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ABSTRACT

Two active transform faults are identified on land in Iceland. This observation leads to a new interpretation of the tectonics of Iceland that is generally consistent with the available geologic, geomorphic, and geophysical data. This new interpretation provides a framework that can be used to relate detailed geologic and geophysical studies in Iceland to worldwide processes at the crests of mid-ocean ridges.

Nearly one-half of Iceland seems to have formed during a period of very slow spreading between about 9 and 20 m.y. B.P. The center of spreading within Iceland apparently shifted from western to eastern Iceland around 7 or 8 m.y. B.P. Iceland, the largest landmass on the mid-ocean ridge system, may have resulted from a change in the stress pattern on a broad fracture zone, allowing large volumes of lava to be erupted while there was little regional spreading.

INTRODUCTION

In this paper, a new interpretation of the tectonics of Iceland is presented that is generally consistent with the geologic, geomorphic, and geophysical evidence in Iceland and the observations of mid-ocean ridges around the world. The most important aspects of this new interpretation are as follows:

1. A tectonic framework of Iceland is outlined that can be used to interpret detailed studies in Iceland in terms of worldwide processes at ridge crests and along fracture zones. All features of geology and geophysics in Iceland can now be studied with this framework in mind and can, therefore, put it to critical test.

2. Two large, active fracture zones are identified on land striking about N. 75° to 80° W. The properties of these zones are similar to the properties of fracture zones observed at sea except that the topographic relief is reduced, probably by erosion, and the rocks are of slightly different chemistry.

3. This study of Iceland shows that large central volcanos on mid-ocean ridges may occur primarily near fracture zones and may originate near the junction of fracture zones and ridge crests. Volcanic activity can apparently persist at a given vent while the vent drifts away from the ridge crest.

4. This study of the geology of a large landmass astride the mid-Atlantic ridge shows that the boundaries between lithospheric plates at ridge crests and along fracture zones are complex in detail.

The Reykjanes Ridge (Fig. 1) enters Iceland on the southwest and the Iceland–Jan Mayen Ridge approaches north-central Iceland. Both ridges appear to have been actively spreading at a rate of about 1 cm/yr for the last 5 to 10 m.y. (Vine, 1966; Vogt and others, 1970). How and if these ridges are joined within Iceland, however, has not been clear. Sykes (1967) proposed the existence of a transform fault north of Iceland on the basis of epicentral locations of earthquakes and one focal mechanism. Stefánsson (1967) noted the possibility of a shear zone in southern Iceland from the distribution of historic earthquakes. Ward and others (1969) assembled the available microearthquake locations and epicenters of historic earthquakes. They showed that the most straightforward interpretation of these data suggests the existence of another transform fault in southern Iceland. They proposed that both transform faults trend east-west and that the eastern Neovolcanic zone is the crest of the ridge. New microearthquake data (Ward and Björnsson, 1971) and two focal mechanisms given below support such a direct interpretation. Most features of the geology and topography of Iceland, however, do not readily fit into this tectonic scheme.

In this paper, a new and slightly more complicated interpretation of these data is given that is quite consistent with the geology of Iceland and with the nature of transform faults observed around the world. At least two active transform fault zones are identified and are shown schematically in Figure 1 striking west-northwest; these are the Reykjanes and Tjörnes Fracture Zones. One other zone, the Snaefellsnes Fracture Zone in west-central Iceland

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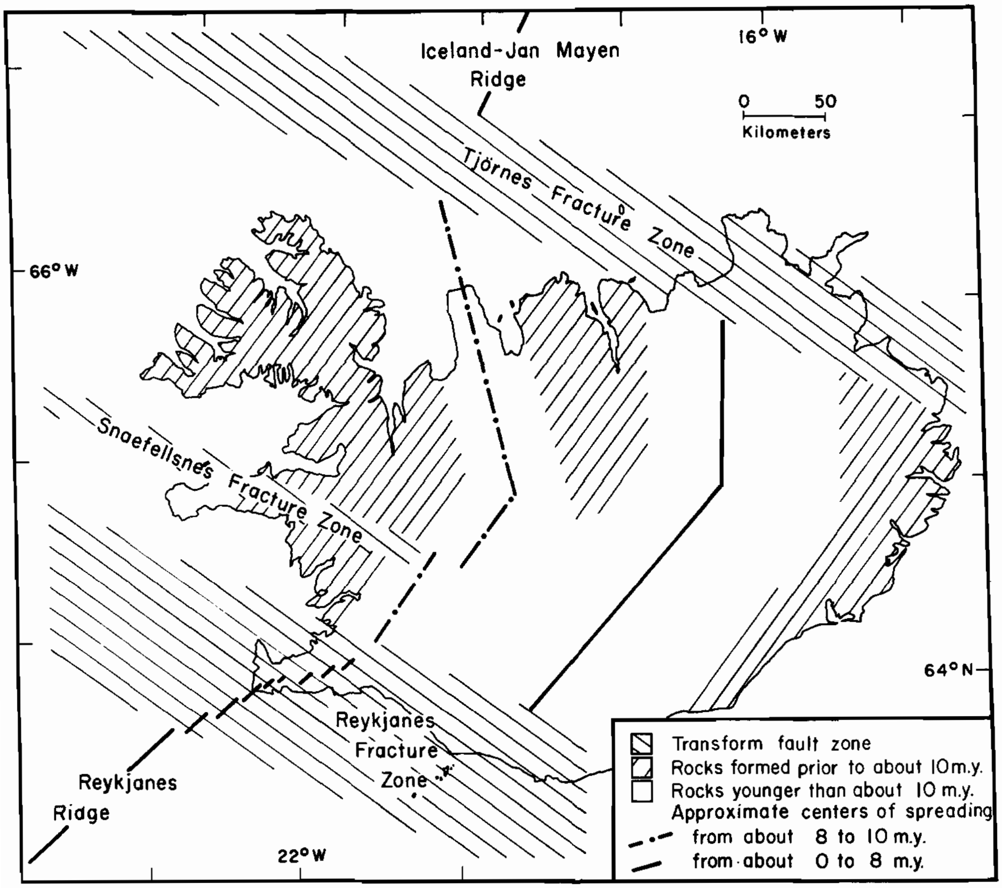

Figure 1. Schematic diagram showing the approximate relation of zones of spreading, ages of rocks, and fracture zones in Iceland.

has been relatively inactive historically but shows signs of having been active during the last 10 m.y. The center of spreading in northern Iceland appears to have shifted eastward about 7 to 8 m.y. ago. To understand the reasons for the identification of these zones, we must examine the observations of fracture zones elsewhere around the world and the trend of other fracture zones in the North Atlantic before looking at the seismological and geological evidence in Iceland.

Other interpretations of the geology of Iceland have been presented. Tr. Einarsson (1965, 1967a, 1968), for example, argues that the structural features of Iceland, including the rift zones, are results of deformation along conjugate shear planes. Th. Einarsson (1967) also concludes that "Iceland has suffered crustal compression and that no dilation or 'drift' has taken place." Bodvarsson and Walker (1964), on the other hand, show that Iceland may be actively drifting apart and that new crust may be formed in the Neovolcanic zone by myriads of dikes. Hast (1969) reports several measurements of *in situ* compressive stress in Iceland. If these shallow measurements at a few selected sites turn out to be valid indicators of regional tectonic stress, they might imply that the ridge near its crest is being pushed apart by intruded material more than it is being pulled apart.

IDENTIFICATION OF TRANSFORM FAULTS IN ICELAND

Characteristics of Transform Faults

Observations of submarine and subaerial transform faults suggest that a transform fault identified on land in Iceland might reasonably be expected to have the following properties:

1. Deformation may take place in a fault zone

from a few kilometers to at least tens of kilometers wide, and there may be a number of other faults and valleys subparallel to the main fracture zone (Hamilton and Myers, 1966; Collette and others, 1969; van Andel, 1970; Heezen, Gerard, and Tharp, 1964; van Andel and others, 1967; Johnson and Heezen, 1967). The trends of transform faults change with changes in the direction of spreading (*see* Francheteau and others, 1970). Multiple fracturing caused by such changes might partially account for the width of the fracture zones and the number of faults within them.

2. Earthquakes should occur along the presently active fracture zones between ridge crests. Focal mechanisms should show strike-slip faulting with the sense of motion opposite that of simple offset of the ridge crests (Sykes, 1967).

3. Magnetic anomalies may be offset across transform faults and disturbed, and of slightly lower intensity, within these fracture zones (Vacquier and Von Herzen, 1964; Phillips and others, 1969). Magnetic anomalies may not be traced easily from sea onto land because of the effects of water on the mineralogy (Barth, 1962), the form of the extrusive material (McBirney, 1963; Kjartansson, 1967; Jones, 1966; Sigvaldason, 1968; Menard, 1964; Moore and Fiske, 1969), and the magnetic intensity (Nagata, 1961; Marshall and Cox, 1971) of individual lava flows. Furthermore, lava is quenched very efficiently under water and, therefore, does not flow as far as it would on land. While magnetic anomalies observed at sea may be accounted for by only the upper 400 m of lava on the sea floor (Talwani and others, 1971) in zones as small as a few hundred meters (Larson, 1970) to a few kilometers wide (Vine, 1966), those observed on land seem generally more complex.

4. Heat flow may be high along transform faults and sometimes even higher than along the ridge crests (Phillips and others, 1969; Von Herzen and Uyeda, 1963; Von Herzen and others, 1970).

5. Rock types may be predominantly serpentinites and peridotites along transform faults, but basalts are usually the dominant types along ridge crests (Shand, 1949; Bonatti, 1968; van Andel, 1968; Fox and others, 1969; Phillips and others, 1969; Miyashiro and others, 1970; Heezen and Nafe, 1964; Heezen, Bunce, Hersey, and Tharp, 1964). Melson and Thompson (1970) report rocks typical of a layered, mafic, igneous intrusion in the Romanche Fracture Zone.

6. Topography of a transform fault may have less relief on land than under the sea because of erosion, glaciation, and the lateral extent of individual lava flows.

7. A transform fault in Iceland need not necessarily look like the San Andreas transform fault (Wilson, 1965) for the following reasons:

A. Iceland has oceanic crust, whereas California has continental crust.

B. Motion on the San Andreas fault began probably 25 m.y. ago (Grantz and Dickinson, 1968) and possibly as early as 60 m.y. ago (Crowell, 1962). The oldest rocks in Iceland are 20 m.y. old.

C. Glaciers, volcanos, and beach erosion processes have been very important in Iceland and of little or no importance along the San Andreas fault.

D. The San Andreas seems to be moving at a rate of 6 cm per year (Atwater, 1970), while faults in Iceland might be expected to be moving only about 2 cm per year.

Trend of Transform Faults in the North Atlantic

The strike of fracture zones in the Atlantic north of the Azores and the strike of fracture zones near Iceland predicted as lines of latitute about various poles of rotation (Morgan, 1968) are summarized in Table 1. Since the precise trend of fracture zones in the northernmost Atlantic has not yet been clearly observed and there is wide variation in the strikes given in Table 1, the fracture zones shown in this paper are simply drawn as straight lines trending about N. 75° W. It should be recognized that, when more data are available, the strike of these fracture zones may be found to vary slightly in different regions.

Regional Setting of Iceland

It is often stated that Iceland lies at the intersection of the mid-Atlantic ridge and a ridge stretching from Greenland to Scotland passing through Iceland and the Faeroe Islands. It may be instructive not to think of this latter trend as a ridge, often referred to as the Wyville-Thompson or Greenland-Scotland ridge, because this terminology tends to obscure the observed topographic and age data. First of all, the mid-Atlantic ridge, or Reykjanes Ridge in this region, gradually shoals south of Iceland (Fig. 2). At 55° N., the crest of the ridge is at a depth of only about 1000 fm; at 64° N., it reaches the surface. Therefore, the fact that Iceland is the largest landmass astride the mid-

TABLE 1. STRIKES OF FRACTURE ZONES IN THE NORTH ATLANTIC, NORTH OF THE AZORES

Latitude	Longitude	Name of fracture zone	Strike	Reference
43° N.	29° W.		N. 65–75° W.	Phillips and others (1969)
53° N.	36° W.	Charlie or Gibbs	B. 85° W.	Johnson (1967); Fleming and others (1970)
69° N.	18° W.	Spar	N. 60–70° W.	Johnson and Heezen (1967)
71° N.	9° W.	Jan Mayen	N. 60–70° W.	Johnson and Heezen (1967)

Strike of the fracture zones near Iceland predicted from poles of rotation defining the movement of Greenland relative to Eurasia

Pole of Rotation		Reference	Strike of fracture zone Reykjanes	Strike of fracture zone Tjörnes
56.3 N.	141.4 E.	Pitman and Talwani (1971). For period 0 to 9 m.y.	N. 79° W.	N. 76° W.
58.0 N.	147.0 E.	Pitman and Talwani (1971). For period 9 to 38 m.y.	N. 83° W.	N. 80° W.
66 N.	124 E.	Horsfield and Maton (1970)	N. 72° W.	N. 69° W.
78 N.	102 E.	Le Pichon (1968)	N. 72° W.	N. 69° W.
73.0 N.	96.5 E.	Bullard and others (1965)	N. 65° W.	N. 61° W.

Atlantic ridge is not a local anomaly at the junction of two linear trends but a regional anomaly along a considerable part of the northern mid-Atlantic ridge.

Secondly, the Greenland-Scotland Ridge consists primarily of two separate island masses, Iceland and the Faeroe Islands, with a short narrow ridge in between. Age determinations in the Faeroe Islands give ages of 50 to 60 m.y. (Tarling and Gale, 1968). This suggests that the Faeroes might best be viewed as part of Rockall Bank, that is, as an old continental fragment of early Eocene and older age (Bullard and others, 1965; Roberts and others, 1970; Scrutton, 1970). The islet of Rockall is made up of 50- to 60-m.y.-old granite (Moorbath and Welke, 1969), but dredge hauls from Rockall Bank suggest that the bank consists primarily of basalts (Sabine, 1960). Strontium and lead isotope measurements indicate that at least part of Rockall Bank has continental affinities (Moorbath and Welke, 1969). The upper crustal structures of northern Rockall (Scrutton, 1970) and the Faeroes (Pálmason, 1965) are similar and together differ from the structure west of the Faeroes (Bott and others, 1971). Changes in the titania and alumina content of basalts from the Faeroe Islands suggest that these lavas become less "intraoceanic" and more "circumoceanic" (Chayes, 1965) with decreasing age (Noe-Nygaard, 1967). Strontium and lead isotope studies would help clarify whether the boundary of the European continental crust should be drawn to include or exclude the Faeroes.

One reason for thinking in terms of a Greenland-Scotland ridge is that the Faeroe lavas are of the same age as the tertiary igneous centers of northwest Scotland (Moorbath and Bell, 1965), and many dikes in both regions trend in a northwest direction (Hald and others, 1969; Noe-Nygaard, 1962; Richey, 1939). Furthermore, many of the tholeiites from Greenland to Scotland have similar chemical compositions — abnormally high in iron, titanium, and phosphorous (Noe-Nygaard, 1966). Noe-Nygaard (1966) suggested that "the early Faeroes, and possibly early Iceland as well, originated on an oceanic fissure system running southeast to northwest; the same system also gave rise to basaltic volcanism in Greenland and in northwest Scotland." This idea will be discussed further below in the passage considering the origin of Iceland.

South of Iceland, spreading has apparently been symmetric about the Reykjanes Ridge (Heirtzler and others, 1966) at a rate of about 1 cm/yr for the last 3.4 m.y. (Vine, 1966). Symmetric magnetic anomalies can be traced for more than 400 km to either side of the ridge (Fig. 2) thus covering the area between the continental slope of Greenland and Rockall

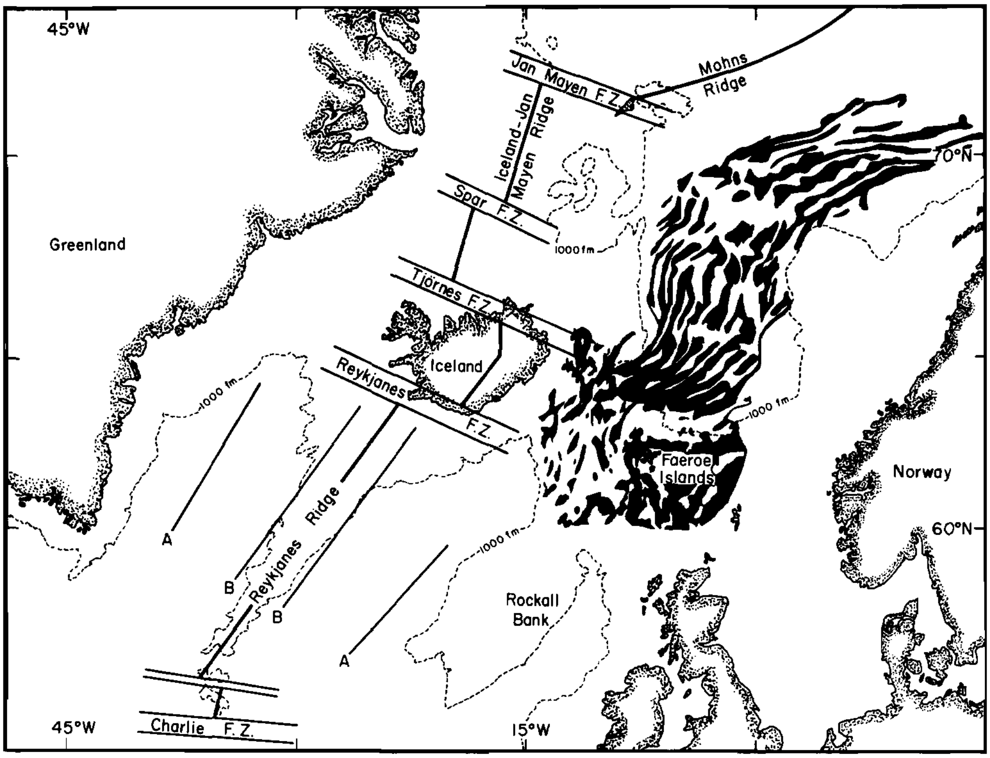

Figure 2. Regional tectonic setting of Iceland. A is magnetic anomaly F of Godby and others (1968). B is magnetic anomaly 5 of Talwani and others (1971) and probably corresponds to an age of about 9 m.y. Some magnetic anomalies of Avery and others (1968) are shown between Iceland and Norway in the region where spreading may have occurred during the Middle to lower Tertiary. Shaded anomalies are negative.

Bank (Godby and others, 1968). There is evidence for at least three periods of spreading beginning about 60 to 70 m.y. B.P. (Vogt and others, 1970), with the most recent episode beginning about 9 or 10 m.y. B.P. after a period of very slow spreading (Avery and others, 1969; Schneider and Vogt, 1968; JOIDES, 1970). The period of slow spreading in the North Atlantic was postulated primarily from the distribution of sediments (Ewing and Ewing, 1967) and from a distinct change in amplitude of high frequency magnetic anomalies (Godby and others, 1968). Pitman and Talwani (1971) date the period of slow spreading at between 9 and 38 m.y. ago and suggest that prior to 9 m.y. ago, the direction of spreading was more nearly east-west than it has been since that time.

North of Iceland, the history of spreading is less clear. Vogt and others (1970) show clear symmetry of magnetic anomalies about the Iceland–Jan Mayen Ridge for at least the last 4 m.y. and possibly the last 10 m.y. Johnson and Heezen (1967) and Vogt and others (1970) suggest that earlier spreading was about an old line of seamounts in the Norwegian Sea and that the axis shifted westward to the Iceland – Jan Mayen Ridge between 40 and 10 m.y. B.P. This interpretation is consistent with the detailed magnetic data of Avery and others (1968). Thus, prior to 10 m.y. B.P., the ridge axis was probably offset in a right lateral sense near Iceland. For the last 5 to 10 m.y., the ridge crest has apparently been offset in a left lateral sense just north of Iceland.

Much of Iceland formed during the proposed period of little or no spreading between at least 9 and 20 m.y. B.P. The oldest rocks in Iceland are about 20 m.y. (Dagley and others, 1967; Moorbath and others, 1968). Tr. Einarsson (1960) estimates these basalts to be 5 to 6 km thick. Bodvarsson and Walker (1964) suggest that they are as much as 10 km thick stratigraphically. Gibson (1966) thinks they may be only 2 to 4 km in vertical thickness. The magnetic stratigraphy in eastern Iceland (Dagley and others, 1967) shows that these lavas may have been as much as 7 km thick by 10 m.y. B.P. Most of these lavas are subaerial and contain fossil flora and layers of lignite and sandstone (Tr. Einarsson, 1960, 1963b). The lignite is up to 90 cm thick and the total thickness of sediments may infrequently reach 50 meters. Sediments are found throughout the flood basalt sequence. Groups of flows can sometimes be followed along strike for more than 50 km. The dips of the flows are very uniform in direction and amount (Walker, 1966). Many central volcanos are found among the flows. "It is apparent that these central volcanos may not always have formed large volcanic cones on the land surface of their day" (Walker, 1966). Eocene flora were tentatively identified in the Tertiary Flood Basalts (Chaney, 1940; Pflug, 1959). These data have been seriously questioned and are no longer widely accepted (Tr. Einarsson, 1967b).

The fact that the lavas in eastern Iceland generally dip toward the Neovolcanic zone (Tr. Einarsson, 1960), thicken up dip (Gibson and others, 1966; Bodvarsson and Walker, 1964), and get younger to the west (Dagley and others, 1967) suggests that there was some spreading between 10 and 20 m.y. B.P., even though it may have been slow.

Thus, it appears that the 4- to 10-km-thick Tertiary Plateau Basalts in eastern Iceland formed predominantly during a period of slow spreading in a subaerial environment and over a long enough time span so that many sedimentary layers could form between lavas. There is little reason so far to assume that the Tertiary Plateau Basalts in western Iceland did not form in the same way.

Seismological Evidence for Transform Faults in Iceland

The distribution of epicenters and the focal mechanisms of earthquakes are the main types of seismological data used to identify transform faults (Sykes, 1967). These data for Iceland, shown in Figure 3, are less complete and less

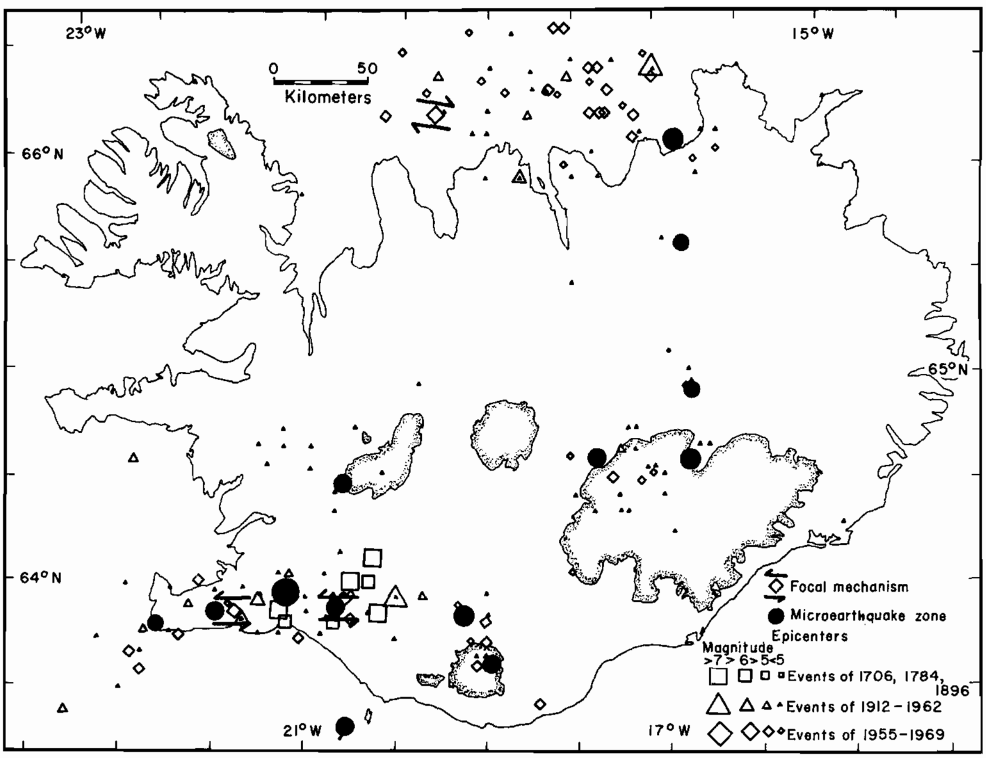

Figure 3. Summary of earthquake epicenters and focal mechanisms determined for Iceland. Stippled areas outline icesheets or jökulls. The epicenters are taken primarily from an unpublished list by E. Tryggvason of earthquakes from 1912 to 1960 and other epicenters from summaries by Tryggvason and others (1958), Sykes (1965, 1967), and Stefánsson (1967), as well as data from the "Seismological Bulletin of Vedustofa Islands" and the "Monthly Seismological Bulletin and Earthquake Data Report" of the U.S. Coast and Geodetic Survey. Many epicenters for 1967 through 1969 were provided by R. Stefánsson.

accurate for the earlier dates. Epicenters derived from intensity studies, epicenters given by Sykes (1965) from 1955 to 1963, and the most recent epicenters of events greater than magnitude 5 are probably accurate to about 10 to 20 km. Zones of microearthquake activity are taken from Ward and others (1969) and Ward and Björnsson (1971). The location of these zones is accurate to within 1 to 5 km in most cases.

Most earthquake activity in Iceland is clearly concentrated in southwestern Iceland or just off the coast north of Iceland (Stefánsson, 1967). The largest earthquakes in Iceland all occurred in these same two zones. Some activity is found west of Langjökull. Sykes (1967) showed that most earthquakes near mid-ocean ridge systems occur either along the crest of the ridge or along the portion of transform faults between the ridge crests. The largest earthquakes typically occur along the transform faults. Thus, the distribution of epicenters in Iceland suggests the presence of a transform fault north of Iceland (Sykes, 1967) and another fault in southern Iceland (Ward and others, 1969).

Focal mechanism solutions constitute perhaps the single most important type of seismological evidence for a transform fault. Two focal mechanisms were obtained for earthquakes in the southern epicentral zone in Iceland. Figure 4 shows a relatively well-determined strike-slip solution for the earthquake of magnitude 5.5 to 6.0 on December 5, 1968, in southwestern Iceland. The smaller circles denote readings that are somewhat ambiguous. One vertical nodal plane strikes about 87° and the other plane strikes about 356° and dips about 75° E. The strikes of these planes are confined by the data to within a few degrees. The east-west nodal plane has the proper orientation and sense of movement (Wilson, 1965; Sykes, 1967) for the proposed transform fault. Figure 5 shows a less well-determined mechanism for the earthquake of magnitude 5 on July 27, 1967, in south-central Iceland. Note that there are only nine unambiguous readings in the solution. The earthquake, however, cannot have much normal or thrust faulting. The azimuths of the nodal planes are approximately east-west and north-south, but could be rotated nearly ten degrees clockwise if only one reading is considered in error.

The focal mechanism of an earthquake of magnitude 7 north of Iceland was determined by Stefánsson (1966) and independently by Sykes (1967). They found that one nodal plane strikes N. 73° W. ± 2°, which agrees well with the strike of fracture zones observed in the North Atlantic north of the Azores. The two focal mechanisms determined in this paper in southern Iceland strike closer to due west. The nodal planes in Figures 4 and 5 cannot, within

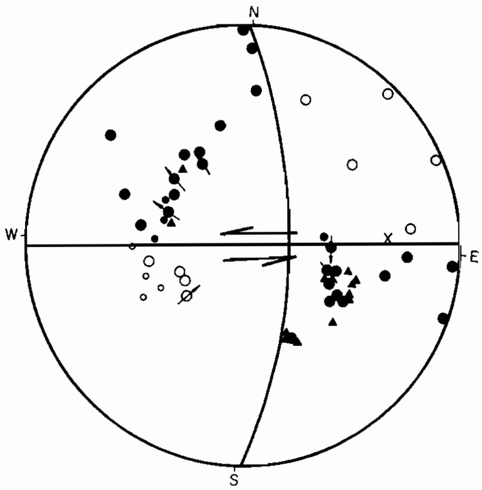

Figure 4. Focal mechanism solution for the earthquake of December 5, 1968, east of Krisuvik. Solid symbols are compressions, open symbols are dilatations, and X's are readings interpreted as near the nodal planes. Dots are for data read by the author and triangles are for data reported by the U.S. Coast and Geodetic Survey. USCGS data near stations read by the author are not plotted. Polarization of S waves, where observed, are shown by arrows through the solid and open circles.

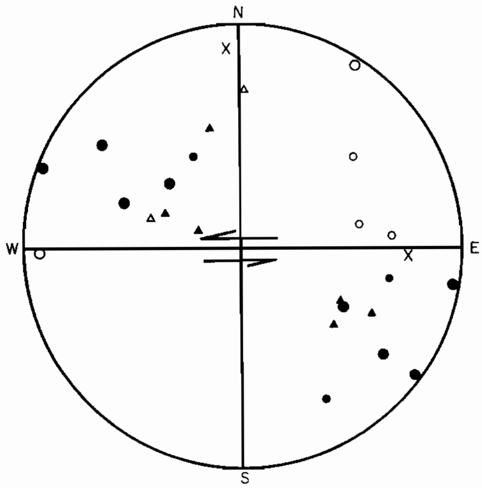

Figure 5. Focal mechanism solutions for the earthquake of July 27, 1967, east of Hveragerdi. The symbols are the same as in Figure 4.

reason, be rotated 15°. The fault length for an earthquake of magnitude 7 may be about 20 times longer than that for an event of magnitude 5 (Wyss and Brune, 1968). Therefore, the focal mechanism of a large earthquake may be much more representative of the regional stress field than the mechanism for a small event. Bolt and others (1968) determined the focal mechanisms for 32 events along the 100 km wide San Andreas transform fault system in California (Wilson, 1965). The magnitudes of these events were from 2.5 to 6.5. The northwest-striking nodal planes for 16 events south of Point Arena strike from N. 14° W. to N. 55° W. The main fault strikes about N. 35° to 40° W. These nodal planes were generally parallel to surface faults. Morgan (1968) found that strikes of nodal planes of several earthquakes along the mid-Atlantic ridge south of the Azores varied from 84° to 103°. A given nodal plane, therefore, may not be parallel to the strike of the whole fracture zone but may well be parallel to a particular fault within the zone.

Thus, the distribution of epicenters and orientation of nodal planes of earthquakes in Iceland strongly support the idea of two presently active transform faults — one in southern Iceland and one off the north coast of Iceland. These seismological data are, in fact, as complete as those given to identify most other transform faults around the world (Sykes, 1967).

Geologic and Topographic Evidence for Transform Faults in Iceland

There is one major geologic and topographic trend in Iceland that strikes northeast in southern Iceland, bends in central Iceland, and strikes nearly due north in northern Iceland. This trend is clearly shown, particularly in the zone of active rifting, by open fissures, volcanic fissures, dikes, grabens, valleys, fault scarps, and the like. These features are interpreted in this paper as being typical of tensional processes along ridge crests. These faults are overwhelmingly dip-slip (Saemundsson, 1967a).

Another major trend can be found, although it is far less obvious. This trend is shown by faults, fissures, valleys, dikes, volcanos, and so on, that strike approximately west-northwest. These features are interpreted here as being typical of strike-slip processes along fracture zones. Although most of the features discussed below do not *individually* constitute convincing evidence for transform faults in Iceland, collectively they show that the west-northwest trend of linear features in Iceland is the second most important geologic and topographic trend

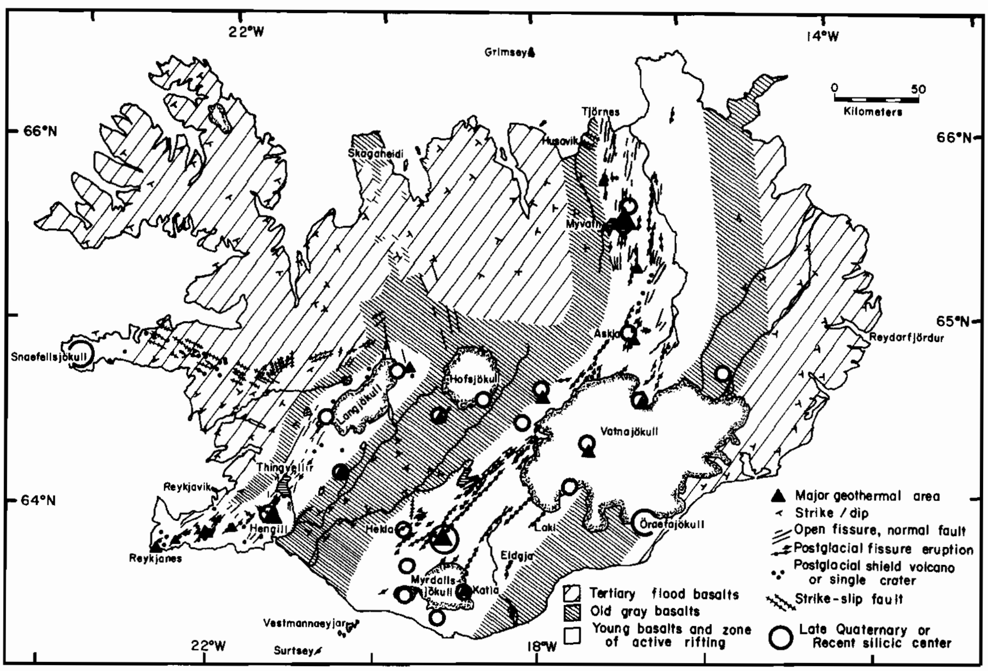

Figure 6. Geologic map of Iceland.

found in the island. This trend is parallel to that of fracture zones in the North Atlantic. Bout (1953) has emphasized the importance of this trend from his study of the geomorphology of Iceland. Winkler (1938) showed the importance of this trend in the strike of fjords in northwestern Iceland. Tr. Einarsson (1963a) emphasized the importance of fractures along this general trend in the formation of the northwest peninsula. A number of valleys have this trend; notable examples are the valleys between Reykjavik and the eastern end of the Snaefellsnes Peninsula and valleys on the northwest peninsula of Iceland.

Sets of *en echelon* fractures trending northeasterly and northerly might be considered to be *en echelon* fractures above a strike-slip fault (Cloos, 1932; Tr. Einarsson, 1968). A detailed study of two areas in Iceland by Nakamura (1970), however, shows a bimodal distribution of fault strikes that is symmetric about the trend of the zone of rifting. Thus, at least some of the *en echelon* features seem related to rifting rather than the strike-slip faulting.

Much of the known geology of Iceland is summarized in Figure 6. These data are taken from a map by K. Saemundsson (*in* Ward and others, 1969), maps by Kjartansson (1962 [1960, 1965, 1968]) and from many other sources cited below. The coverage is by no means homogeneous or complete. Features of this map will now be discussed in relation to the three proposed fracture zones.

Reykjanes Fracture Zone

A 75- to 100-km-wide zone, measured from northeast to southwest, in southwestern Iceland that includes all of the Reykjanes Peninsula is interpreted here as a fracture zone (Fig. 2). Right-lateral offsets appear to be small in the southern part but add up to about 40 km of offset of the ridge crest. The major offset of about 100 km seems to occur near the northern boundary (Fig. 7). The gradual offset is suggested by the *en echelon* distribution of volcanos and eruptive fissures on the peninsula and in the region just southwest of Reykjanes (Tr. Einarsson, 1968). This offset is also suggested in the magnetic profiles of Talwani and others (1971) and Serson and others (1968) southwest of Reykjanes and the detailed topographic profiles by Ulrich (1960) in the same area. Detailed magnetic profiles on the Reykjanes Peninsula are also in agreement with this inter-

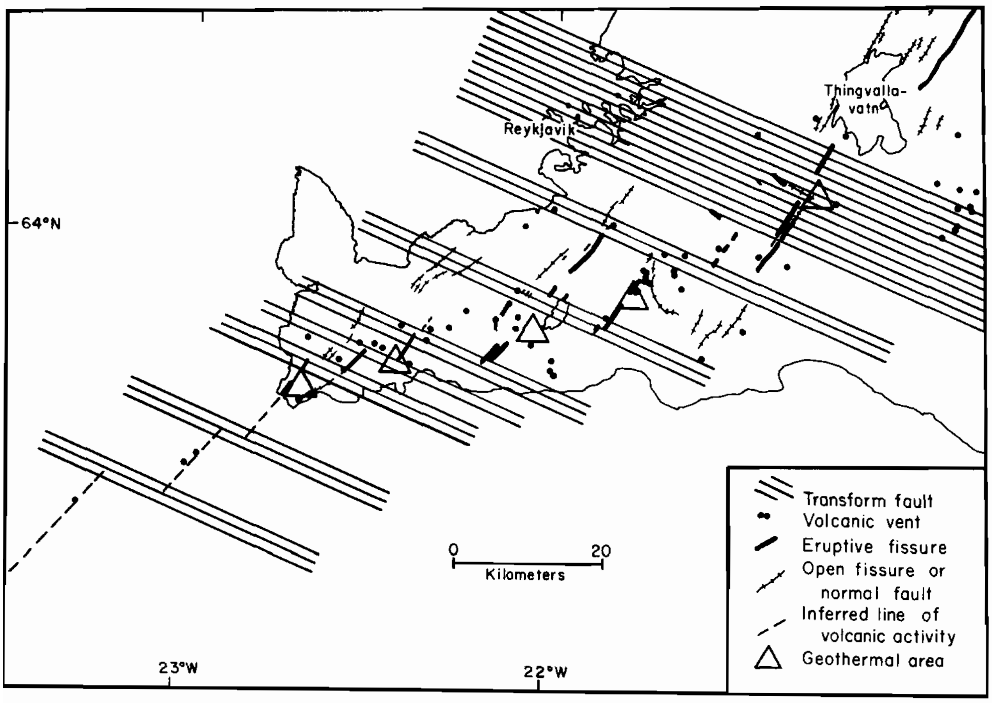

Figure 7. Map of the Reykjanes Peninsula in southwestern Iceland showing mapped fissures, faults, and volcanos. The transform faults are inferred and are shown schematically. They have not been observed or mapped directly. Inferred lines of volcanic activity are taken from Einarsson (1968).

pretation (Science Institute, [Univ. of Iceland] 1970). The individual transform faults within the zone are shown schematically in Figure 7. These faults are not observed in the field but are inferred from the magnetic and topographic profiles and the geology.

The major offset and the region that has been the most seismically active in historic times occur near the northern part of this zone. Several faults have been mapped here. Tryggvason (1955) noted a few somewhat obscure "tectonic fissures" running N. 50° W. near the power dam just southeast of Thingvellir. Saemundsson (1967b) mapped several faults striking N. 50° to 70° W. in Hengill, the major geothermal area just southwest of Thingvellir. Similar faults were suggested in this region by Tr. Einarsson (1962). Saemundsson (1967b) also pointed out a northwest-trending fissure volcano in Hengill and another about 12 km to the west-southwest. Nearly all of the region in south-central Iceland where these faults might be expected to continue is covered by alluvium and young lava flows (K. Saemundsson, 1970, personal commun.) and has been transgressed by the sea since the last glaciation (Kjartansson, 1962).

Near Reykjavik, there is a major change in the age and lithology of the volcanics in a north-south direction. Here the zone of active rifting changes from a southwest trend to a westward trend (Fig. 6), but the strike of the individual faults remains the same. The islands just north of Reykjavik trend in the west-northwest direction, and the same trend is suggested in the bathymetry southeast of Snaefellsjökull (1:50,000 series topographic maps, AMS, sheets 1513-I, II, and III). Near the eastern end of the presently active section of the proposed fracture zone, there is a valley 1,500 m deep that strikes just north of west in the region west of Myrdalsjökull in south-central Iceland. The mountain on the southern side of this valley is elongated in an east-west direction. The relative positions of the mountains on either side suggest a possible left-lateral offset of 15 to 20 km. The left-lateral motion is the proper sense for the proposed transform fault.

Pálmason (1967a) studied the crustal structure of southern Iceland in detail. He found that layer 2 ($V_p \approx 5$ km/sec) was only absent on the Reykjanes Peninsula, that is, near the western end of the proposed fracture zone. Similar abrupt changes in crustal structure are noted across the Mendocino Fracture Zone (Dehlinger and others, 1967; Shor and others, 1968).

From the heat-flow data given by Pálmason (1967b) for 11 localities in Iceland, three of the four wells with heat flow greater than 3 microcal/cm^2 sec and gradients greater than 70° C/km lie near the northern edge of the Reykjanes Fracture Zone. The fourth well is in northwestern Iceland and may possibly be related to another fracture zone near the bend of linear features in central Iceland discussed below.

The eruptive fissures in Figure 7 might be considered to be centers of spreading occurring at the crest of the ridge. They coincide with the central magnetic anomaly. Generally only one line of these fissures occurs between two transform faults shown in the figure. The interesting point here is that when an eruptive fissure crosses a proposed transform fault, the fissure becomes a noneruptive open fissure or normal fault. Thus, large zones of noneruptive fissures (Icelandic gja) may be most indicative of the proximity of a fracture zone rather than simply the crest of a ridge.

Snaefellsnes Fracture Zone

Saemundsson (1967a) mapped a "very conspicuous fault zone" 10 to 15 km wide cutting across Tertiary Plateau Basalts on the eastern end of the Snaefellsnes Peninsula. The faults are diffuse and the fractured area is split into a number of parallel grabens and horsts, each of limited extent. Sigurdsson (1967a) pointed out that the trend of this zone continues in submerged hills off the coast. Few earthquakes were recorded from this zone, suggesting that it has only been slightly active recently. Postglacial volcanism, however, shows that this zone was quite active since the last glaciation (Saemundsson, 1967a). It may be that the small block bounded by the Reykjanes Fracture Zone, the Snaefellsnes Fracture Zone, and the Thingvellir rift zone is being gently folded and deformed in order to allow some spreading in the Thingvellir rift zone, while the main focus of spreading is presently in the eastern limb of the zone of active rifting. Sigurdsson (1970) independently suggested a similar origin for the Snaefellsnes Fracture Zone. This fracture zone may also be an old fracture that extended east-southeastward through the southern edge of Vatnajökull and through the largest volcano in Iceland, Öraefajökull (Fig. 6).

Tjörnes Fracture Zone

The fracture zone just north of Iceland proposed by Sykes (1967) from earthquake data is apparently only clearly exposed on land near Tjörnes. The rocks on Tjörnes are marine sediments and basalts tentatively dated as Upper Pliocene to early Quaternary. Local dips of the basal basalts are as large as 30° to the northwest (Áskelsson, 1960; Th. Einarsson and others, 1967). The sedimentary rocks are unlike other rocks exposed in Iceland. The peninsula "is (geologically) isolated; it is separated by an area much disturbed by faults" (Tr. Einarsson, 1958). The primary fault zone strikes west-northwest (Strauch, 1963) and contains steeply dipping basalts that are heavily fractured and very much altered. A number of other faults striking west-northwest can be clearly observed from air photographs taken just to the south near Husavik. Van Bemmelen and Rutten (1955) mapped faults along this trend but to the southeast. The suggestion made here is that the Tjörnes rocks either lie to the north of a narrow fracture zone, or more likely, that they lie within and near the southwestern edge of a broad fracture zone. The distribution of earthquake epicenters suggests that this zone may be as much as 50 km wide. Part of this estimate of the width is probably due to the poor accuracy of the epicentral locations. Grimsey, the island just north of Iceland, contains Tertiary Flood Basalts.

No clear trace of this proposed fracture zone is seen in the bathymetry north of Iceland. The sea floor, however, has not been mapped in detail in this region. Local sedimentation, erosion, and volcanism might easily obscure any fracture zone trending along the coast. There is active volcanism in the rift zone east of the faults mapped by van Bemmelen and Rutten (1955). A number of submarine lava eruptions, particularly in the 18th and 19th centuries (Berninghausen, 1964; Thorarinsson, 1967b) were reported along the eastern part of this proposed fracture zone.

Dearnley (1954) mapped a northwest-striking dike in shattered and tilted basalts in northeastern Iceland in a region that could be an extension of the fracture zone. This area and the region just to the north have not been mapped well enough, however, to see clearly whether there is or is not an extension of the fracture zone through the region of Tertiary Flood Basalts.

Layer 2 is found near Tjörnes (Pálmason, 1963), so that the lack of layer 2 on the Reykjanes Peninsula does not seem to be typical of the fracture zones discussed here.

Askja Bend in the Neovolcanic Zone

In central Iceland, the eastern neovolcanic zone bends from a north-northeast trend south of Askja to a more northerly trend north of Askja. Van Bemmelen and Rutten (1955) mapped several west-northwesterly trending faults and a small graben just east and north of Askja. In the northwest peninsula of Iceland, Sigurdsson (1967a) mapped the orientation of 2035 dikes, faults, joints, and so on, from aerial photographs. In the northern two-thirds of the peninsula, there is a strong northerly trend of these features; but in the southern one-third of this area, these features strike northeasterly or west-northwesterly. Jónsson (discussion in Stefánsson, 1967) noted west-northwest–striking faults north of Hofsjökull.

A similar shift in the trend of dikes is seen in eastern Iceland from the maps of dikes near Reydarfjördur (Gibson and others, 1966). This change in direction, however, is not as convincing. Dearnley (1954) shows that many dikes and two faults farther north in eastern Iceland trend nearly N. 30° E. rather than to the north.

The data presently available (Fig. 6) suggest a bend in the trend of Old Gray Basalts north of Langjökull. This bend does not lie on the same line as those discussed above.

The important conclusion is that the bend in the trend of linear features seems to have been important throughout the formation of Iceland and that a line through the axes of these bends is roughly parallel to the fracture zones discussed above. The bend may, for example, reflect the change in the axis of spreading north of Iceland; it may reflect old zones of weakness in the lithosphere. No seismic activity has been reported along the line of these bends except at the volcano Askja in central Iceland.

NEW INTERPRETATION OF THE GEOLOGY OF ICELAND

The identification of two active transform faults in Iceland is the key observation leading to the new interpretation of the geology of Iceland, summarized schematically in Figure 1. In addition, all the observations discussed in this paper have been used to identify and determine the size of the fracture zones, centers of spreading, and geologic regions shown in the figure.

Some additional comments need to be made regarding the ages of rock units in Iceland.

Age of the Old Gray Basalt

Two different geologic units outside of the zone of active rifting are shown in Figure 6. The Tertiary Flood Basalts, described above, are interpreted in this paper as having been formed primarily between 9 and 20 m.y. B.P., during a period of very slow spreading. The Old Gray Basalts are similar to the flood basalts except that they contain thick intercalations of clastic rocks, tillites, palagonite breccias, and pillow basalts, all of which suggest the presence of ice. The boundary between the Old Gray Basalts and the underlying Tertiary plateau is indistinct in some places and in other areas has not been mapped at all. It is then drawn on the map according to what is suggested by morphological features (Kjartansson, 1962).

The age of the first glaciation in Iceland is not entirely clear. The Pliocene-Pleistocene boundary can probably be dated at 1.8 m.y. B.P. (Hays and others, 1969). McDougall and Wensink (1966) and Th. Einarsson and others (1967) found tillites in Iceland that were 2 to 3 m.y. old. Data collected just northeast of Newfoundland tentatively suggest that the onset of glaciation occurred at about 3 m.y. B.P. (JOIDES, 1970). In the Wrangell Mountains of Alaska, Denton and Armstrong (1969) found evidence for glaciation which occurred as early as 10 m.y. ago. Thus, from glacial evidence, the Old Gray Basalts could have begun forming around 3 m.y. ago and perhaps even as much as 10 m.y. ago.

Dagley and others (1967) studied the magnetic stratigraphy of 1,140 lavas in east-central Iceland. The rocks older than 10 m.y. extend from the east coast to about 15° W., where there is a discontinuity in the sequence according to age determinations and the next rocks to the west were around 3.1 m.y. old.

The discontinuity in the sequence of Dagley and others is partially explained by problems in stratigraphic correlation across a syncline or flexure (Walker, 1964). An additional explanation may be that the center of spreading between 9 or 10 m.y. ago and about 7 or 8 m.y. ago was north of Langjökull in the Langjökull-Skagaheidi zone. Tr. Einarsson (1959, 1962) described many areas of rocks younger than the Tertiary Flood Basalts in this area (Fig. 6) but older than the present period of normal magnetic polarity. Saemundsson (1967a) emphasized that this zone may have been a former volcanic belt. Morphologically, this belt is distinctive. It is the one region in Iceland where most linear topographic features strike north-northwest. The flexure along the eastern edge of the zone of Old Gray Basalts in northeastern Iceland (Walker, 1964) might then be interpreted as forming during the opening of this eastern ridge crest but prior to active volcanism. On the basis of these rather tenuous arguments, it is suggested in Figure 1 that parts of the western zone, including some Old Gray Basalts, were formed between 8 and 10 m.y. ago. Detailed paleomagnetic and stratigraphic mapping should be carried out to test this assertion. Until further evidence is found, the zone is left in Figure 6 with rock units as shown by Saemundsson (*in* Ward and others, 1969). A change in the rate of spreading around 5 m.y. B.P. was postulated on the mid-Atlantic ridge from data collected near 27° N. (Phillips, 1967; Pitman and Talwani, 1971).

Tests of This New Interpretation of the Tectonics of Iceland

Detailed paleomagnetic stratigraphy and age dating should be done throughout Iceland to help define the boundary between the Tertiary Flood Basalts and Old Gray Basalts. This type of study should lead to a better understanding of the period of presumed slow spreading prior to about 10 m.y. and of how rapidly spreading changes occur. According to the tectonic framework presented here, the oldest rocks in Iceland may well occur on the western edge of the northwestern peninsula. So far, data of Moorbath and others (1968) support this prediction.

A few tectonic features that do not readily fit into this hypothesis should be examined. For example, west of Hekla, in south-central Iceland, there are a few north-south–trending faults with observed strike-slip motion.

Surveys of displacement or strain should show spreading and strike-slip motion. Surveys presently underway are primarily designed to measure spreading motion. First-order triangulation networks established in 1955 as a topographic map base should be resurveyed in the regions of the proposed transform faults. The strike-slip motion may be spread out over a zone many tens of kilometers wide.

The rocks in the fracture zone may well have compositions that differ from the rocks elsewhere in Iceland. Peridotites are not observed in Iceland but are observed in many submarine transform faults. This observation probably says more about the origin of peridotites than does the presence or absence of a transform fault. Many basalts in Iceland do contain as much as 30 percent olivine by volume (Jónsson, 1967; Walker, 1959; Tómasson, 1967; Jakobsson, 1966). Such ultra-basic rocks might be more abundant in the fracture zones than along ridge crests.

Many more west-northwest–trending faults in the proposed fracture zones should be found by detailed studies of structure and geomorphology. New fracture zones elsewhere in Iceland may be found.

SPECULATION ON THE ORIGIN OF ICELAND

Wilson (1963) suggested that Iceland may be attributed to a particularly productive source of magma in the mantle. Another possible explanation for the existence of Iceland is that it was formed by a large volume of lava extruded from a broad fracture zone, particularly when the fracture zone was undergoing distortion as the center of spreading shifted. Menard and Atwater (1969) call such a fracture zone "leaky" and propose that topographic ridges parallel to the main trend of the fracture zone can form in such a leaky zone. Thus, although fracture zones generally are not characterized by intense volcanism, they can become centers of spreading and volcanism when stressed during changes in the direction of spreading. Such a fracture zone might be an important source of flood basalts.

It was suggested above that the ridge crest was probably offset near the present latitude of Iceland between about 20 or 30 m.y. and 70 m.y. B.P. Between about 10 and 20 or 30 m.y., the active center of spreading north of this offset appears to have shifted from the Norwegian Sea westward to the Iceland–Jan Mayen Ridge (Fig. 8). Large changes in the stress field along the fracture zone could easily accompany such a shift. The bend of volcanic features in central Iceland may also be closely related to the stress change. It is proposed here that the fracture zone was distorted, allowing extraordinary amounts of lava to be extruded at a time when perhaps there was little spreading elsewhere. Menard and Atwater (1968) have already proposed that fracture zones can act as spreading centers during changes in the direction of spreading. The northern end of the Reykjanes Ridge may also have been distorted so that new lavas increased the elevation of the ridge toward Iceland. The important feature of this explanation for the origin of Iceland is that it implies Iceland was not formed because of some deep-seated difference in the mantle but simply by a slight complication in standard ridge-forming processes. This feature suggests, then, that a detailed study of Iceland can be directly applicable to our understanding of spreading elsewhere around the world and that Iceland is not as anomalous as is often assumed.

As discussed earlier, Noe-Nygaard (1966) suggested that many of the rocks on the so-called Wyville-Thompson Ridge from Greenland to Scotland formed from a fissure system along the same trend about 50 to 60 m.y. ago. This interpretation raises the possibility that the major shift in spreading occurred as early as 50 m.y. ago or that there was more than one time when the fracture zone in this area was stressed.

After the formation of the Tertiary Flood Basalts, ending about 9 to 10 m.y. B.P., spreading may have begun in Iceland along the western zone of rifting and the Skagaheidi-Langjökull zone, and this spreading continued for 2 or 3 m.y. Then the zone of most active spreading may have become the eastern limb of the present zone of active rifting offset along the two proposed transform faults that are presently active. The appropriate gap in the ages of the lava flows along the eastern margin of the eastern zone of active rifting is described elsewhere in this paper. Some very minor spread-

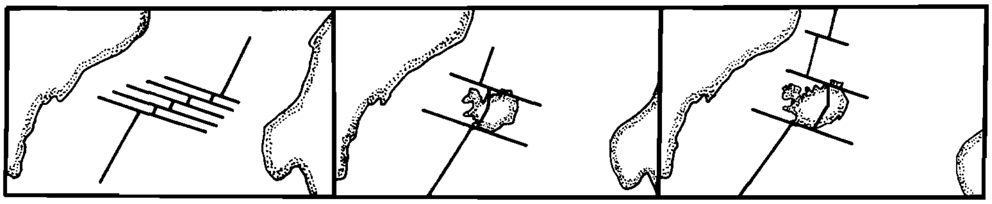

Figure 8. A summary of the formation of Iceland. The left-hand map shows how the North Atlantic may have looked about 40 m.y. ago. Greenland is shown on the west and Norway on the east. The center map shows the same area about 9 m.y. ago with the center of spreading in western Iceland. The right-hand map shows Iceland at present. Norway has been moved away from Greenland in this sequence of pictures by the amount of spreading predicted by Pitman and Talwani (1971) on the basis of magnetic anomalies.

ing may have continued in the Thingvellir zone partially taken up by minor folding to the west and deformation along the Snaefellsnes Fracture Zone.

If we take the simplest and most naive approach toward spreading in Iceland, we might assume that the ridge has spread at a rate of 1 cm/yr on each side for the last 9 m.y. and, therefore, the zone of new crustal material should be about 180 km wide. The width across the zone of Old Gray Basalts and the zone of active rifting in southern Iceland measured along a west-northwest–striking line is about 200 km. In northern Iceland, the width across the northeastern and the older northwestern zones interpreted as spreading centers is about 170 km. This is good agreement considering the problems of defining the edges of these zones and the simplicity of the model.

The Iceland region might best be compared to the region in the South Atlantic near 10° N. and 40° W. where the ridge is cut by a large number of fracture zones and valleys striking nearly east-west. The difference between these two areas may simply be that there have been major changes in the centers of spreading and rates of spreading in the North Atlantic caused by a complex sequence of motions of the North American, Greenland, and European crustal plates. The Jan Mayen Fracture Zone also would have been stressed, although not necessarily in the same manner, at the time of the shift in spreading centers. The island of Jan Mayen exists but there is no land mass similar to Iceland in this region. The essential difference may be that near Iceland, a number of fracture zones seemed to have existed over several degrees of latitude.

Several critical tests can be made to test these two alternative, although not mutually exclusive, hypotheses for the origin of Iceland. The Sr^{87}/Sr^{86} ratio should be determined for rocks from the Faeroe Islands, and detailed magnetic surveys and perhaps drilling studies should be carried out along the ridge between Iceland and the Faeroes to resolve whether the Faeroes can be considered as part of Rockall Bank or part of a northwest-trending ridge.

LESSONS TO BE LEARNED IN ICELAND ABOUT STRUCTURES AND PROCESSES ALONG MID-OCEAN RIDGES

One of the main features of this new interpretation of the geology of Iceland is that structures and processes observed in detail in Iceland can be directly related to structures and processes less well observed along submarine ocean ridges. Several important observations can be made from data already available.

Prevalence and Location of Acid Volcanism

Walker (1959, 1966) found that 14 percent of the rocks in a 4,450-m section of Tertiary Flood Basalts were of acid or intermediate composition. In a 5,000 km^2 area, he found 9 percent acid rocks. Thorarinsson (1967a) concluded that about 10 percent of all eruption products in Iceland were acid and intermediate. The largest rhyolitic zone in Iceland is just north of Mýrdalsjökull in the zone of active rifting. There are many outcrops of acid rocks in the Old Gray Basalts and Tertiary Flood Basalts.

Gale and others (1966) dated 16 acid intrusive rocks from southeastern Iceland and seven from just east of Snaefellsjökull. The ages range from 1.5 to 10 m.y., and all rocks are intrusive into Tertiary Flood Basalts, the majority of which are interpreted in this paper as older than 10 m.y. The interesting feature in southeastern Iceland is that the intrusives lying in lines parallel to the Neovolcanic zone are youngest close to the zone of recent volcanic activity and oldest farthest away from this zone. Thus, acid intrusion is not limited to the central active zone but may occur 50 or more km from its center.

This discussion has some bearing on the size of the zone of active rifting shown in Figure 6. The rocks in the region near Hofsjökull have been called Old Gray Basalts by Kjartansson (1962 [1965]) and part of the zone of active rifting and volcanism by Saemundsson (*in* Ward and others, 1969). Much of this area is either covered by glaciers or glacial drift so that outcrops are few. There is one large acid volcanic complex just southwest of Hofsjökull. In Figure 6, this complex is considered to be extrusive on top of the Old Gray Basalts.

The mobility of water in fractured regions may be important in the formation of acid volcanism. Large volumes of water are necessary to form rhyolites, and Kennedy (1955) showed that water near the magma will tend to enter and be dissolved. Walker (1966) notes that old acid volcanic centers in eastern Iceland are places of unusually vigorous hydrothermal alteration. Rhyolites are found in most of the present major geothermal areas of Iceland.

The presence of acid rocks in Iceland has led some people to conclude that Iceland is an old piece of continental crust (for example, Holmes, 1965). Detailed seismic refraction data (Pálmason, 1963, 1967a, 1971), isotopic age data (Moorbath and others, 1968), Sr^{87}/Sr^{86} studies (Moorbath and Walker, 1965), lead isotopic studies (Welke and others, 1968), and shoreline geometry of Greenland and Europe (Bullard and others, 1965) do not support this idea. Sigurdsson (1967b) concludes that differentiation can account for the acid magma in Iceland. The existence of large amounts of acid rock in Iceland suggests that these rocks may be more prevalent than generally thought to be on mid-ocean ridges.

Origin of Central Volcanos

Major, active, central volcanos in Iceland (Fig. 6) seem to be formed near ridge-crest and fracture zone intersections or at bends in the ridge crests discussed above (Fig. 1). Katla and Hekla in south-central Iceland and Askja in central Iceland are classic examples. The Hengill area in southwestern Iceland might be considered as a developing major central volcanic complex (K. Saemundsson, 1970, personal commun.). Eruptions at most other regions in the zone of active rifting are from fissure volcanos such as Eldgja and Laki, which are northeast of Katla, or the numerous fissures and volcanic cones near Myvatn in northern Iceland. Central vents often form along fissures, as observed during eruptions in Hawaii, but these vents rarely seem to develop into major volcanos. Hekla might be considered intermediate between a fissure volcano and a strato-volcano (Thorarinsson, 1967a).

A number of large glaciers or jökulls have formed in Iceland on high mountainous ranges. Recent volcanic activity is well known under Vatnajökull and Myrdalsjökull (for example, Berninghausen, 1964). The western edges of these two glacial massifs lie in the Neovolcanic zone. The eastern end of Vatnajökull lies on Tertiary Flood Basalts. Öraefajökull, the largest central volcano in Iceland, lies on the southeastern end of Vatnajökull near the boundary between Old Gray Basalts and Tertiary Flood Basalts. It last erupted in 1727. Snaefellsjökull is a recently active volcano on the western end of Snaefellsnes Peninsula, 150 km from the western limb of the zone of active rifting.

Menard (1969) discusses the origin of volcanos in the oceans. He shows that most volcanic seamounts increase in size with distance from a mid-ocean ridge crest and that they may be active while drifting at distances of tens to hundreds of kilometers from the ridge crest. He points out that the volcanos form at "favored locations" in the sea floor but that the reason for this favoritism is not clear, due to the few data on oceanic islands. Using Menard's reasoning, it is not surprising to find some of the largest active central volcanos in Iceland outside of what we have interpreted as the presently spreading ridge crest.

Some large basaltic volcanos in Iceland that cannot be termed central volcanos have also formed in fracture zones or near bends in the zone of spreading. Surtsey, for example, is a volcanic island near the southern end of the fracture zone south of Iceland (Fig. 6). This volcano formed in 1963 and stopped erupting in 1967 (Thorarinsson, 1967b). From the *en echelon* nature of the fracture zone proposed in this paper, Surtsey may be about 100 km east-southeast of the ridge crest. There are many seamounts in this area (Norrman, 1969), but few have reached the surface. Ward and Björnsson (1971) recorded high seismic activity about 10 km northeast of Surtsey in 1968. Pálmason and others (1965) reports finding rocks interpreted as Tertiary Flood Basalts in a 1,565-m-deep well on the Vestmannaeyjar, 15 km northeast of Surtsey. The Vestmannaeyjar are probably of the same origin as Surtsey. The major offset of the southern transform fault seems to occur 20 to 50 km to the north of the Vestmannaeyjar.

Langjökull is near the intersection of the Snaefellsnes Fracture Zone and the western limb of the zone of active rifting. Snaefellsjökull is within 20 km of an extension of this rift zone. Hofsjökull is just east-southeast (that is, along the direction of spreading) of the apparent bend in the western zone of active rifting thought here to be actively spreading 7 or 8 m.y. ago. Myrdalsjökull lies near the junction of the southernmost fracture zone and the eastern zone of active rifting. The southern end of Vatnajökull lies on an east-southeast extension of the Snaefellsnes Fracture Zone and the northern end lies just south of the bend in the zone of active rifting near Askja. All of these massifs could be volcanic complexes that formed near fracture zones and ridge crest intersections or near bends in the center of spreading. Kjartansson (1967) compares these table mountains under glaciers to the origin of seamounts under water.

Many other volcanic islands around the world are extremely close to, if not on, fracture zones; these include Jan Mayen (Johnson and Heezen, 1967), the Galapagos (Herron and Heirtzler, 1967), Easter Island (Menard, 1966), Rodrigues and Prince Edward Island, Ile Amsterdam, and Ile St. Paul (Le Pichon and Heirtzler, 1968), Revilla Gigedo Islands (Menard, 1969) and the Azores (Le Pichon, 1968; Sykes, 1967). Other islands such as the Canary (Bosshard and MacFarlane, 1970) and Cape Verde Islands, St. Helena, Ascension, and Bouvet may well occur on or very near fracture zones. Loncarevic and others (1966) suggested that zones of crustal weakness transverse to the strike of the ridge are important in the origin of volcanos. Their detailed study of the mid-Atlantic ridge near 45° N. did not show clear offsets of the ridge near the three pairs of volcanos found along east-west trends. Their observations do not rule out the possibility of fracture zones with little or no offset.

Although all seamounts and large central volcanos may not originate in the same way, many of the largest appear to be related, at least spatially, to fracture zones. This is particularly true of islands formed by alkali basalt, and Engel and Engel (1964) point out that most islands in the ocean basin consist of alkali basalts. Perhaps fracture zones are one of the few areas where large volumes of magma can reach the surface through a single vent where differentiation can take place. All fracture zones need not necessarily be associated with central volcanos, because the proximity of a fracture zone may be only one of a number of conditions necessary for the formation of many of these volcanos.

Geothermal Areas and Regions of High Heat Flow

All major geothermal areas in Iceland occur within the zone of active rifting or near centers of volcanism (Fig. 6). Bodvarsson (1961) defined major geothermal areas in Iceland as those with temperatures greater than 200° C at depths of a few hundred meters. Heat output at the surface within these areas is as much as 50 to 100 microcal/cm^2 sec. Temperature gradients nearby are often in excess of 150° C/km (Pálmason, 1967b). These areas appear to be controlled by faults and fissures (Bodvarsson, 1961) that allow circulation and free convection of meteoric water (Árnason and others, 1969) to depths of at least 2 km and possibly 10 km (Pálmason, 1967b; Banwell, 1963; Elder, 1965). A full understanding of these high-temperature areas may improve our understanding of zones of high heat flow observed at sea and aid in placing new constraints on petrologic models for the mantle. Furthermore, the convection of water in the upper crust, clearly observed in Iceland, can explain why low values of heat flow are often recorded in pockets of sediments along the ridge crest (Le Pichon and Langseth, 1969).

There is some indication in Iceland that the major geothermal areas occur along fracture zones, near the junction of ridge crest and fracture zones (Fig. 7), near bends in the trend of linear volcanic features and rifts, or near centers of acid volcanism (Fig. 6). J. N. Brune (1970, personal commun.) noted a similar relation between geothermal areas north of the Gulf of California and the junction of a ridge crest and a fracture zone. Geothermal areas have not been found near some recently active volcanos in Iceland such as Hekla and Öraefajökull. High temperature activity is found in northeastern Iceland just east of Myvatn. This region is not near the proposed fracture zones but was a center of volcanic activity in fissures and small central vents during the 18th century (Thorarinsson, 1960). Major geothermal areas may explain the high heat flow in the fracture zones. At least the process of convection of surface water in cracks appears to be an important method of heat transport (Pálmason, 1967b).

Problems of Correlating Aeromagnetic Surveys over Land and Sea

Serson and others (1968) presents 21 aeromagnetic profiles over Iceland in which no clear, long linear anomalies are found parallel to the zone of active rifting. Large positive and negative anomalies are found that appear to this author to be primarily associated with volcanos, volcanic complexes, and known intrusives and are not correlated in amplitude across the island. As discussed earlier in this paper, the mineralogy and physical dimensions of extrusives may be quite different on land than at sea. Furthermore, pillow lavas, because they are fine grained, may have higher remanent magnetism (Nagata, 1961; Luyendyk and Melson, 1967; Marshall and Cox, 1971). The profiles of Serson and others (1968) between 62° and 63° N. show a clear extension of the linear patterns on the Reykjanes Ridge (Heirtzler and others, 1966). Farther north, the correlation breaks down (Talwani and others, 1971). Ulrich (1960) shows that the crest of the ridge at 63° N. is less than 200 m deep. This depth might also be considered as approximately the depth of the shelf around Iceland. This part of the ridge, therefore, may well have been near sea level during the Pleistocene (Shepard, 1963; Veeh and Veevers, 1970). Thus, it may not be possible to trace magnetic lineations observed at sea onto land. Sigurgeirsson (1967) and the Science Institute [University of Iceland] (1970) found linear magnetic anomalies in southwestern Iceland that can be traced from Reykjanes eastward to Hengill and northward to Langjökull, that is, along the zone of active rifting. It is not clear yet how these anomalies relate in age and amplitude to the anomalies observed at sea.

Importance of Subsidence along the Ridge Crest

Tryggvason (1968) concludes that subsidence on the order of 50 m has taken place in the Thingvellir graben in southwestern Iceland during the last 9,000 yrs. On the Reykjanes Peninsula, Tryggvason (1970) estimates a similar rate of 5 mm subsidence per year over a period of 8,000 to 12,000 yrs. Saemundsson (1967b) mapped subsidence along faults in the Hengill region, south of Thingvellir, of as much as 240 m. He found that the older rocks showed more subsidence than the younger rocks, suggesting that this process has lasted for some time. Palagonite breccia believed to have been formed near sea level was found in a well at the southwest tip of the Reykjanes Peninsula at a depth of about 1500 m (S. Björnsson, 1970, personal commun.). This well is situated in the central part of the rift zone. All these observations show that the rate of local subsidence along ridge crests may be as much as one-quarter of the rate of spreading.

CONCLUSIONS

In this paper, a new interpretation of the tectonics of Iceland is presented that is generally consistent with the geologic, geomorphic, and geophysical evidence in Iceland and the observations of mid-ocean ridges around the world. The most important feature of this interpretation is that it provides a framework that can be used to relate detailed studies in Iceland to worldwide processes at mid-ocean ridge crests and along transform faults. This new interpretation should be regarded as a hypothesis to be critically tested.

The major features of this hypothesis are summarized schematically in Figure 1 and are the following:

1. Two major, active fracture zones are identified on land striking west-northwest in southern and northern Iceland.
2. The major part of the Tertiary Plateau Basalts were formed during a period of very slow spreading, probably between 9 and 20 m.y. ago.
3. The Old Gray Basalts began forming at least 3 m.y. B.P. and possibly even 10 m.y. B.P.
4. Volcanic intrusion into old rocks can occur 50 km or more from the center of the central active zone or zone of most recent spreading. Extrusion at the ridge crest, however, is apparently spread over a smaller zone only a few kilometers to tens of kilometers wide.
5. Acid and intermediate volcanics make up roughly 10 percent of the rocks in Iceland. Acid rocks may be just as common along other ridge crests.
6. Many major volcanos may originate near the intersections of fracture zones and ridge crests. Historically active volcanos in Iceland outside of the central active zone fit the observations by Menard (1969) of drifting volcanos elsewhere around the world.
7. Iceland may have been formed by a change of the stress pattern on a broad fracture zone, allowing large volumes of lava to be erupted while there was little regional spreading. This hypothesis implies that Iceland is not as anomalous as it has seemed and that it may offer an excellent laboratory for studying worldwide processes at the boundaries of lithospheric plates along ridge crests and transform faults.

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