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EVOLUTION OF THE AXIAL RIFTING ZONE IN NORTHERN ICELAND AND THE TJÖRNES FRACTURE ZONE.

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Abstract

Bathymetry, stratigraphic correlations and distribution of of volcanism indicate that the Tjörnes Fracture Zone (TFZ) is composed of several subsiding troughs and volcanic chains having N-S trend, thus differing structurally from the undivided axial rifting zone in northern Iceland. The N-S troughs across the TFZ developed successively as spreading axes across the TFZ. Thus a spreading axis shifted from a position at 18° West to a position at 17° West during late Matuyama to early Brunhes times. The southern margin of the TFZ is bounded by WNW-ESE trending oblique-slip faults observed on land to the south of Tjörnes peninsula and traceable on the sea bottom for 70 km to the WNW of Tjörnes. The strike-slip along these faults amounts to possibly some 60 km, most of which was accomplished prior to the development of the presently active spreading axis of the Axarfjördur trough. The southern boundary of the TFZ cannot be traced as distinct faults across the flood basalt areas east of the axial rifting zone. However, a former position of it is indicated by juxtaposed rock series of widely contrasting ages.

Available K-Ar ages and paleomagnetic stratigraphy indicate a gap in the lava succession in eastern Iceland between approximately 8 and 4 my ago. This is correlated with a major shift and reorganization of the axial rifting zones which affected the TFZ as well. Flexuring of the Tertiary basalts and accumulation of sediments in the resulting trough preceded formation of the present day rifting zone in northern Iceland 4 my ago. Before this event the Reykjanes - Langjökull rifting zone in SW-Iceland extended up to Skagi on the north coast to join more or less directly with the Kolbeinsey Ridge. The Tertiary basalts of northern and eastern Iceland formed in this western rifting zone of which the northern part is now extinct. Accreting plate margins in the Iceland region moving WNW relative to a stationary mantle hot spot plume under Iceland could explain the shift of a ridge segment to a new position above the hot spot east of the formerly active zone.

CONTENTS

1. Introduction.

Just north of Iceland earthquake epicenters are distributed along a broad E-W trending zone (Tryggvason, 1959, Sykes, 1967), Ward (1971) discussed this feature in terms of a fracture zone which according to him strikes northwesterly and is clearly exposed on land only near Tjörnes peninsula. A geological approach to the structure of a fracture zone is thus possible in this particular case.

The idea of an eastward drift of the Tjörnes peninsula along WNW-trending right lateral faults was discussed among Icelandic geoscientists already in 1967, but the evidence for the fault was not published. Likewise the evidence for a shift of the rifting zone from the western to the eastern part of Iceland evolved some years ago among Icelandic geologists but it was not mentioned in print until 1971 (Ward, 1971). There is increasing evidence for the shift from both geology and geophysics.

The purpose of this paper is twofold:

1. To sum up the broad geological features of the Tjörnes Fracture Zone and to demonstrate the evidence available for right lateral displacements associated with it.

2. To discuss and interpret data having bearing on a shift of the axial rifting zone in northern Iceland to the present position about 4 my ago.

The term axial rifting zone is preferred to the more general term of active volcanic zone to designate the continuation of the axis of the Mid-Atlantic Ridge through Iceland along stretches between fracture zones.

Stratigraphic subdivisions based on the geomagnetic time scale (Cox, 1969) are used throughout the paper, this method of correlation being unambiguous and easily applicable in a young volcanic terrain. The onset of the ice age within the flood basalt succession of Iceland is marked by the appearance of tillites, brown sand- or conglomerate beds and thick hyaloclastites instead of dominantly red dust and weathering beds, showing a drastic climatic change. K-Ar datings and paleomagnetic correlations (McDougall & Wensink, 1966 ; Piper, 1971 ; Noll & Saemundsson, 1973) show that the tillite beds first become abundant upwards of the Mammoth event of the Gauss epoch, about 3 my ago. A climatic change at about the same time is further borne out by a change in both marine organisms and land vegetation preserved in the fossiliferous deposits of the Tjörnes peninsula in northern Iceland (Th. Einarsson et al. 1967). In the following discussion flood basalts older than the Mammoth event of the Gauss are referred to as Tertiary. From the Mammoth event upwards they are considered as belonging to the Quaternary period although this term is avoided.

2. Structure of the axial rifting zone in northern Iceland and its continuation across the Tjörnes Fracture Zone.

The axial rifting zone in northern Iceland is structually complex. West of the Jökulsá river (Fig. 1) it consists of several elongated units trending NNE-SSW which are arranged in echelon. Each of these units is made up of a fissure swarm with normal faults, eruptive and open fissures passing through a central volcano which marks the place where the activity of the swarm is most intense. This is considered as the surface equivalent of eroded central volcanoes and related dyke swarms well exposed in eastern Iceland (Walker, 1963). Surface volcanism of two such swarms fades out south of Axarfjördur. This occurs after the intersection with WNW trending large faults south of Tjörnes peninsula, referred to here as the Húsavík faults. The fissure swarms, however, extend far beyond surface volcanism displaying fault escarpments and open fissures. The Húsavík faults from the southern margin of the TFZ. They are discussed in a later section of this paper and interpreted as having a large dextral strike-slip component.

East of the Jökulsá river volcanism and rifting are less prominent and central volcanoes are noticeably absent. Late Pleistocene fissure volcanism is predominant and postglacial volcanic activity is very subordinate. A marked change in both trend and frequency of fissure volcanoes indicates the intersection of the axial rifting zone with the TFZ.

The axial rifting zone is offset by about 100 km along the TFZ which strikes near to N 67° W. North of the TFZ spreading is resumed by the Kolbeinsey Ridge segment of the Mid-Atlantic Ridge (Sigurdsson & Brown, 1970; Vogt et al., 1970) which extends well into the Icelandic shelf area. The TFZ thus occupies a stretch 75 km wide which is defined by the onset of the Kolbeinsey Ridge in the north and the Húsavík faults in the south.

It is evident from surface geology and the bathymetry of the TFZ that it is more complex in structure than the ridge segments to the north and south. The TFZ appears to be composed of several N-S trending tension fault zones and volcanic chains distributed between Slétta and Skagi (Fig. 2). The easternmost of these features is the Slétta peninsula with three swarms of volcanoes and faults (Fig. 1). Two of these swarms, both in the west of Slétta, are highly mobile and continue south into one of the fissure swarms of the axial rifting zone.

Immediately west of Slétta the 25 km broad Axarfjördur depression (Fig. 2) extends across the Tjörnes Fracture Zone in direct continuation of the western part of the axial rifting zone in northern Iceland. The Axarfjördur depression is a downfaulted through which has subsided 1000 m or more relative to its uplifted western margin at Tjörnes where Tertiary rocks are exposed up to 727 m altitude. A 365 m deep borehole on land in the Axarfjördur through penetrated 250 m of sediments and hyaloclastites before it reached a basaltic basement at 250 m depth. Seismic refraction measurements indicate a depth of 400 - 700 meters to Tertiary basalts in this area (Pálmason, 1963). Volcanism is not known to have occurred within the trough but is present along its western margin in the submarine volcanic chain of Mánáreyjar. This chain extends for about 40 km to the north of the Tjörnes peninsula. Morphologically it is 5 km wide and about 100 m high above the adjacent sea floor. The crest is dotted with hillocks which may represent the remnants of volcanic cones. They reach sea level in the islands of Mánáreyjar (Thorarinsson, 1965). To the south of Mánáreyjar the margin of the Axarfjördur trough is intensely blockfaulted. The faults have N-S trend and downthrow on the east side. They run across the eastern half of the Tjörnes peninsula. There are no signs of volcanism along this fault swarm, and a lava cover of late Matuyama to early Brunhes age (Fig. 3) appears to have flowed into the area from the southeast. South of the Húsavík faults the N-S faults bordering the Axarfjördur trough merge with the westernmost volcanically active fissure swarm of the axial rifting zone. Since there is so little volcanism within the Axarfjördur trough it appears that this trough is presently undergoing ductile thinning and near surface tensional faulting, mainly along the margins but to a lesser extent also in continuation of the NNE-SSW fissure swarms of the axial rifting zone farther south.

The interpretation of the Húsavík faults as a dextral transform fault zone calls for a spreading axis to the west within the TFZ. There is little evidence available at the present to support this. However south of the Kolbeinsey Ridge a N-S oriented, 300-400 m deep trough of unknown origin is present (Fig. 2). The most likely explanation is that it formed by subsidence (Tr. Einarsson, 1963), in which case it would be analogous to the Axarfjördur trough. Recent seismic profiles provided by the U.S. Naval Oceanographic Office indicate that the trough contains sediments up to 500 m in thickness, and further that it is bounded by a fault in the south at 66°17´N, coinciding with the proposed continuation of the Húsavík faults. Present data is, however, insufficient to make further conclusions on the origin of this feature.

Also inadequately known is the area to the NNE of Skagi. Earthquake epicenters (Fig. 2), Pleistocene volcanic activity (Everts et al., 1972) and pronounced N-S trending morphological features indicate considerable tectonic activity in that area.

The island of Grímsey lies in the center of the Tjörnes Fracture Zone. It consists of gently SW dipping plateau basalts with intercalated conglomeratic sediments and hyaloclastites (Th. Einarsson, 1962) suggesting glacial conditions at the time of formation and an age younger that mid-Gauss. This is in a striking contrast to the SW-dipping basalts of the coastal areas to the south of Grímsey which are well down in the Tertiary sequence. Furthermore Grímsey is cut by only a few N-S trending dykes and the secondary mineralization is insignificant in contrast to the coastal area to the south where dykes and secondary infillings are abundant. Thus a considerable difference in the level of erosion is also present between Grímsey and the coastal area, explicable only in terms of a different geologic history. Most probably the island of Grímsey is a remnant of a more extensive volcanic area related to a spreading axis of Gauss to Matuyama age which extended across the TFZ and became inactive sufficiently long ago for erosion to expose dykes and carve out the morphology of the peninsular shelf around it.

3. The Húsavík faults: their disruption of the flood basalts and their possible extension.

The Húsavík faults trend N 60°- 65 W and can be followed as a distinct morphological feature for over 25 km from near the eastern margin of the axial rifting zone to the sea just north of Húsavík village (Fig. 3). To the north of the Húsavík faults, rather steep northerly dips occur in the west of the Tjörnes peninsula. The stratigraphically lowest unit there is a plateau basalt series of about 1000 m visible thickness, which is unconformably overlain by about 1000 m thick mainly marine sedimentary sequence and basalts of Pliocene and Pleistocene age (Th. Einarsson, 1971). The age of the plateau basalt series is unknown except what can be inferred from the overlying sediments. For reasons given in a later section of this paper an age of less than 8 my is attributed to the plateau basalt series.

Immediately to the south of the Húsavík faults late glacial and postglacial rocks are found which have not been tilted but further south their basement rocks are exposed (Fig. 1). They strike parallel to the volcanic zone and are tilted east towards it by up to 4°. The rocks belong to the uppermost sequence of plateau basalts with intercalated tillites and hyaloclastites and are almost certainly of upper Matuyama age. The age difference of the rocks across the Húsavík faults is, therefore, between 3 and 7 my. It is improbable that this could have been brought about by vertical displacements alone, although this obviously was a factor. Accumulation of volcanic rocks within the rifting zone to the southeast associated with subsidence and westward drift past the Tjörnes peninsula along the Húsavík faults is considered a more reasonable explanation.

The southern boundary of the TFZ is thus clearly expressed along the stretch where crustal elements have moved in opposite directions. A geological survey of the plateau basalts of the NE-corner of Iceland in the prolongation of the Húsavík faults was undertaken by the author to examine whether traces of former, now inactive positions were present. The plateau basalts in this area dip west towards the axial-rifting zone. To the north of the prolongation of the Húsavík faults the Tertiary flood basalts extend as far west as the east side of Slétta (Fig. 1) where they disappear beneath volcanic rocks of Brunhes age. Tertiary age is indicated by virtually a total lack of detrital beds indicative of glacial or fluvioglacial action during the building up of this sequence. Also the paleomagnetism does not yield a pattern similar to the Matuyama and Gauss epochs.

To the south of the extrapolation of the Húsavík faults the situation is quite different. The Tertiary flood basalts having generally gentle dips in the east suddenly plunge by up to 20° - 35° towards the axial rifting zone (Fig. 1). This flexure (Rutten and Wensink, 1960 ; Walker, 1964) can be followed from the south coast, south of the Vatnajökull ice sheet up to Vopnafjördur in the north where it fades into a narrow fault swarm which continues up to the coast south of Langanes. To the west the flexured lavas are overlain by basalts having gentler dips and usually separated from the flexured lavas by thick detrital beds. The flood basalts between the flexure and the Brunhes epoch rocks have been correlated with the upper Gilbert trough Matuyama epochs (Wensink, 1964 ; Vilmundardóttir, 1972), based on K-Ar datings, paleomagnetism and morainic intercalations.

The extrapolation of the Húsavík faults thus separates the non-flexured Tertiary sequence to the north from a flexured Tertiary sequence and a flood basalt sequence of upper Gilbert to Matuyama age, to the south.

These relationships indicate a relatively unbroken sequence of volcanic extrusions within the axial rifting zone south of the Húsavík faults over a period of time going back to about 4 my ago. No such continuity is apparent to the north of the extrapolation of the Húsavík faults. A scar marking a former position of the southern TFZ boundary is thus present although hidden because of some overlap. There are no signs that the TFZ was operative during the formation of the Tertiary flood basalts in this area because their flexuring marks the beginning of a discontinuous development across the southern boundary of the TFZ. We will come back to the significance of the flexure in a later section of this paper.

4. Further evidence of strike-slip movement along the Húsavík faults.

4.1 Alteration and crushing of rocks, thermal waters and drilling near the Húsavík faults.

The rocks in the vicinity of the Húsavík faults are, as could be expected, extremely shattered and brecciated and are extensively pervaded by veins of calcite and zeolites (Tr. Einarsson, 1958). The same applies to the basalts to the south and west of Flatey. Obliquely slickensided fault planes are exposed in the area of the Húsavík faults (Trifonov, pers. comm.).

Several natural hot springs occur along the Húsavík faults near the coast and on drilling a hot water aquifer with temperature of about 100°C was found (Tómasson et al., 1969). The deepest drillhole, 1506 m (Fig. 3) penetrated highly crushed basalts, breccias and sediments containing secondary minerals amounting locally to more than 50% of the rocks. This borehole came into the oblique-slip faults at 250 m depth. A 637 m deep borehole 800 m to the SE penetrated less altered basalts with hyaloclastite and conglomerate interbeds. Temperatures of less than 50°C were encountered. This borehole is located south of the oblique-slip faults and is thought to be wholly within basalts of upper Matuyama age.

4.2 Volcanism near the Húsavík faults.

Volcanic activity along the Húsavík faults is insignificant, the only major eruption being an interglacial shield volcano, Grjóthals, some 5 km south-east of Húsavík village a short distance to the south of the faults. The lavas from the volcano have been piled up against the fault escarpment and some have flowed over it and are found as remnants in the area just to the north of Húsavík (Fig. 3).

The island of Flatey which lies immediately to the north of the Húsavík faults (Fig. 2) is made up of a non-tilted interglacial lava flow (Péturss. 1934 ; confirmed by Tr. Einarsson, pers. comm.). The most reasonable explanation is that this lava is the result of an eruption on the fault located in this area rather than it originating in the volcanic areas to the SE. This view is supported by examination of the submarine topography.

4.3 The submarine continuation of the Húsavík faults.

The submarine topography to the northwest of Tjörnes shows an offset of the Grímsey-shoal to the east relative to the nearest mainland peninsula, of which it is evidently a morphologic continuation (Fig. 2). The offset is marked by the depth contours clearly tracing deep embayments in the shoal platform close to the coast in direct continuation of the Húsavík faults. The morphological offset is difficult to estimate but possibly amounts to about 5 km. This is interpreted as right lateral displacement in support of the transform fault concept.

During an earthquake episode in 1872 one major shock and several aftershocks occurred in the area between Flatey island and the mainland 25 km NW of Húsavík village on the proposed transform fault. In the year 1260 a great earthquake ravaged the island of Flatey (Thoroddsen, 1925). Severe earthquakes are likewise reported from Húsavík and Flatey in 1755 (Thoroddsen, 1925). This indicates a close connection between the two areas as could be expected if they lie on the same fault zone.

5. The magnitude of strike-slip movement along the Húsavík faults.

Most of the Tjörnes Fracture Zone is under water and we are as yet in a position only to examine the southeastern part of this fracture zone. As mentioned previously, spreading apparently occurs along several N-S trending features which lie across the TFZ. However, it is not known how the total spreading rate of 2 cm/yr is divided among them. The Húsavík faults are transformed stepwise into N-S trending tension faults at their southeastern end (Fig. 3). The transition is completed near the middle of the westernmost NNE-SSW fissure swarm of the axial rifting zone. This indicates that from the total spreading of the axial rifting zone only half of the spreading contributed by this particular swarm is transformed to a more westerly spreading axis, probably located in the trough south of Kolbeinsey. Farther east the presence of fissure swarms continuing into the Axarfjördur trough and along the Slétta peninsula indicates that most of the spreading within the TFZ is presently accomplished along these structures. It is therefore expected that the lateral offset currently taking place along the Húsavík faults is relatively small and that the main offset is accomplished farther north consistent with the distribution of earthquake epicenters (Fig. 2).

The only direct evidence of the total movement along the southern margin of the TFZ is provided by the approximately 5 km offset of the Grímsey shoal relative to the nearest mainland peninsula. It must be stressed that we are in this case dealing with the lateral displacement of a morphological structure which is composed of two different geological units. Tertiary basalts on land to the south and much younger basalts on the Grímsey shoal to the north, which were probably erupted along a spreading axis right in this area in Gauss to Matuyama times. The offset of 5 km is therefore a minimum value.

A much greater displacement is rendered likely when the short distance of less than 50 km between Tertiary exposures in the east of Tjörnes and SE of Slétta (Fig. 1) is viewed against the distance of 120 km between formations of comparable age on both sides of the axial rifting zone to the south. This discrepancy is readily explained if a spreading axis across the TFZ was located in the Grímsey shoal area from 4.0 until 0.7 my ago. It is obvious that a spreading axis positioned in this area for more than 3 my would yield a lateral displacement of about 60 km along the Húsavík faults. However, these faults lost much of their significance as strike-slip faults when the spreading axis shifted from the Grímsey shoal to the Axarfjördur - Slétta area at about 0.7 my ago.

6. Eastward shift of the axial rifting zone in northern Iceland.

North of the Langjökull glacier (for location see Fig. 1, inset map) runs the axis of a syncline the flanks of which comprise the flood basalts of the whole of NW and middle northern Iceland. This structure led to the proposal of a former volcanic zone continuous through Iceland from the Reykjanes Ridge to Skagi in the north, of which the segment between Langjökull and Skagi is now extinct (Saemundsson, 1967) This was based on the interpretation of the regional dips of the Icelandic basalt pile as being mainly inherited from the process of burial and sagging within the axial rifting zones.

The Langjökull-Skagi zone became inactive before the onset of glaciations in the mid-Gauss. This is shown by the absence of glacial vestiges near the axis of the syncline. Recently published K-Ar ages of Pleistocene basalts from Skagi (Everts et al., 1972) concern some flows and plugs which were erupted after erosion had carved out a deeply incised landscape. Those basalts are apparently unrelated to the former volcanic zone now indicated by the synclinal structure. It seems likely that the extinction of volcanism in this zone was concurrent with the opening of the present day axial rifting zone in northern Iceland. Evidence from the stratigraphy, structure and thermal history of the basalt pile bordering this zone in the east gave the stimulus to the idea of the shift. Fig. 4 shows a correlation of the stratigraphic column in eastern Iceland (Dagley et al., 1967) with the geomagnetic time scale (Cox, 1969 ; Talwani et al., 1971). This correlation shows a hiatus of about 4 my between about 8 and 4 my ago. The hiatus is represented by an unconformity characterized by 1) a strong tectonic disturbance and increase in dip (the flexure of Walker, 1964) of the lower series, and 2) accumulation of beds up to several hundred meters thick of fluviatile and lacustrine sediments, tuffs and agglomerates on the tilted surface which is finally overlain by 3) a relatively undisturbed upper flood basalt series characterized by abundant morainic intercalations except in the lowest part. To the west of the volcanic zone an angular unconformity is also present. Thick detrital beds accumulated there also in the downflexured depression before and in the early stages of the upper flood basalt series. The position of the flexure in this area is shown on Fig. 1 as traced by the author during a short reconnaissance mapping. The flexured rocks can be followed east of the rifting zone along the southeast side of the Vatnajökull ice sheet. Further a marine ingression is known to have occurred in Mýrdalur in the southernmost part of this zone as is shown by fossiliferous sediments brought up as xenoliths (Áskelsson, 1960). A comparison of the fauna with Tjörnes indicates an age younger than mid-Gauss.

The volcanic islands of Vestmannaeyjar lie in the extreme south of this presumably newly established rifting zone. A 1565 m deep borehole on the largest island penetrated 180 m of volcanic breccia succeeded by 700 m of sediments. From 870 m to bottom the borehole penetrated zeolitized basalts of transalcaline composition (Pálmason et al.,1965 ; Jakobsson,pers. comm.) similar to those of the transitional alkali basalt province to the NE (Jakobsson,1972). The age of the basalts is unknown but Tertiary age has been suggested for the lowest part of them (Pálmason et al. 1965) and even for the basaltic basement as a whole (Th. Einarsson,1967). This is consistent with the low thermal gradient of 63°C/km (Palmason,1973). It has been suggested that the sediments between 180 and 870 m depth below Vestmannaeyjar formed at least partly in the same sedimentary basin as the marine strata represented by the xenoliths of Mýrdalur (Th. Einarsson,1967 ; Alexandersson,1972).

The flexuring and the sedimentation within the resulting trough is interpreted as the beginning of the shift of the axial rifting zone from the Langjökull - Skagi area to the present position in northern Iceland. The development of central volcanoes (Fig. 1) within the newly formed volcanic zone apparently did not start until very recently along the presently most active part of the volcanic zone west of the Jökulsá river. This appears to have been preceded by a long period of purely basaltic volcanism.

The sedimentary sequence in the west of the Tjörnes peninsula (Strauch, 1963) was most probably formed within a subsiding trough which lay across the TFZ, offset west relative to the newly established axial rifting zone (Fig. 5). Facies studies (Strauch 1963) have shown that the shores bounding this trough in the south and east oscillated in the area of southern and central Tjörnes and the trough was open towards NW permitting transgressions from that direction. Had this trough formed the continuation of the trough which preceded the formation of the axial rifting zone we would expect to find evidence for the western shores rather than for the eastern ones as observed. This strongly suggests that both troughs developed independantly.

The trough in which the Tjörnes beds were deposited probably began to form when the rifting zone shifted its position between 4 and 5 my ago. The sediments were subsequently buried by volcanism during the upper Gauss epoch. This is concluded from lavas superimposed on the sediments and preserved in NW-Tjörnes which have been correlated with the upper Gauss (Th. Einarsson et al., 1967). The lavas which build up the island of Grímsey and the shelf around it probably are remnants of a lava succession which formed after this trough had developed into a volcanically active spreading axis. It is not known when volcanic activity in this trough came to an end. It is likely, however, that this occurred during late Matuyama or early Brunhes epoch some 0.7 my ago at the same time as the Axarfjördur-Slétta structures began to develop. It is known from paleogeographic and lithofacies studies (Th. Einarsson, 1971)) that the Tjörnes peninsula was low ground, the northern part even below sea level, in late Matuyama times. During this time thick, in part marine sediments accumulated which were subsequently inundated by lava flows from the south or south-east. Possibly these sediments, referred to as Breidavík beds by Strauch (1963) and Th. Einarsson et al. (1967), accumulated in a tectonic depression initiating the later Axarfjördur trough.

A good agreement is observed between heat flow data (Palmason, 1973) and the geology of Iceland if interpreted in terms of a shift of the axial rifting zone. In the areas bordering the Langjökull - Reykjanes rifting zone where volcanism has persisted over a long period thermal gradients are high and decrease gradually away from it. The volcanic zone farther east and the bordering areas yield low gradients as would be expected if this volcanic zone had been superimposed on a crust created within the Reykjanes - Langjökull zone and which had already cooled down. Heat flow data from northern Iceland are very meagre, however they are compatible with an eastward shift of the rifting zone (Palmason, 1973). Furthermore the poorly developed low-temperature geothermal activity in the zones flanking the rifting zone in northern Iceland as compared to the very active low-temperature areas on either side of the Reykjanes - Langjökull zone strongly favor a different history for those two rifting zones.

At this stage the reason for the eastward shift of the rifting zone remains obscure. However, ideas on the role of hot spots (Morgan, 1971 ; Holden and Dietz, 1972) in plate tectonics might offer a clue. According to this hypothesis a stationary plume where hot material rises from deep within the mantle, is situated beneath Iceland. Westward drift of the lithospheric plates in the Iceland region over a stationary mantle hot spot plume would move the spreading axis westwards with respect to the hot spot. At some stage a segment of the ridge shifts to a new position in focus with the hot plume. The length of the shifted segment is probably closely related to the dimensions of the hot plume. This would logically explain the eastward shift of the rifting zone. Fig. 5 shows a possible reconstruction of Iceland 4.5 my ago according to the available evidence, which has been discussed in this paper.

7. Summary and conclusions.

The main conclusions of this paper can be summarized as follows:

1) A large discontinuity is present in the stratigraphic succession of eastern Iceland involving a hiatus of approximately 4 my between about 8 and 4 my ago. Prior to about 4 my ago a volcanic zone existed between Skagi and Langjökull some 150 km west of the presently active rifting zone in northern Iceland. The Tertiary plateau basalts in northern and eastern Iceland up to about 4 my age were erupted there. The basalts of middle northern Iceland should, according to this, be less than 8 my old.

2) The present day rifting zone in northern Iceland and probably also its continuation southwestwards opened up at slightly more than 4 my ago following a period of downbuckling. Fluviatile and lacustrine sediments and tuffs accumulated in the downbuckled trough to be followed by transgression of the sea in the extreme south.

3) The Tjörnes Fracture Zone became operative at the same time as a dextral transform fault zone between the new rifting zone and the Kolbeinsey Ridge. The 75 km wide fracture zone is composed of several subsiding troughs and volcanic chains having N-S trend, which appear to be distributed along the entire length of the fracture zone.

4) The N-S troughs and volcanic chains within the Tjörnes Fracture Zone developed successively as spreading axes across the fracture zone. The first of those involved the western part of Tjörnes where a thick in part marine succession was laid down in a subsiding trough, later modified into a volcanically active spreading axis, lavas of which are preserved in NW-Tjörnes and Grímsey. This spreading axis was succeeded during late Matuyama to early Brunhes times by the Axarfjördur trough and Slétta volcanic chains which have since acted as the most significant spreading axis across the Tjörnes Fracture Zone.

5) The southern margin of the Tjörnes Fracture Zone is represented by large oblique-slip faults, the Húsavík faults, south of Tjörnes which trend approximately 60°-65° W. They can be traced on land for some 25 km and for an additional 70 km on the sea bottom to the NW.

The faults are transformed into tension faults at the intersection with the axial rifting zone southeast of Tjörnes.

6) The trace of a former position of the southern margin of the Tjörnes Fracture Zone is present in the plateau basalts east of the rifting zone in the Northeast of Iceland, where Tertiary flood basalts are in juxtaposition against flood basalts of upper Gilbert to Matuyama age. The juxtaposition of the two rock units does not extend beyond the flexure which initiated the opening of the present day axial rifting zone.

7) Accreting plate margins in the Iceland region moving WNW relative to a stationary hot spot under Iceland could explain the shift of a ridge segment to a new position above the hot spot east of the formerly active zone.

Acknowledgements.

The author is grateful to G.L. Johnson who read a preliminary draft of this article and suggested many improvements. He also provided a seismic profile across the area south of Kolbeinsey and around Grímsey. Thanks are due to K. Grönvold and G. Pálmason for their encouragement and many fruitful discussions.

References.

Alexandersson, T. 1972. The sedimentary xenoliths from Surtsey: Turbidites indicating shelf growth. Surtsey Research Progress Report 6, 101 - 116.

Áskelsson, J. 1960. Fossiliferous xenoliths in the móberg formation of south Iceland. Acta nat. Isl. 2, 3, p. 1-30.

Cox, A. 1969. Geomagnetic Reversals. Science 163, 3864, p. 237 - 245.

Dagley, P., Wilson, R., Ade-Hall, J.M., Walker, G.P.L., Haggerty, S.E., Sigurgeirsson, Th., Watkins, N.D., Smith, P.J., Edwards, J., Grasty, R.L. 1967. Geomagnetic polarity zones for Icelandic lavas. Nature 216, 5110, p. 25 - 29.

Einarsson, Th. 1962. "Report on ground water in Grímsey". State Electricity Authority Report, mimeographed, p. 1-5 (in Icelandic).

Einarsson, Th. 1967. The extent of the Tertiary basalt formation and the structure of Iceland. In "Iceland and Mid-Ocean Ridges", Soc. Sci. Isl. Rit 38, p. 170-179.

Einarsson, Th. 1971. "Geology" p. 1 - 254, Reykjavík (in Icelandic).

Einarsson, Th., Hopkins, D.M. and Doell, R.R. 1967. The stratigraphy of Tjörnes, northern Iceland and the history of the Bering Land Bridge. The Bering Land Bridge, ed. D.M. Hopkins, Stanford Univ. Press, Stanford, Calif., p. 312 - 325.

Einarsson, Tr. 1958. A survey of the geology of the area Tjörnes - Bárdardalur in northern Iceland including paleomagnetic studies. Soc. Sci. Isl. Rit 32, p. 1-79.

Einarsson, Tr. 1963. "On submarine geology around Iceland" Náttúrufrædingurinn 32, 4, p. 155-175 (in Icelandic with an English summary).

Einarsson, Tr. Personal communication (Flatey).

Everts, P., Koerfer, L.E. and Schwarzbach, M. 1972. Neue K/Ar-Datierungen isländischer Basalte. N. Jb. Geol. Paleontol Mh., 5, p. 280-284.

Gale, N.H., Moorbath, S., Simons, J. and Walker G.P.L. 1966. K-Ar ages of acid intrusive rocks from Iceland. Earth Planet. Sci. Letters 1,5 p. 284-288.

Holden J.C. and Dietz, R.S. 1972. Galapagos Gore, NazCoPac Triple junction and Carnegie/Cocos Ridges. Nature 235, p. 266-269.

Jakobsson, S.P. 1972. Chemistry and distribution pattern of Recent basaltic rocks in Iceland. Lithos 5, 365-386.

Jakobsson S.P. Personal communication (composition of basalts underneath Vestmannaeyjar.

McDougall, J, and Wensink, H. 1966. Paleomagnetism and geochronology of the Pliocene - Pleistocene lavas in Iceland. Earth Planet. Sci. Letters 1,4 p.232-236.

Moorbath, S., Sigurdsson, H. and Goodwin, R. 1968. K-Ar ages of the oldest exposed rocks in Iceland. Earth Planet. Sci. Letters 4, 3, p. 197-205.

Morgan, J. 1971. Convection plumes in the lower mantle. Nature 230, p. 42-43.

Noll, H. and Saemundsson, K. 1973. K-Ar ages of rocks from Húsafell in West-Iceland. In prep.

Palmason, G. 1963. Seismic refraction measurements of the basalt lavas in northern and eastern Iceland. Jökull (Reykjavík) 13, p. 40-60.

Palmason, G. 1973. Kinematics and heat flow in a volcanic rift zone with application to Iceland. In press.

Palmason, G., Tómasson, J., Jónsson J. and Jónsson, Í. 1965. "Deep drilling in the Vestmannaeyjar". State Electricity Authority Report 43 pp. Mimeographed (in Icelandic).

Péturss, H. 1934. "The earthquakes in northern Iceland and the geology of Iceland". Ferdabók ed. by Vilhj. Þ. Gíslason, p. 221-222, 1959.

Piper, J.D.A. 1971. Ground magnetic studies of crustal growth in Iceland. Earth Planet. Sci. Letters 12, p. 199-207.

Rutten, M.G. and Wensink, H. 1960. Structure of the central graben of Iceland. Intern. Geol. Congr. Part 18, p. 81-88 Copenhagen.

Saemundsson, K. 1967. An outline of the structure of SW-Iceland. In "Iceland and Mid-Ocean Ridges", Soc. Sci. Isl. Rit 38, p. 157-161.

Sigurdsson, H. and Brown, M.G. 1970. An unusual enstatite - forsterite basalt from Kolbeinsey, north of Iceland. J. Petrol, 11, 2, p. 205-220.

Sykes, L.R. 1967. Mechanism of earthquakes and nature of faulting on the Mid-Ocean Ridges. J. Geophys. Research 72, 8, p. 2131 - 2153.

Talwani, M., Windisch, C.C. and Langseth, M.G. Jr. 1971. Reykjanes Ridge crest. A detailed geophysical study. J. Geophys. Research 76, 2, p. 473-517.

Thorarinsson, S. 1965. "Submarine eruptions off the coasts of Iceland". Náttúrufrædingurinn 35, 49-74 (in Icelandic with an English summary).

Thoroddsen, Th. 1925. Geschichte der isländischen Vulkane, p. 1-458, Copenhagen.

Tómasson, J., Pálmason, G., Jónsson, J. and Björnsson, S. 1969. "Geothermal prospection around Húsavík". National Energy Authority Report, mimeographed, p. 1-50 (in Icelandic).

Trifonov., V.G. Personal communication (obliquely slicken-sided fault planes east of Húsavík.

Tryggvason, E. 1959. "Seismicity of Iceland and surrounding areas". Náttúrufrædingurinn 25, p. 194-197 (in Icelandic with an English summary).

Vilmundardóttir, E.G. 1972. "Report on geological investigations at Jökulsá í Fljótsdal in the summer 1970". National Energy Authority Report, mimeographed (in Icelandic with an English summary).

Vogt, P.R., Ostenso, N.A. and Johnson, G.L. 1970. Magnetic and bathymetric data bearing on sea floor spreading north of Iceland. J. Geophys. Research 75, 5, p. 903-920.

Walker, G.P.L. 1963. The Breiddalur central volcano, eastern Iceland. Quart. J. Geol. Soc. London 119, 1, p. 29-60.

Walker, G.P.L. Geological investigations in eastern Iceland. Bull. Volcanol. 27, p. 1-15.

Ward, P.L. 1971. New interpretation of the geology of Iceland. Bull. Geol. Soc. Am. 82, p. 2991-3012.

Figure captions.

Fig. 1

Structural map of NE-Iceland. Trends in the axial rifting zone and its continuation across the land portion of the Tjörnes Fracture Zone are shown. West of the Jökulsá river volcanism of the axial rifting zone is discontinued at the southern margin of the Tjörnes Fracture Zone. The trace of a former position of its margin is indicated by the juxtaposition of plateau basalts of different age south of Langanes and at the end of the flexure near Vopnafjördur. From this the general trend of the Tjörnes Fracture Zone appears to be near N 67° W although individual faults bounding it like the Húsavík faults may have a more northerly strike. Note the apparent absence of central volcanoes between the Tertiary and presently active ones.

Fig. 2.

Bathymetry north of Iceland according to depth soundings reported on the Icelandic Hydrographic Service maps 1:250,000 sheets nr. 4 and 61 (1955 and 1961) and 1:750,000 sheet nr. 17 (1971). Earthquake epicenter locations after Ward (1971) with additions through 1969 from the "Monthly Seismological Bulletin and Earthquake Data Report" of the U.S. Coast and Geodetic Survey. Note the ridge and trough topography within the Tjörnes Fracture Zone marked by broken lines.

Fig. 3.

The oblique-slip fault zone near Húsavík. The deepest borehole near Húsavík penetrates highly crushed and brecciated rocks from 250 m down to 1150 m, which were interpreted by Tómasson (1969) as highly altered sediments based on borehole cuttings and two cores. An alternative interpretation would be that these rocks are fault breccias of two closely spaced oblique-slip faults. The foreset beds forming the base of the Grjótháls lava probably represent a submarine facies of this flow. The boundary altitude of 200 m north of the faults and 100 m south of them probably represents the sea level at the time of eruption. It is thus an absolute measure of the displacement by the faults since the time of eruption of the Grjótháls lava (last interglacial ?). The Húsavík faults on entering the NNE-SSW volcanically active fissure swarm of the axial rifting zone swing SSW and are transformed into tension faults.

Fig. 4.

Correlation of the stratigraphic column in eastern Iceland (Dagley et al., 1967) with the geomagnetic time scale (Cox, 1969, Talwani et al., 1971). The correlation is based on: 1) the occurrence of tillites and hyaloclastites which become abundant from the Mammoth event of the Gauss upwards (McDougall & Wensink, 1966 ; Piper, 1971 ; Noll & Saemundsson, 1973). Interpretation of the two earliest glacial horizons as pre-Mammoth is corroborated by a new survey of the Fljótsdalur section by Vilmundardóttir (1972) and by K-Ar datings from an overlapping section further north (McDougall & Wensink, 1966). 2) The upper long normal interval which is correlated with ridge anomaly 5, a conclusion favoured by Dagley et al., (1967). 3) K-Ar datings. Those of McDougall & Wensink (1966) and a few (Thingmúli and Gerpir) from (Moorbath et al, 1968) are shown in addition to those shown in the Dagley et al. (1967) paper.

Fig. 5.

Reconstruction of the rifting zones in Iceland before eastward shift to the present position. The axial rifting zone continues north from the Reykjanes Ridge and joins the Kolbeinsey ridge more or less directly. To the east new rifting zones have begun to develop as troughs where thick sediments are being deposited. Offset positions of these troughs within and to the south of the TFZ is responsible for the discontinuity of the flexured zone at Vopnafjördur. The directions of plate motion are taken to be approximately N67°W and N113°E which is parallel to the strike of the Spar and Jan Mayen Fracture Zones. More significantly this is also very near the strike of the Iceland segment of the Wyville-Thomson aseismic ridge fixed by the nearest approach of the Icelandic shelf to the Greenland shelf and the N45°W striking segment of the Wyville-Thomson ridge southeast of Iceland. The trend of the Húsavík faults is between N60°-65°W whereas the general trend of the TFZ and two others further south is more east-westerly. Spreading rates are after Talwani et al. (1971) and Vogt et al. (1970). Positions of earlier rifting zones are marked by synclinal structures of the Tertiary lava pile. The reconstruction south of 65° is merely an attempt to show how the two spreading axes might substitute each other in amount of spreading rates and accretion since 4,5 my ago. The attenuation along those axes leads necessarily to a rotation of the crustal element between them.

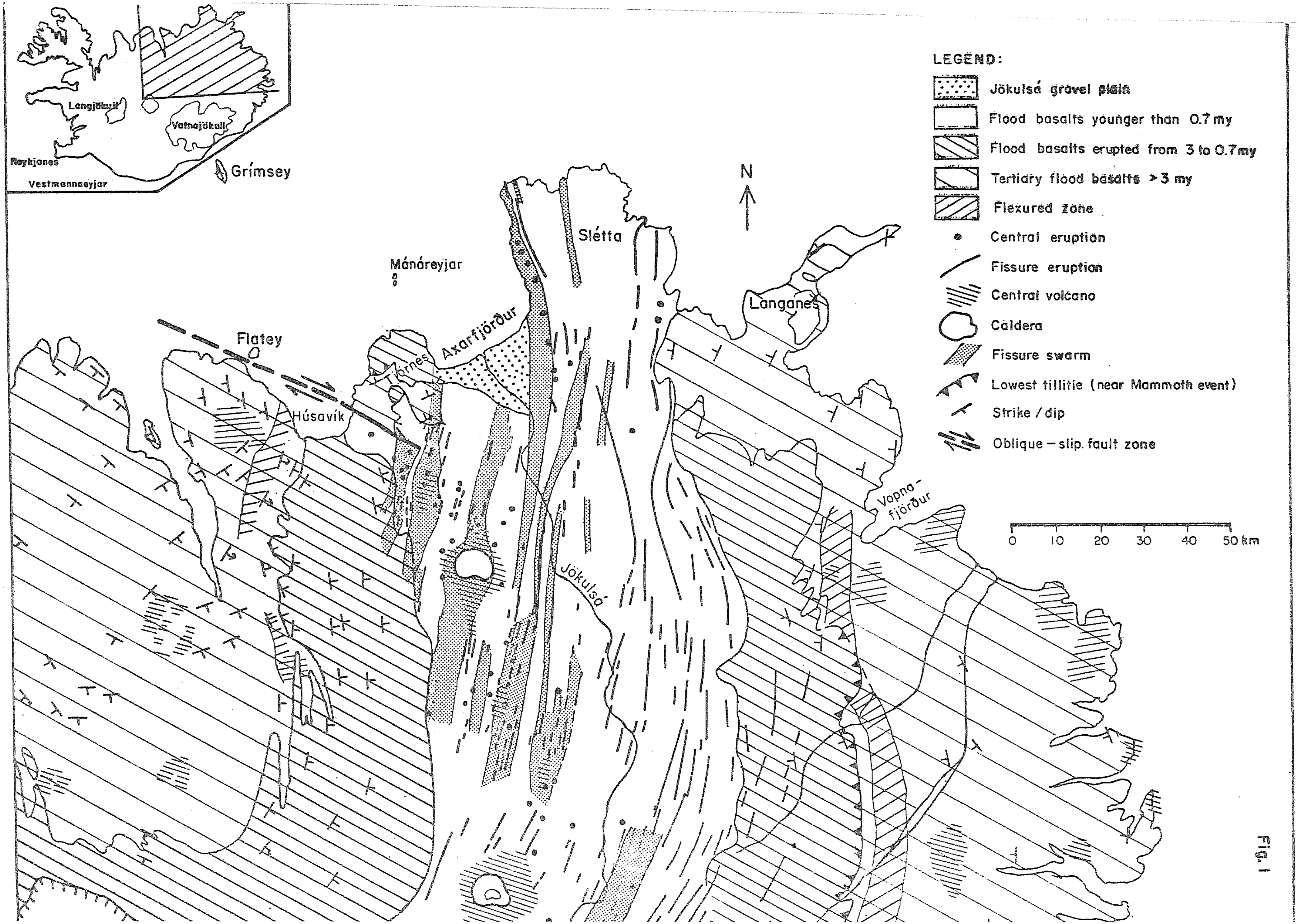
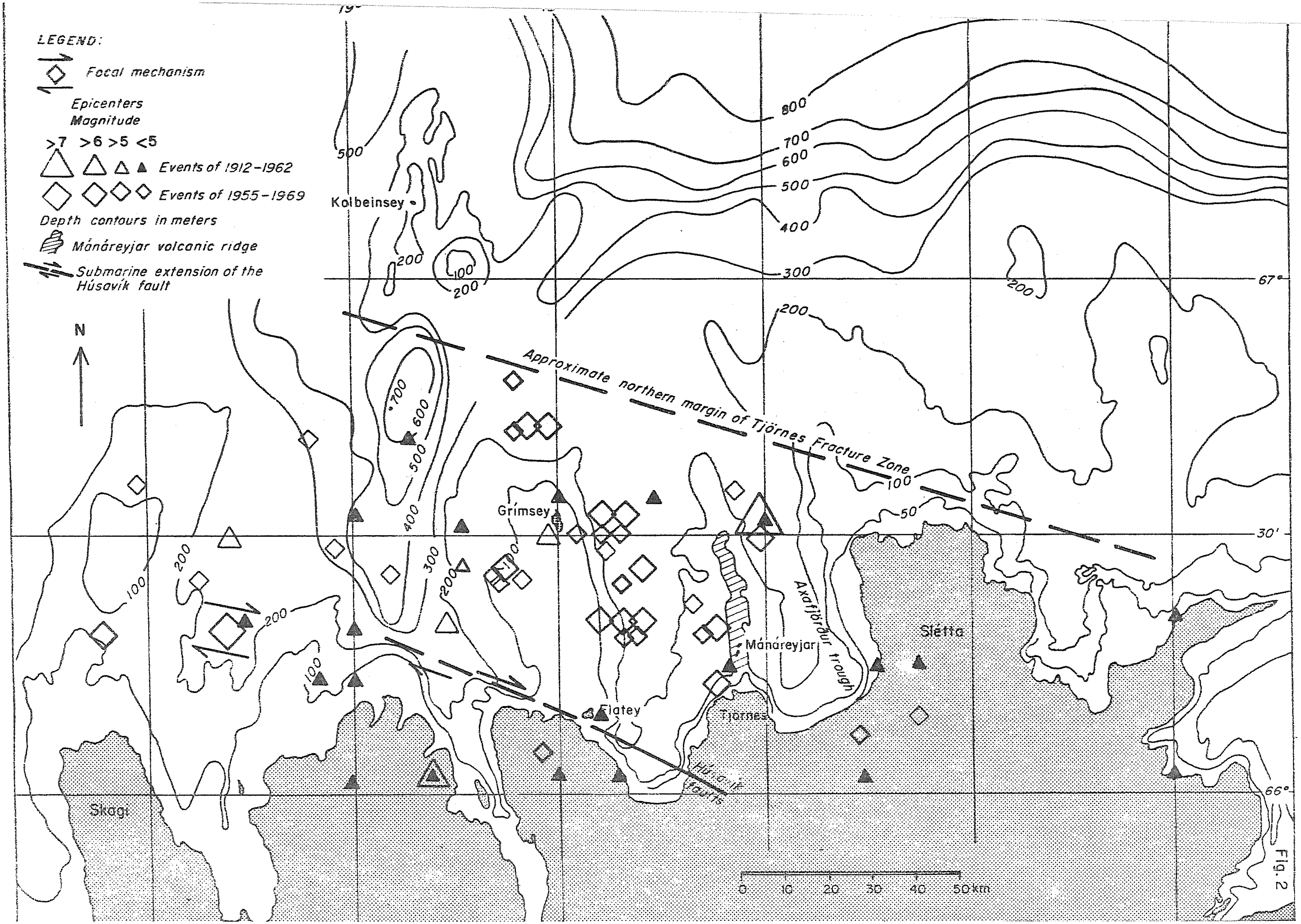
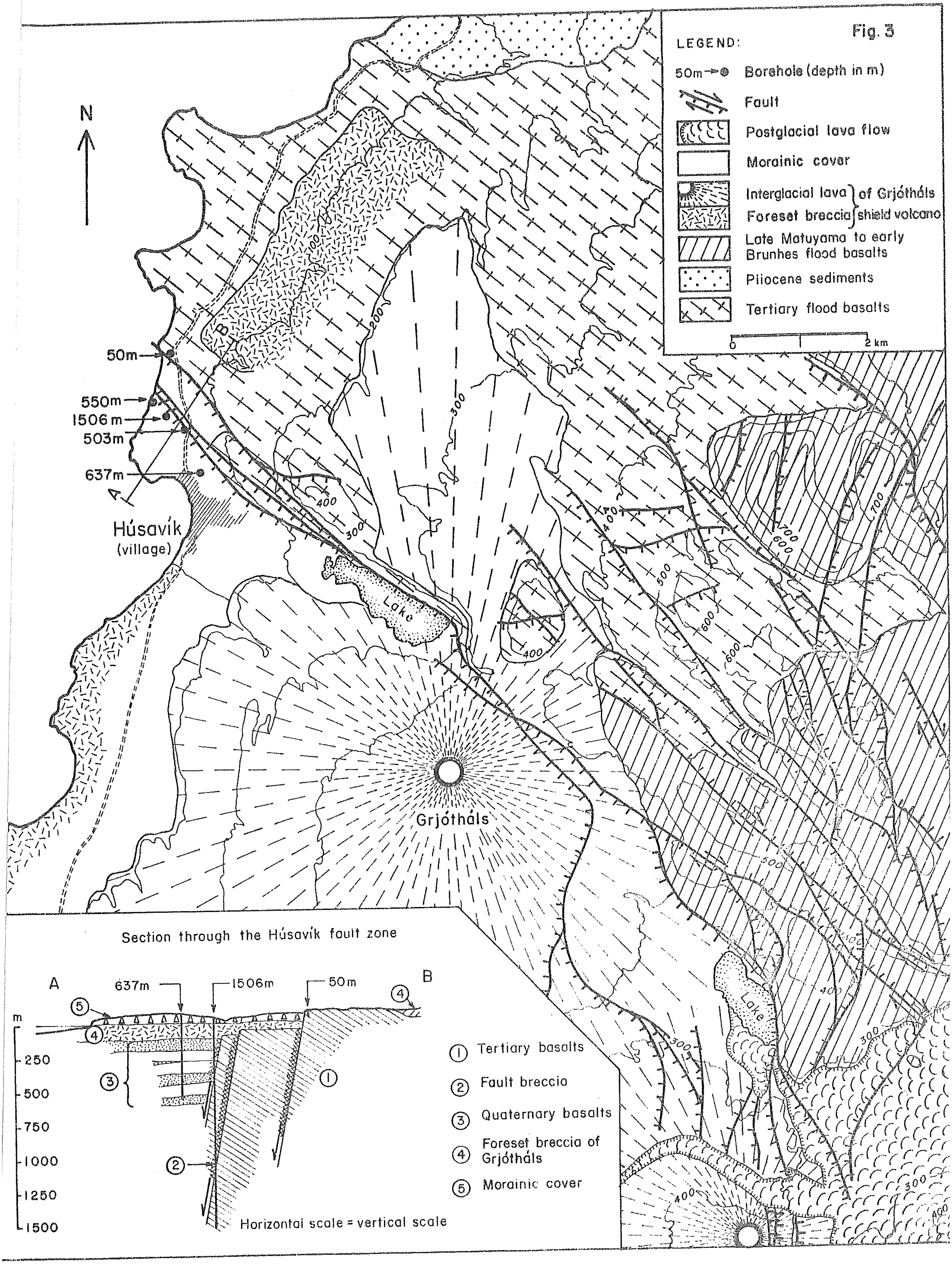

LEGEND:
Jökulsá gravel plain
Flood basalts younger than 0.7 my
Flood basalts erupted from 3 to 0.7 my
Tertiary flood basalts > 3 my
Flexured zone
Central eruption
Fissure eruption
Central volcano
Caldera
Fissure swarm
Lowest tillite (near Mammoth event)
Strike / dip
Oblique – slip. fault zone
0 10 20 30 40 50 km
N
Langjökull
Vatnajökull
Reykjanes
Vestmannaeyjar
Grímsey
Mánáreyjar
Flatey
Húsavík
Tjörnes
Axarfjörður
Slétta
Langanes
Vopna-fjörður
Jökulsá

Fig. I



LEGEND:
Focal mechanism
Epicenters
Magnitude
>7 >6 >5 <5
Events of 1912-1962
Events of 1955-1969
Depth contours in meters
Mánáreyjar volcanic ridge
Submarine extension of the Húsavík fault
N
Kolbeinsey
Grímsey
Flatey
Tjörnes
Mánáreyjar
Axafjörður trough
Slétta
Skagi
Approximate northern margin of Tjörnes Fracture Zone
Húsavík faults
67°
30'
66°
800
700
600
500
400
300
200
100
50
0 10 20 30 40 50 km

Fig. 2



Jarðfræðikort, Húsavík og nágrenni

Fig. 4

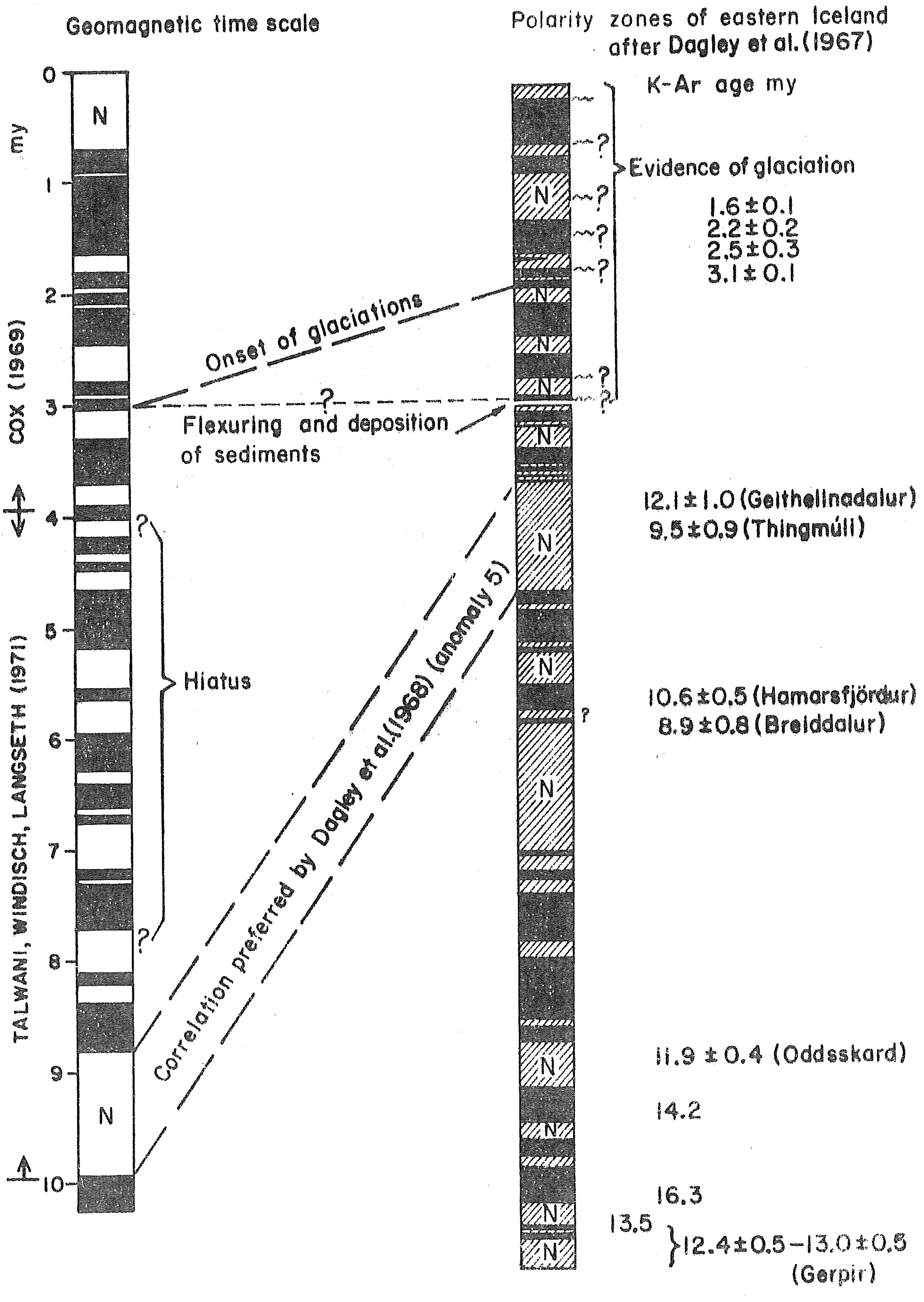
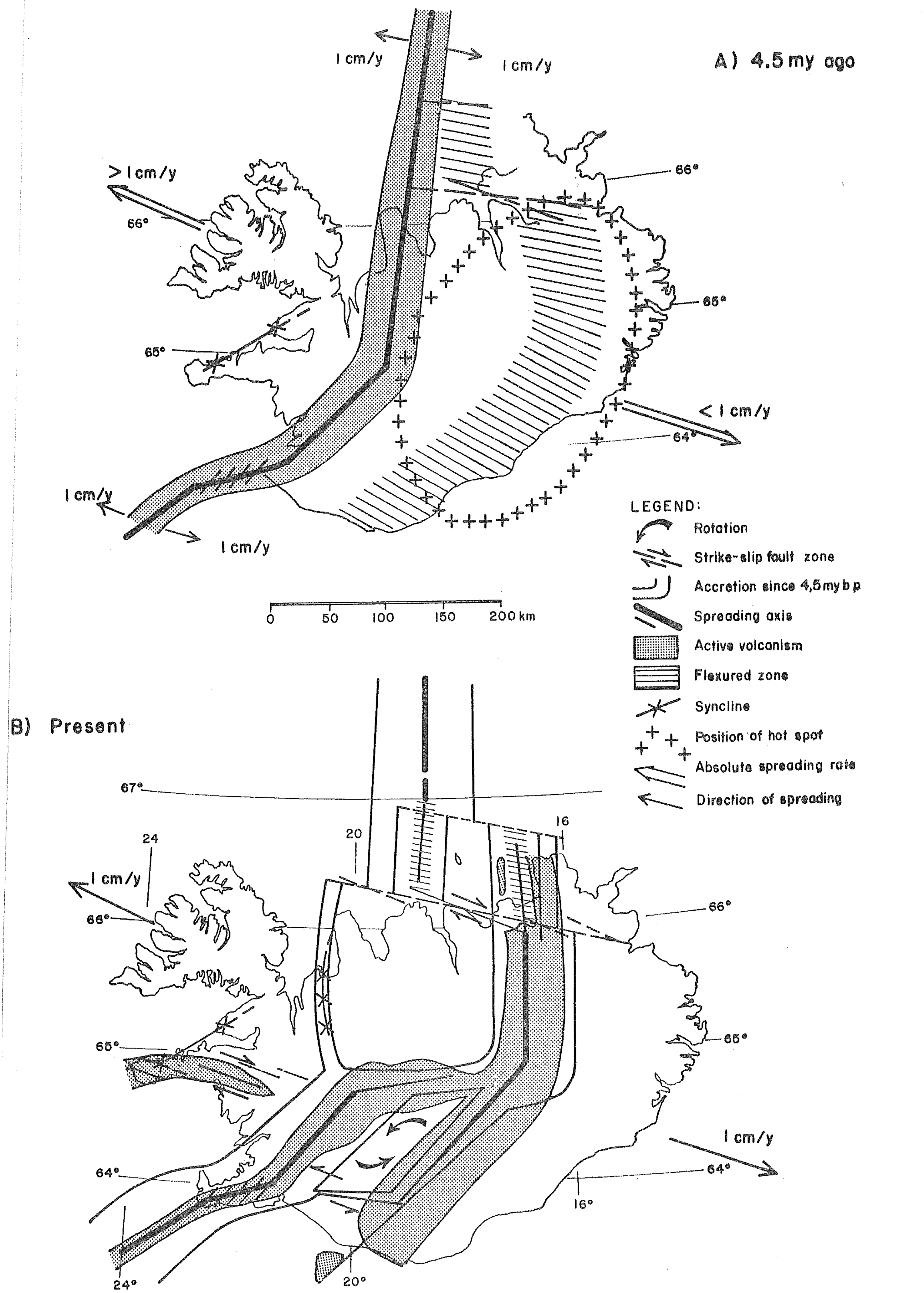

Geomagnetic time scale
Polarity zones of eastern Iceland after Dagley et al. (1967)
K-Ar age my
my
COX (1969)
TALWANI, WINDISCH, LANGSETH (1971)
0
1
2
3
4
5
6
7
8
9
10
N
N
Evidence of glaciation
1.6 ± 0.1
2.2 ± 0.2
2.5 ± 0.3
3.1 ± 0.1
Onset of glaciations
Flexuring and deposition of sediments
Hiatus
12.1 ± 1.0 (Geithellnadalur)
9.5 ± 0.9 (Thingmúli)
Correlation preferred by Dagley et al. (1968) (anomaly 5)
10.6 ± 0.5 (Hamarsfjördur)
8.9 ± 0.8 (Breiddalur)
11.9 ± 0.4 (Oddsskard)
14.2
16.3
13.5
12.4±0.5–13.0±0.5
(Gerpir)

Fig. 5


A) 4.5 my ago
1 cm/y
1 cm/y
>1 cm/y
66°
65°
66°
65°
< 1 cm/y
64°
1 cm/y
1 cm/y
0
50
100
150
200 km
LEGEND:
Rotation
Strike-slip fault zone
Accretion since 4,5 my b p
Spreading axis
Active volcanism
Flexured zone
Syncline
Position of hot spot
Absolute spreading rate
Direction of spreading
B) Present
67°
24
20
16
1 cm/y
66°
66°
65°
65°
1 cm/y
64°
64°
16°
24°
20°