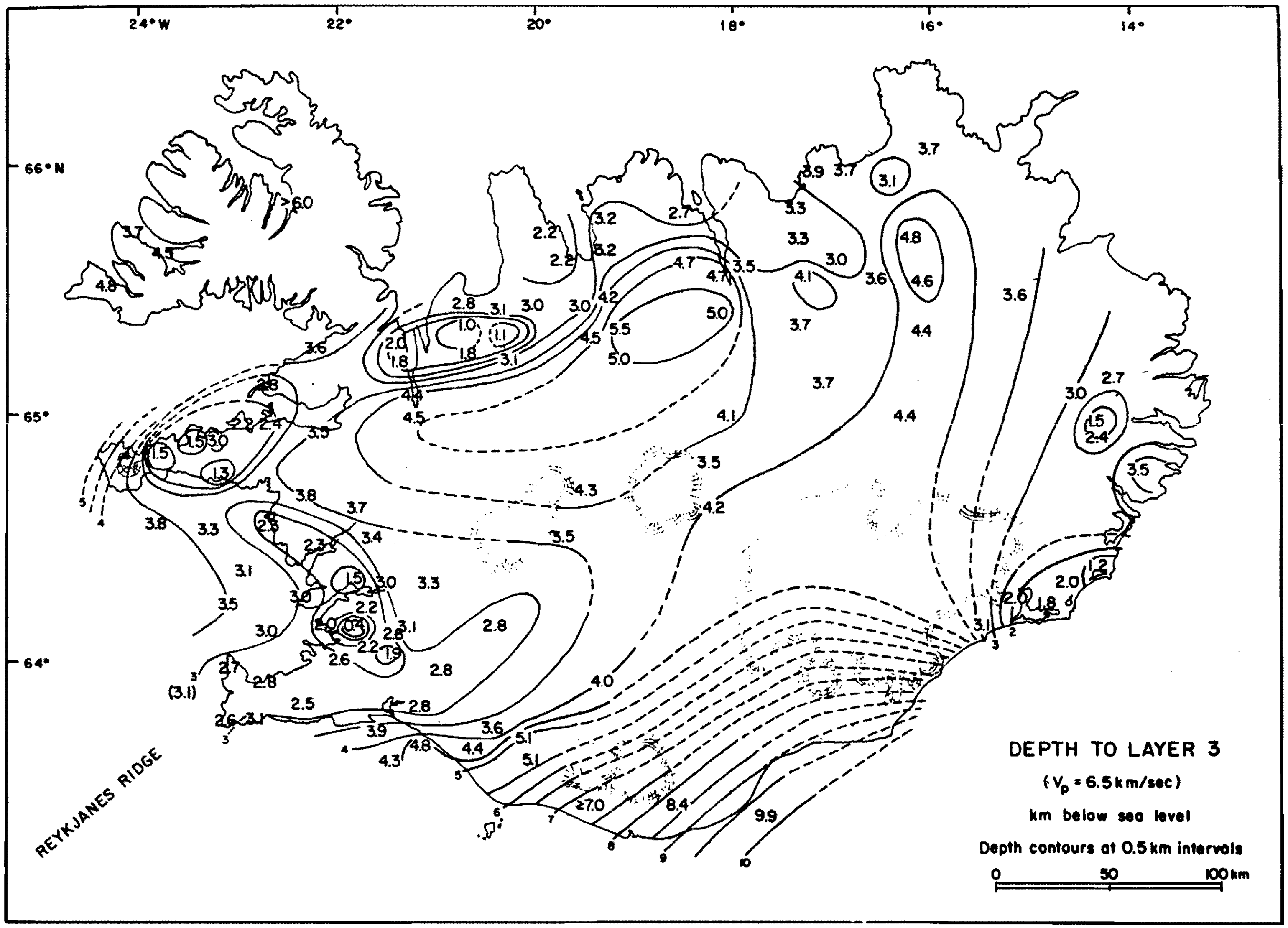

24° W
22°
20°
18°
16°
14°
66° N
65°
64°
REYKJANES RIDGE
DEPTH TO LAYER 3
(V_p = 6.5 km/sec)
km below sea level
Depth contours at 0.5 km intervals
0
50
100 km
>6.0
3.7
4.5
4.8
3.6
3.5
2.8
2.4
1.5
3.0
1.3
3.8
3.3
3.1
3.7
3.4
2.3
2.2
2.0
0.4
2.6
1.9
2.7
(3.1)
2.5
2.6
3.9
4.3
4.8
4.4
5.1
≥7.0
8.4
9.9
10
9
8
7
6
5
4
3
2
1.0
1.1
1.8
4.5
4.2
5.5
5.0
4.7
3.2
2.2
4.1
4.3
4.0
2.8
3.9
4.6
4.4
3.6
1.2

FIG. 6

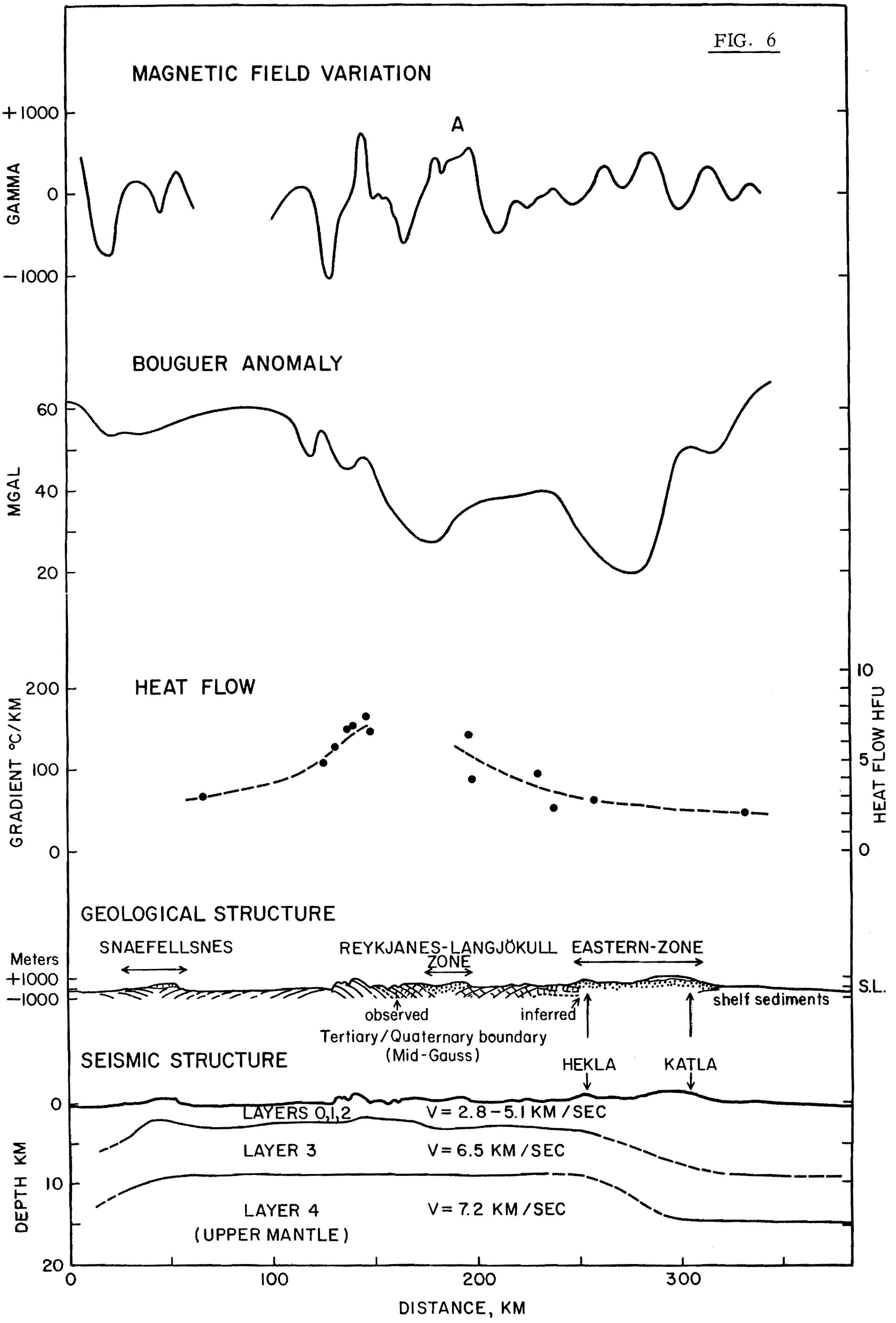

MAGNETIC FIELD VARIATION
+1000
GAMMA
0
−1000
A
BOUGUER ANOMALY
60
MGAL
40
20
HEAT FLOW
200
GRADIENT °C/KM
100
0
10
5
0
HEAT FLOW HFU
GEOLOGICAL STRUCTURE
Meters
+1000
−1000
SNAEFELLSNES
REYKJANES-LANGJÖKULL ZONE
EASTERN-ZONE
S.L.
shelf sediments
observed
inferred
Tertiary/Quaternary boundary
(Mid-Gauss)
SEISMIC STRUCTURE
HEKLA
KATLA
0
LAYERS 0,1,2
V= 2.8 – 5.1 KM/SEC
LAYER 3
V= 6.5 KM/SEC
DEPTH KM
10
LAYER 4
(UPPER MANTLE)
V= 7.2 KM/SEC
20
0
100
200
300
DISTANCE, KM

FIG. 7

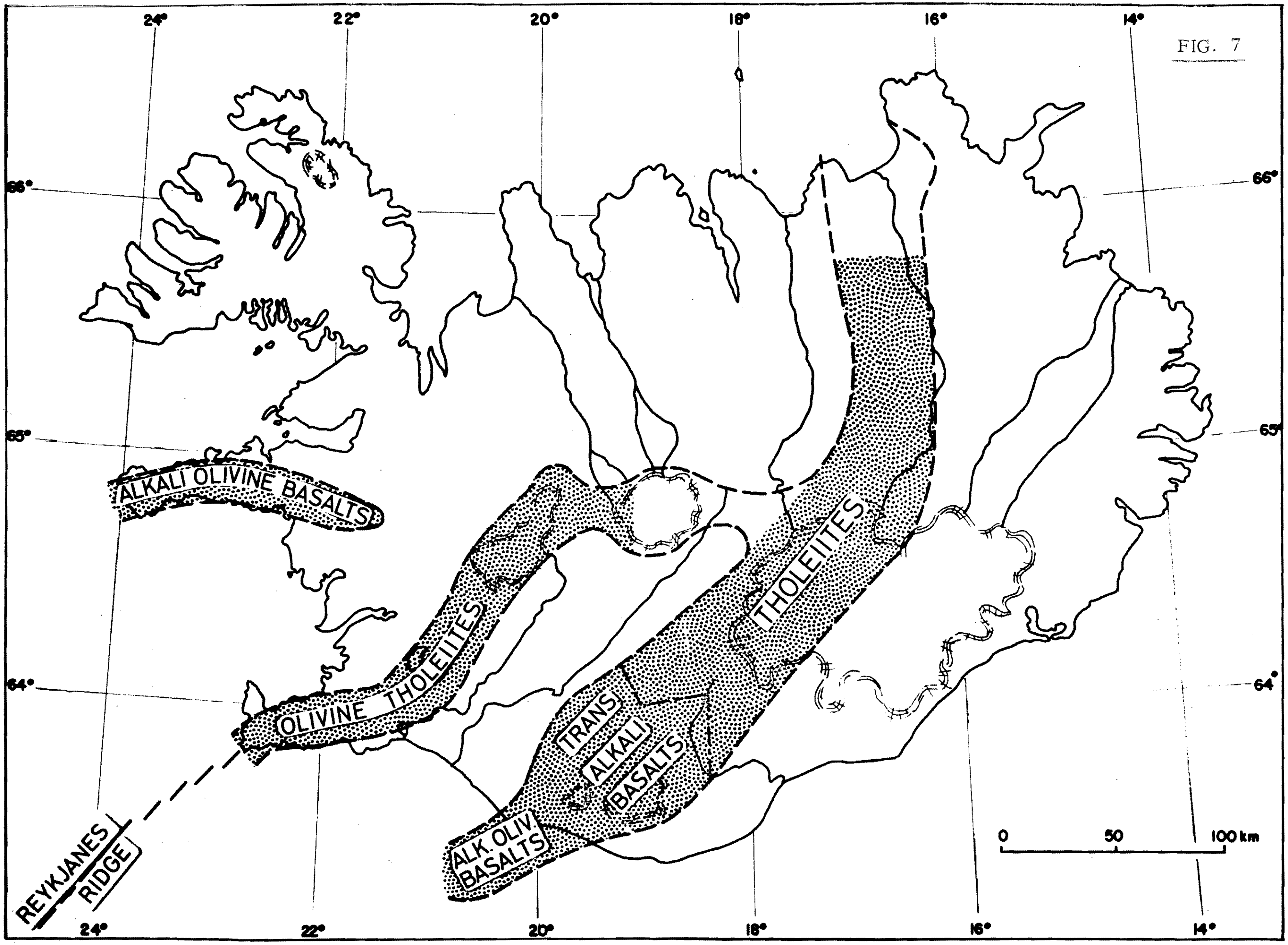
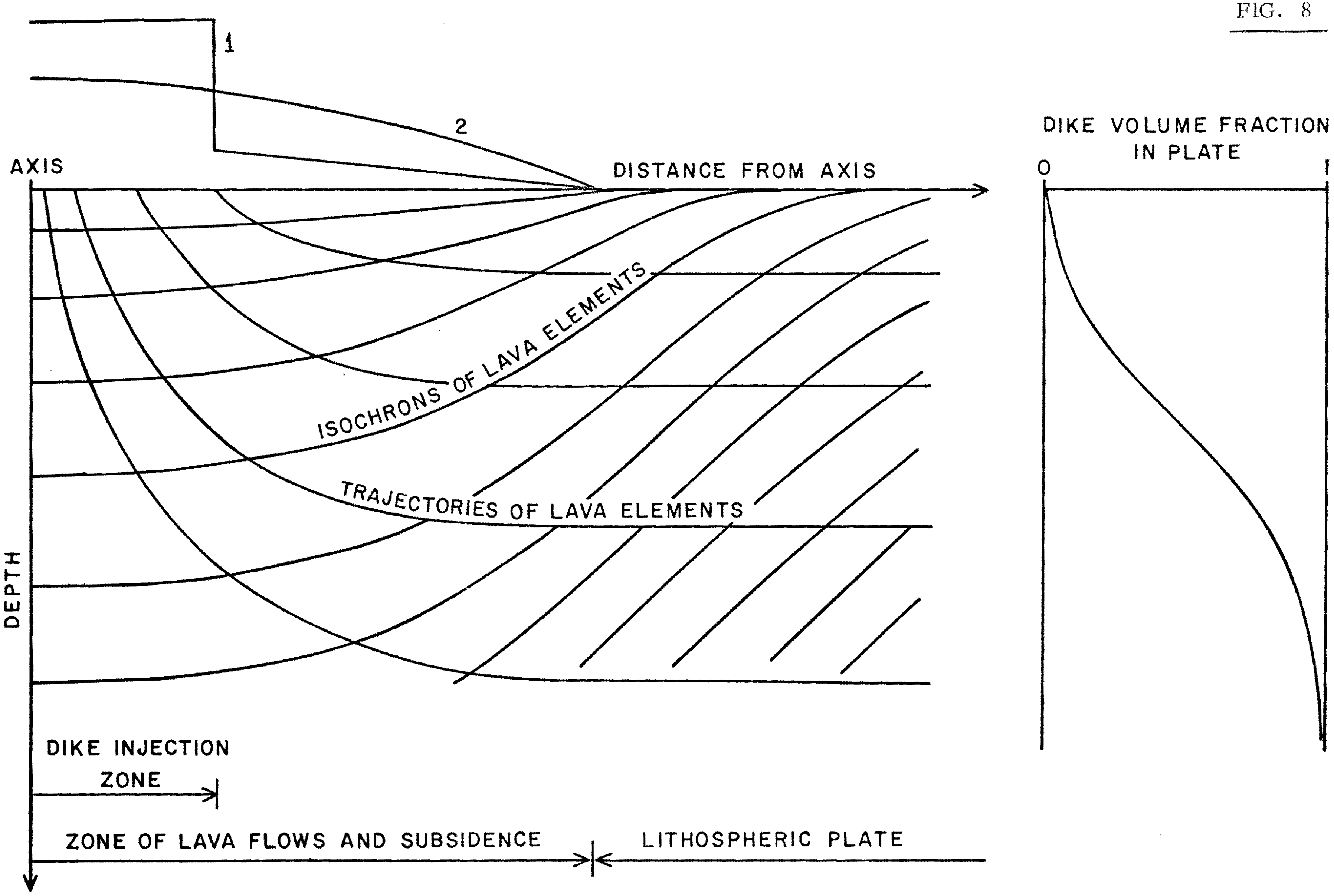

24°
22°
20°
18°
16°
14°
66°
65°
64°
ALKALI OLIVINE BASALTS
THOLEIITES
OLIVINE THOLEIITES
TRANS ALKALI BASALTS
ALK. OLIV. BASALTS
REYKJANES RIDGE
0
50
100 km

FIG. 8


1
2
AXIS
DISTANCE FROM AXIS
ISOCHRONS OF LAVA ELEMENTS
TRAJECTORIES OF LAVA ELEMENTS
DEPTH
DIKE INJECTION ZONE
ZONE OF LAVA FLOWS AND SUBSIDENCE
LITHOSPHERIC PLATE
DIKE VOLUME FRACTION IN PLATE
0
1