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RECENT GROUND DEFORMATION IN CONTINENTAL AND OCEANIC RIFT ZONES

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ABSTRACT

The active rift zones of the world form a continuous chain of volcanically and seismically active belts in the world oceans, the mid-ocean ridges, with a few extensions into the continents. Furthermore, active rift zones of limited length exist at several location on the continents, such as the Baikal zone, the Rhine graben and the Rio Grande graben. Ground deformation in four segments of the world rift zones, as deduced from geodetic observations are discussed. These zone segments are: The North Atlantic rift zone where it crosses Iceland, the East African rift zone in Ethiopia and Djibouti, the Baikal rift zone in southern Siberia and the Rhine graben in Germany. The results indicate that the existing topographic relief is increasing, low areas are subsiding and high regions are rising. A significant part of the deformation in Iceland and Afar seems to be associated with discrete rifting events which occur at intervals of decades or centuries and are closely related to volcanic activity.

INTRODUCTION

The mid-ocean rift system, roughly 60.000 km in length, is presently recognized by numerous earth scientists as accreting plate boundaries, where the crust on opposite sides moves away from each other, and new crust is formed. This view is supported by a multitude of observations, such as parallel stripes of magnetic anomalies, earthquake focal mechanism, sediment thickness and age of basement rocks.

The surface deformation associated with this relative displacement of the oceanic crust cannot be observed in detail due to the water cover, except where the crest of the mid-ocean ridges are above sea level, as in Iceland, or where the rift system enters the continents, as in Afar.

Rift systems do also occur in the continents, such as the East-African rift zone, the Baikal rift zone, the Rhine graben, rifts in western North America, and the Jordan Valley rift. These rift zones are characterized by recent volcanism, seismic activity and normal faulting, and their structure indicates that recent tensional processes in the continental rift zones are similar to those of the mid-ocean ridges.

The present review deals with the most recent deformation of a few segments of the rift zones based on precise geodetic measurements. The precise observations needed to detect ground deformation in the rift zone were rarely made before about 1960 but increasing effort has been placed on such observations during the last two decades. This short period of precise observation puts severe limitations to the conclusions which can be drawn from them, especially with regard to variation with time in the deforming processes.

Four regions, where some information has been obtained on recent deformation, are here selected as examples of continental and oceanic rift zones.

Iceland is a portion of the Mid-Atlantic ridge. Geodetic measurements aimed at deformation studies were initiated in 1938. Increasing effort has been placed on these measurements since 1965.

The north end of the East Africa rift system in Ethiopia and Djibouti is a border case between oceanic and continental rift zones. Geodetic measurements for deformation purposes were started in 1969.

The Baikal rift zone lies in central Asia and has no connection to the mid-ocean ridges. Extensive remeasurements of level lines during the last decades show the vertical component of ground deformation, but no data on measured horizontal displacements are known to the present author.

The Rhine graben lies in southern Germany and has no obvious connection with the mid-ocean rift system. Great effort has been made to determine the present ground deformation with geodetic means over several decades.

Most other rift zones of the world have not been investigated in such a detail that a clear picture of their present ground deformation have been obtained. The principal exception is the Rio Grande rift in New Mexico, U.S.A., but a comprehensive treatment of the present state of knowledge of the structure and processes at work related to this rift zone has been published recently (Riecker, 1979).

THE ICELAND RIFT SYSTEM (Fig. 1)

The rift system in Iceland is a direct continuation of the Mid-Atlantic ridge to the south and the Kolbeinsey ridge to the north, although branchings and offsets (transform faults?) occur in South Iceland and off the north coast (Fig. 1).

The open fissures and graben structures in the Iceland rift zone were early recognized as a sign of yield to a regional east-west tensional stress (Nielsen, 1930), and an estimate of the rate of tensional movement in recent times in North Iceland, based on open fissures in postglacial lavas, gave a value of 3.56 m per km per 1000 years (Bernauer, 1943). This value was obtained by measurements in the

Krafla fissure swarm in North Iceland, which is some 3 to 5 km wide and Bernauers result indicate an average widening of this fissure swarm of some 10 to 15 meters per 1000 years during the last 5000 to 10.000 years.

In light of these rather obvious signs of recent tensional movement, and the rather crude estimates of the rate of movement, an effort to observe this rate by direct measurements was started in 1938 by establishing a network of precisely measured bench marks across the rift zone in North Iceland (Niemczyk and Emschermann, 1943). Remeasurements of this network were delayed by the second world war but since 1965 has it been remeasured several times and extended greatly both by adding bench marks and introducing new and more precise measuring techniques (Gerke, 1969; Gerke, 1974; Spickernagel, 1966; Schleusener and Torge, 1971). Further measurements of crustal movement in the Iceland rift zone have been performed since 1966 (Tryggvason, 1968; Decker et al., 1971; Brander et al., 1976).

A dramatic rift event in North Iceland which started in 1975 has caused great increase in the effort aimed at understanding the tectonic processes in Iceland (Björnsson et al., 1977). Much of this effort has been towards measuring ground movement and crustal deformation.

MEASURED HORIZONTAL DEFORMATION IN SOUTHWEST ICELAND (Fig. 2)

Precise distance measurements on the southwest tip of the Reykjanes peninsula in 1968 to 1972 show some significant but small length changes (Brander et al., 1976). The network consists of some 40 bench marks and the measured lines are usually about one km. These measurements support the hypothesis of a left lateral transform fault on the Reykjanes peninsula (Tryggvason, 1968) although the measured displacements are not parallel to the active zone, but a significant tensional component is indicated. Thus the active zone of the Reykjanes peninsula can be termed as a leaky transform fault where the opposite sides are moving at an average rate of 9 mm per year relative to each other (Brander et al., 1976).

The Thingvellir area has been the subject of a great effort to determine horizontal deformations. Measurements by a group from Imperial College in London 1968 to 1972 across the Thingvellir graben show significant length increases of 11 and 14 millimeters on two lines while all other lines in the nearly 30-line measuring program showed no significant length changes. This result indicates that the Thingvellir graben is widening at an average rate of about 3 mm/year (Brander et al., 1976).

Another series of distance measurements in the Thingvellir area was made by a German team in 1967 and 1971 (Gerke, 1974). The first interpretation indicated that no horizontal displacement of bench marks could as yet be established in geodetic control network covering an area of 20 km in N-S direction by 30 km in E-W direction. A much smaller quadrilateal across the Thingvellir graben showed a general increase of line length of about 10 ppm on the average, which is interpreted as a widening of the graben of about 1 cm per year (Gerke, 1974).

A third series of distance measurements across the Thingvellir area was made by a team from the U.S.A. in 1967, 1970 and 1973 (Decker et al., 1971; Decker et al., 1976). The first remeasurement showed no significant length changes in the Thingvellir area, while the second remeasurement in 1973 showed some significant length changes of 1 to 3 centimeters. The whole Thingvellir graben seem to have widened by about 2.0 centimeter from 1967 to 1973 or about 3 mm per year on the average, in good agreement to the values obtained by the Imperial College.

It is of interest to compare results of the U.S.A. team and the German team, which partly used the same bench marks. The distance from point 5001 on the west side of the Thingvellir graben to point 3212 in the center of the graben increased by 1.2 cm from 1967 to 1971 according to the German measurements, and by 2.8 cm from 1967 to 1973 according to the U.S. measurements. The distance from 5001 to 539 on the east side of the graben increased by 2.3 cm from 1967 to 1970 according to the U.S. measurements, by 3.4 cm from 1967 to 1971 according to the German measurements and by 3.0 cm from 1967 to 1973 according to the U.S. measurements.

VERTICAL DEFORMATION IN SOUTHWEST ICELAND (Fig. 2)

Precise leveling along several selected lines in the rift zone in southwest Iceland in 1966 to 1971 show definite vertical displacements (Tryggvason, 1974). On the Reykjanes peninsula, near Vogar, a tilt towards south or southeast is observed, at a rate of approximately 0.4 microradians per year, in addition to some fault displacements. The observed displacement of about 7 mm on the fault Hrafnagjá and indication of minor displacements (about 1 mm) on two other faults are supposedly caused by an earthquake swarm in 1967 located 20 to 25 km southwest of the leveling line (Tryggvason, 1970).

A leveling line across the Thingvellir graben shows a subsidence centered in the eastern part of the graben, but no fault displacements. Tilt rates of about 0.26 microradians per year are observed near the major faults on either side of the graben, and this tilt rate seems to be maintained towards the ends of the 10 km leveling line. Thus the eastern part of the Thingvellir graben is subsiding at a rate of about one millimeter per year relative to the west end of the leveling profile about 5 km northwest of the area of greatest observed subsidence. Apparently, the subsidence bowl extends outside the line of precise leveling, so the total subsidence may be considerably more than one millimeter per year (Tryggvason, 1974).

DEFORMATION IN THE EAST RIFT ZONE

Precision leveling across the lava shield of the new volcanic island Surtsey was performed several times from 1967 to 1970 (Tryggvason, 1970 and 1972). These levelings show that the whole lava shield was subsiding, and the rate of subsidence decreased approximately by a factor 2 each year. Maximum subsidence of about 30 cm/year was observed at the highest elevation in 1967-1968 but in 1969-1970 this had decreased to about 10 cm/year. Most of this subsidence is interpreted as due to cooling of the volcanic pile, which in places exceeds 200 m in thickness.

Distance measurements across the volcanic fissure of Heimaey during the eruption of 1973 (Brander and Wadge, 1973) showed a progressive right lateral shear on the eruption fissure from early February to April 1973, but the eruption started on January 23, 1973. The measured rate of deformation decreased nearly exponentially with time and the time constant was about 7.5 days. The calculated total strain along the principal strain axes was: ε_1 = 36 ppm (compression) and ε_2 = -420 ppm (dilatation), and the direction of the axis of maximum compression was N45°E (Brander and Wadge, 1973).

Precision levelings along short leveling lines in the vicinity of the volcano Katla, in the Mýrdalsjökull glacier in 1967 to 1971 showed no progressive ground deformation, but significant response to snow accumulation on the glacier This was interpreted as an indicator of low viscosity material below an elastic crust of 6.5 to 8.5 km thick (Tryggvason, 1973).

Distance measurements across the East rift zone north of the volcano Hekla in 1967, 1970 and 1973 show 6 to 7 cm ($\pm$3 cm) widening of a 10 km wide zone about 25 km northeast of Hekla between 1967 and 1970, which may have occurred during the Hekla eruption in May to June 1970 (Decker et al., 1971). However, the same section of the measuring line showed some contraction, although barely significant, between 1971 and 1973. The whole rift zone shows no significant extension or contraction for the period 1967-1973 (Decker et al., 1976).

MEASURED DEFORMATION IN THE NORTH RIFT ZONE BEFORE DECEMBER 1975 (Fig. 3)

An extensive geodetic network was established in 1938 across the North rift zone in Iceland in order to observe slow ground deformation (Niemczyk and Emschermann, 1943). Remeasurement of this network in 1965 showed westward displacements of up to 4.8 m for bench marks near the center of the network, when two endpoints about 115 km apart were considered stable. Reexamination of the result indicated systematic errors caused by different scales in the western and the eastern part of the network in the 1938 measurements. Adjustments for this apparent scale error reduced the computed displacement of the bench mark to be within the confidence limits of the measurements, resulting in no significant horizontal deformation between 1938 and 1965 (Gerke, 1969).

Further remeasurements in 1971 and 1975 with increasing accuracy showed a zone of disturbance, coinciding roughly with the N-S trending Krafla fissure swarm and stable blocks on either side. During the period 1965 to 1971 did the stable blocks move towards each other by up to 50 cm in the southern part of the area of measurements and about 10 cm in its northern part while bench marks within each stable block did not move relative to each other. Bench marks within the disturbed zone were displaced northwards up to about 20 cm. During the period 1971 to 1975 the same zone of disturbance appeared, and the stable areas on either side moved away from each other by some 30 cm in the southern part of the network and 10 cm in its northern parts. Two points within the disturbed zone moved significantly southwards (Gerke et al., 1978).

A small profile (3 km long) across the Krafla fissure swarm near Hrútafjöll (65°50´N) was measured in 1938 and again in 1965, 1967 and 1971. According to these measurements, the fissure swarm was contracted some 54 cm between 1938 and 1965, expanded about 5 cm from 1965 to 1967 and did not change in width between 1967 and 1971. The measurements of 1938 were not as accurate as later measurements and should be judged with caution (Gerke, 1974). Another source reports contraction of 45.4 cm from 1938 to 1965 and a further contraction of 2.4 cm from 1965 to 1967 (Gerke, 1969).

Vertical control of this line in 1938, 1965 and 1967 (in 1938 partly triangulation, otherwise precision leveling) indicated a subsidence of the 3 km wide graben of the Krafla fissure swarm of about 17 cm relative to the west flank of the graben between 1938 and 1965 (Spickernagel, 1966). The east flank of the graben was uplifted 11 cm relative to the west flank during the same interval. From 1965 to 1967 no movement was indicated on the graben faults but a general tilt towards west of roughly 7 microradians resulting in an uplift of the east flank of the graben by about 20 millimeters relative to the west flank (Gerke, 1969).

A small network across the Fremri Námur fissure swarm (Klaustur) was measured in 1965, 1968 and 1971. An extension of the 2.5 km wide fissure swarm of about 6.5 cm is indicated from 1965 to 1971 or roughly 1 cm per year (Gerke, 1974). Precision leveling showed some barely significant vertical displacements.

Precision leveling along a 3.3 km east-west profile across the Theistareykir fissure swarm at latitude 65°58´N was performed in 1966, 1968, 1970 and 1972. The result showed progressive tilt of the ground towards east of 0.3 microradians per year on the average. The west end of the profile tilted about 0.7 microradians per year while the central and east part tilted only 0.2 microradians per year on the average (Tryggvason, 1974).

Short leveling profiles 4 km to the east and five km to the west of the above profile were leveled in 1970 and 1972. The eastern profile indicated westward tilt of 0.4 ± 0.2 microradians per year while the western profile showed a tilt of about 0.7 microradians per year towards east. Three short profiles in the Laxá area, wholly to the west of the North Iceland rift zone were measured in 1970 and 1973. They all showed eastward tilt of 0.3 to 1.0 microradians per year (Tryggvason, 1974).

MEASURED DEFORMATION IN NORTH ICELAND AFTER DECEMBER 20, 1975

An episode of repeated rifting, faulting and volcanic eruptions started in the North Iceland rift zone on December 20, 1975 (Björnsson et al., 1977). A variety of measurements made within the rift zone since 1975 show a continuous procession of events of rifting, vertical and horizontal ground movement, earthquake swarms and volcanic activity. All this activity has been in the Krafla fissure swarm, one of several fissure swarms in the North Iceland rift zone (Fig. 3). Similar events of rifting, faulting and volcanic activity are reported in the Askja fissure swarm in 1874 to 1875, and the Krafla fissure swarm in 1724 to 1729, and opening of fissures is reported in the Theistareykir fissure swarm in 1618 (Björnsson et al., 1977). Thus it seems that major tectonic eposides occur in the North Iceland rift zone approximately once in 100 to 150 years, and each episode is confined to only one of the several fissure swarms making up the rift zone (Björnsson et al., 1979).

The measurements and observations which have been applied to monitor the tectonic episode which started in 1975 in North Iceland include precision levelings (Björnsson, 1976), tilt measurements (Tryggvason, 1978a; Sindrason & Ólafsson, 1978), gravity measurements (Torge and Drewes, 1977; Torge and Kanngieser, 1978), measurements of width of fissures (Björnsson et al., 1979), change of river courses and lake shores (Tryggvason, 1976) and distance measurements with geodimeter (Tryggvason, 1978b; Gerke et al., 1978).

The ground deformation in the North Iceland rift zone since 1975 has been characterized by successive uplift and subsidence of the area of the Krafla central volcano (Krafla caldera). Each period of uplift has lasted from one to seven months while the subsidence lasts from about one to 20 days. During the subsidence events, certain portion of the fissure swarm, outside the Krafla caldera, is widened through fissuring and faulting. Sometimes the same portion of the fissure swarm is affected by several subsidence events while other parts of the swarm are affected by only one subsidence event. The maximum widening of the fissure swarm in one event may exceed 2 meter (Björnsson et al., 1979). The total widening of the fissure zone has been measured to exceed 3 meter in places (Tryggvason, 1980). The widening seem to take place in only about one km wide zone along the central axis of the fissure swarm. The segment of the swarm which is active in each subsidence event may exceed 20 km in length while about 80 km of the fissure swarm has been active in one or more of the 10 subsidence events which occurred in 1975 through 1978 (Tryggvason, 1980). During the widening of the fissure zone, open fissures are formed and the central part of the fissure swarm subsides relative to its flanks by an amount similar to or slightly less than the widening. The flanks of the fissure swarm are at the same time uplifted relative to areas farther away from the swarm. This uplift may be roughly 20 per cent of the widening (Björnsson et al., 1979; Tryggvason, 1980). The area immediately outside the zone of widening is simultaneously contracted in east-west direction, the contractional strain being greatest (up to 1.8×10^{-4}) nearest to the zone of active fissuring but diminishing with distance. At 40 km distance from the fissure zone, the horizontal displacement is only some 15 per cent of the displacement at the flanks of the fissure swarm (Björnsson et al., 1979; Tryggvason, 1979; Gerke et al., 1978).

A short summary of the deformation of the Iceland rift zone:

The rift zone and its surrounding is continuously stretched in east-west direction and at the same time the central part of the rift zone subsides. This stretching and subsidence affects a zone some 80 km wide and the subsidence rate appears to be about 1 cm/year at its center (Tryggvason, 1974) but the rate of widening has not been established by direct measurements. When tensional stress has reached some critical value, the crust fails along the central axis of the rift zone, as happened in North Iceland in 1975, and magma intrudes the fissure at depth, but above the magma the fissure collapses forming a narrow zone of intense faulting and subsidence (Tryggvason, 1980). The flanks of the fractured zone are contracted to release the tensional stress that has been built up since previous fracturing. This contraction results in uplift of the flanks to approximately the same level as they had immediately after previous rifting episode. The rifting episode may be multiple as has been observed in North Iceland from 1975 to 1979 and in 1874-1875. The 1975 to 1979 rifting episode in North Iceland has resulted in a total widening of some 5 m (the measured amount of 3 to 4 m plus some rifting in 1975 and 1976 before extensive measuring program started), and about 80 km segment of the rift zone was active. The total uplift of the flanks of the fissured zone is poorly determined as 50 to 100 cm and the subsidence of the 1 to 2 km wide zone of intense fracturing may be about two meter on the average. The contraction of the flanks of the fissured zone amounts to nearly 2×10^{-4} and the widening of a 80 km wide zone centered in the zone of fissuring is probably 0.5 to 1.0 m. This means that some contraction has taken place at distances greater than 40 km from the fissure zone, if we assume constant rate of movement of the main body of the crustal plates.

The total widening of the fissure zone of roughly 5 m may be considered to represent the stretching of the crustal plate since 1730, at the end of the Mývatn fires volcano-tectonic episode which affected the same area as the present episode, or in 250 years. This represents 2 cm per year as the average widening of the rift zone, if no creep or displacements caused by earthquakes has occurred during this period.

THE EAST AFRICAN RIFT ZONE IN ETHIOPIA AND DJIBOUTI (Fig. 4)

The East African rift system is one branch of the rift systems extending from the triple junction in the Afar area. The other two branches are the Red Sea - Dead Sea rifts and the Gulf of Aden rifts and its continuation in the Carlsberg ridge (Laughton, 1966). This whole rift system is commonly considered as a continent-ward extension of the mid-ocean ridge system, which has not as yet formed oceanic area due to its low age and/or slow plate movements. The age of the East African rift and the associated volcanism has been determined as roughly 25 million years (Rogers, 1966; Logatchev et al., 1972; Williams, 1972).

The seismicity of the East African rift system clearly shows that it is presently tectonically active and focal plane solutions indicate a tensional stress field in south-easterly direction in East Africa while in the Gulf of Aden and the Red Sea the rifting is related to a tensional stress field in north-easterly direction (Fairhed & Girdler, 1972).

Direct measurements of ground deformation in the East African rift system include tidal gauge observations in the Red Sea and Gulf of Aden, and geodetic measurements in the Afar region and the rift valley of Ethiopia.

In Aden, tide gauge shows a gradual rise of the sea level by about 2.7 mm/year from 1937-1967, indicating a subsidence of the station of the order of one mm/year, when eustatic rise of sea level is subtracted from the observed rise (Faure, 1975).

A network of 22 geodetic stations was established in the republic of Djibouti in 1972 and 1973 by the Institut Geographique National in the area of the Asal-Ghoubbet graben. This network was measured with geodimeter and triangulation in order to detect ground deformation. A precision leveling line along about 100 km of the road crossing the graben was also established and leveled.

A volcanic fissure eruption occurred in the Asal-Ghoubbet graben in November 1978, accompanied by an intense earthquake swarm and rifting of the ground. Remeasurement of the

1972-1973 network in November 1978 and March 1979 showed the following ground deformation:

A three km wide zone along the Asal-Ghoubbet graben was widened up to 2.4 m. Greatest widening was observed across the Ghoubbet bay and the total length of the widened zone is about 25 km.

The flanks of the widened zone were compressed in direction perpendicular to the zone by up to 0.9×10^{-4} or even somewhat more.

The zone of widening was heavily faulted and it subsided up to 70 cm while its flanks were uplifted as much as 18 cm. This uplift decreases with distance from the faulted zone and seem to disappear in less than 5 km (Allard et al., 1979; Tarantola et al., 1979; Kasser et al., 1979; Ruegg et al., 1979).

The average spreading rate of the Asal rift has been estimated as 1.5 cm/year (Delibrias et al., 1975; Mohr, 1978), although measurements of fault displacements, dikes and fissures indicate a slower spreading rate of 0.3 to 0.6 cm/year on the average (Schaefer, 1975). This indicates that the rifting of 1978 has resulted from accumulation of tensional stress over a period of a few centuries.

An extensive work of repeated distance measurements in the Ethiopian rift valley has been conducted since 1969 (Mohr et al., 1975, 1978). The principal result of the first five years of measurements were as follows:

Several of the lines of measurements show significant increase in length, although this is near the error limit of the measurements, but no measured lines show significant shortening. The average lengthening has been interpreted as tensional strain rate of $6\text{-}16 \times 10^{-7}$/year and widening of the rift zone of 3-5 mm/year. Small right lateral shear movement is indicated (Mohr et al., 1978). The direction of the lines, which show significant increase in length from 1969 to 1974, is approximately SE-NW while all lines, which have other orientations, show no significant length changes (Mohr et al., 1978, Fig. 7). Thus the tensional strain axis in the Ethiopian rift zone near 8°30´N is approximately SE-NW and strain rate in this direction, within the rift zone is roughly $10 \pm 5 \times 10^{-7}$ per year.

THE BAIKAL RIFT SYSTEM (Fig. 5)

The Baikal rift system extends over a distance of 2500 to 3000 km in SW-NE direction from northwestern Mongolia to South Yakutia near the southern edge of the Precambrian Siberian platform (Florensov, 1966; Logatchev and Florensov, 1978). This rift system has no evident structural connections with other active rift systems, and lies entirely within the Asiatic continent. The rift system is characterized by deep sedimentary basins and the deep fresh water basin of Lake Baikal along the elongated Baikal uplift, high degree of seismicity and low degree of volcanic activity (Kiselev et al., 1978; Solonenko, 1978).

The earliest volcanic activity associated with the Baikal rift zone may be as old as late Cretaceous but the greater bulk of the fissure eruptions are of Miocene or early Pliocene age (Kiselev et al., 1978).

The evolution of the rift system and its sedimentary basins appears to have come in two major stages. The earlier stage of Eocene to early Pliocene age is characterized by slow plastic deformation of the basement, while the later stage, from middle Pliocene to Recent, was dominated by rapid deformation and faulting (Logatchev and Florensov, 1978).

The high seismicity of the rift offers excellent opportunity to study the stress field from solution of earthquake focal mechanism. A great number of fault plane solutions show that the tensional axis is predominantly horizontal and perpendicular to the direction of the rift zone, except at both ends of the zone, where the tensional axis is near vertical (Golenetsky and Misharina, 1978).

Repeated levelings by the Institute of Geology and Geophysics of the U.S.S.R. Academy of Sciences, indicate that the whole Baikal area is being uplifted. A very striking aspect of this uplift is the high correlation between the land elevation and rate of uplift. The rift zone and its immediate surroundings show the highest rate of crustal movements, where 100 m increase in elevation corresponds to one mm/year increase in the rate of uplift, and the maximum rate of uplift is about 26 mm/year (Kolmogorov and Kolmogorova, 1978).

The present information on the vertical component of crustal deformation in the Baikal area seem to indicate that a large area centered near Lake Baikal is being uplifted. This dome of uplift has a diameter of more than 1000 km, and its central part is uplifted at a rate of 2 to 3 cm/year.

The volume of the uplift per unit time can be crudely estimated from the existing information (Kolmogorov and Kolmogorova, 1978). Taking the area of uplift as 10^6 km^2 and the average uplift 10 mm/year, the volume of uplift becomes 10 km^3/year.

No measurements show the horizontal component of crustal deformation in the Baikal area, but focal mechanism solution of earthquakes indicate tension perpendicular to the rift zone (Golenetsky and Misharina, 1978). The magnitude of this tensional deformation is very much in doubt. Most of the earthquakes in the rift zone are associated with normal faulting and the epicenters are concentrated along elongated belts, parallel to the rift system (Golenetsky and Misharina, 1978) but correlation between these belts of high seismic activity and the belts of steep gradient in vertical crustal movement (Kolmogorov and Kolmogorova, 1978) is not clear.

THE RHINE GRABEN (Fig. 6)

The Rhine graben is a part of a discontinuous system of rifts, grabens and seismically active zones, which probably extend from the Atlantic-Arctic mid-ocean ridge off northern Norway to the Mediterranean in Italy. The best known sections of this system are the Oslo graben in Norway where faulting started in Permian times and the Rhine graben where vertical movement started in lower Oligocene and is continuing at present (Bederke, 1966). The Rhine graben is about 300 km long and 30-40 km wide and its direction is about N21°E.

The present day stress field in Central Europe as deduced form focal plane solutions of earthquakes and in-situ stress measurements shows the mean direction of the horizontal component of maximum compressive stress σ_1 H = 142° ± 20° (Ahorner, 1975; Greiner, 1975). The focal plane solutions for earthquakes in and around the Rhine graben show strike-slip mechanism to dominate, and if the slip-plane is subparallel to the graben, left-lateral displacement is indicated (Ahorner, 1975).

Extensive geodetic observations of the Rhine graben area over several decades have been treated in order to detect crustal deformation. These include gravity and gravity gradient observations, tilt observations, precision leveling, triangulation, and distance measurements (Mälzer and Schlemmer, 1975; Groten et al., 1979; Mälzer et al., 1979). It appears that the geodetic observations to date fail to show significant horizontal component of deformation while the vertical component is convincingly demonstrated. Inside the Rhine graben subsidence dominates. The average rate of subsidence in the northern part of the Rhine graben near Ludwigshafen and Worms is 0.3 to 0.7 mm/year (Groten et al., 1979) and similar subsidence values are reported by Mälzer et al. (1979) using a different treatment of the data from northern part of the Rhine graben. More irregular subsidence is indicated in the southern part of the graben (Mälzer and Schlemmer, 1975). Subsidence of approximately 1.0 mm/year is found near Breisach and near Kehl although subsidence of 0.2 to 0.4 mm/year seem to be more common. Even uplift of up to 0.4 mm/year is indicated ın the Rhine graben between Rastatt and Bruchsal.

The observed rate of vertical ground movement correlates well with the thickness of Pliocene and Pleistocene sediments. The maximum thickness of Pliocene sediments in the northern part of the Rhine graben is about 760 m and that of Pleistocene sediments about 380 m. This shows that the present rate of vertical ground movement is roughly 10 times greater than the average rate since the beginning of Pliocene (Illies et al., 1979).

In the areas immediately outside the Rhine graben, uplift of 0 to 0.2 mm/year is indicated in the Renish Massif in the north while slight subsidence is indicated in the Black Forest area (Mälzer and Schlemmer, 1975; Mälzer et al., 1979).

The horizontal component of deformation in the Rhine graben area, although not as yet clearly demonstrated by direct measurements, can be inferred from seismicity, stress and strain relief measurements and the vertical movement. Focal mechanism of earthquakes shows that some widening of the Rhine graben occurs, but the major part of the horizontal deformation is left-lateral shear (Ahorner, 1975). The seismotectonic slip rate has been estimated as 0.05 mm/year in the upper Rhine graben, while the geodetically inferred slip rate is 0.2 to 0.7 mm/year (Ahorner, 1975). This indicates that most of the geodetic slip rate occurs as a seismic creep, or else, that it occurs in few large earthquakes, none of which has occurred since 1700, in the time interval considered by Ahorner.

Although the present tectonics of the Rhine graben area is primarily left-lateral shear, indications are, that earlier in the history of the rift system, tension perpendicular to the graben direction prevailed (Illies, 1975).

CONCLUDING REMARKS

The present rate and nature of ground deformation in the rift zones of the world is known to a limited degree on a few short segments of these zones, and still fewer segments are considered here as illustrative examples. The present state of knowledge is insufficient to form an accurate model of the rift zone deformation, but a few aspects are emerging.

The tensional strain rate perpendicular to the rift zones is in the oceanic rift in Iceland and Ethiopia of the order of 10^{-6} per year during periods of low activity. In Iceland, and probably also in Afar, major rifting episodes occur at intervals of roughly one century. During these rifting episodes, contractional strain of roughly 10^{-4} occur on the flanks of the rift zone, releasing all the tensional strain which has been built up during the roughly 100 years of quiescence. Similarily the tilt rate towards the rift zone is observed to be 0.4 to 0.6 x 10^{-6} during quiet periods in Iceland, while tilt of about 100 x 10^{-6} away from the rift zone occurs during a rifting episode (Tryggvason, 1980). Another interpretation, equally true, is that the flanks of the rift zone, together with the rift zone itself subsides continuously during quiet periods but the flanks are uplifted, probably by nearly the same amount, during the brief rifting episodes. The rift zone itself subsides further during the rifting episodes. Thus the land elevation immediately outside the rift zone oscillate up and down without any indicated net vertical displacement while the narrow rift zone subsides continuously at a rate of a few millimeters per year between rifting episodes and subsides further some tens of centimeters during these episodes.

Rifting episodes in both Iceland and Afar are associated with magmatic activity (Björnsson et al., 1977; Kasser et al., 1979). The interpretation of this association in Iceland is that rifting does not occur unless molten magma is available to fill the fissure in a form of a dike up to a shallow depth. The subsidence of the rift zone is then due to collapse of the near-surface formation into the fissure above the dike. The brittle-elastic model proposed to explain observed deformation in Afar (Tarantola et al., 1979) seem not to require molten magma to intrude the formed fissure, although it occurred during the observed rifting event in 1978.

The deformation within and near the two continental rift zones, the Rhine graben, and the Baikal rifts, seems to differ significantly from that of the oceanic rift zone in Iceland and in the Afar rift zone, which also may be termed as oceanic. The rate of deformation in the Rhine graben is quite slow, at least one order of magnitude slower than in Iceland and Afar. The deformation of the Baikal rift zone appears to be dominated by large scale uplift of a vast area. This has been correlated to a large volume of the upper mantle with abnormally low seismic velocity and probably higher temperature than normal upper mantle (Zorin and Flovensov, 1979). Then the uplift is due to isostatic adjustment and the rifting due to tensional stress above the slowly rising high temperature mantle material.

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FIGURE CAPTIONS

Fig. 1. The rift system of Iceland slightly simplified. The principal rift zones are shown with four or five parallel lines and other volcanic zones with three parallel lines. Zones of seismic activity connecting the rift zones (transform faults) are shown with two parallel lines. The boundary of the Iceland platform is indicated by the 400 m depth contour.

Fig. 2. Details of the West Rift Zone in Iceland with en echelon fissure swarms. Each fissure swarm consists of a graben with numerous open fissures while few open fissures are found between the swarms.

Fig. 3. Details of the northern part of the North Rift Zone in Iceland. A rifting episode which started in 1975 has caused widening of the Krafla fissure swarm of about 5 m. The area of repeated inflation and deflation during the rifting episode is centered about 12 km northeast of lake Mývatn.

Fig. 4. The Afar rift system showing approximate location of individual rift zones (four parallel lines) and possible fracture zones (two parallel lines). Approximate boundaries of the rifted areas are shown by broken hachured lines. The Asal rift zone became active in November 1978. (Mostly after Kronberg et al., 1975).

Fig. 5. The Baikal rift system. Broken hachured line shows the boundary of the rift system (Solonenko, 1978) and thin lines show the observed rate of uplift in mm/year (Kolmogorov and Kolmogorova, 1978).

Fig. 6. The outlines of the Rhinegraben (hachured lines) and connected fault systems (dashed lines). The approximate termination of the graben towards north and south is shown by dotted lines. (Largely from Illies, 1975).

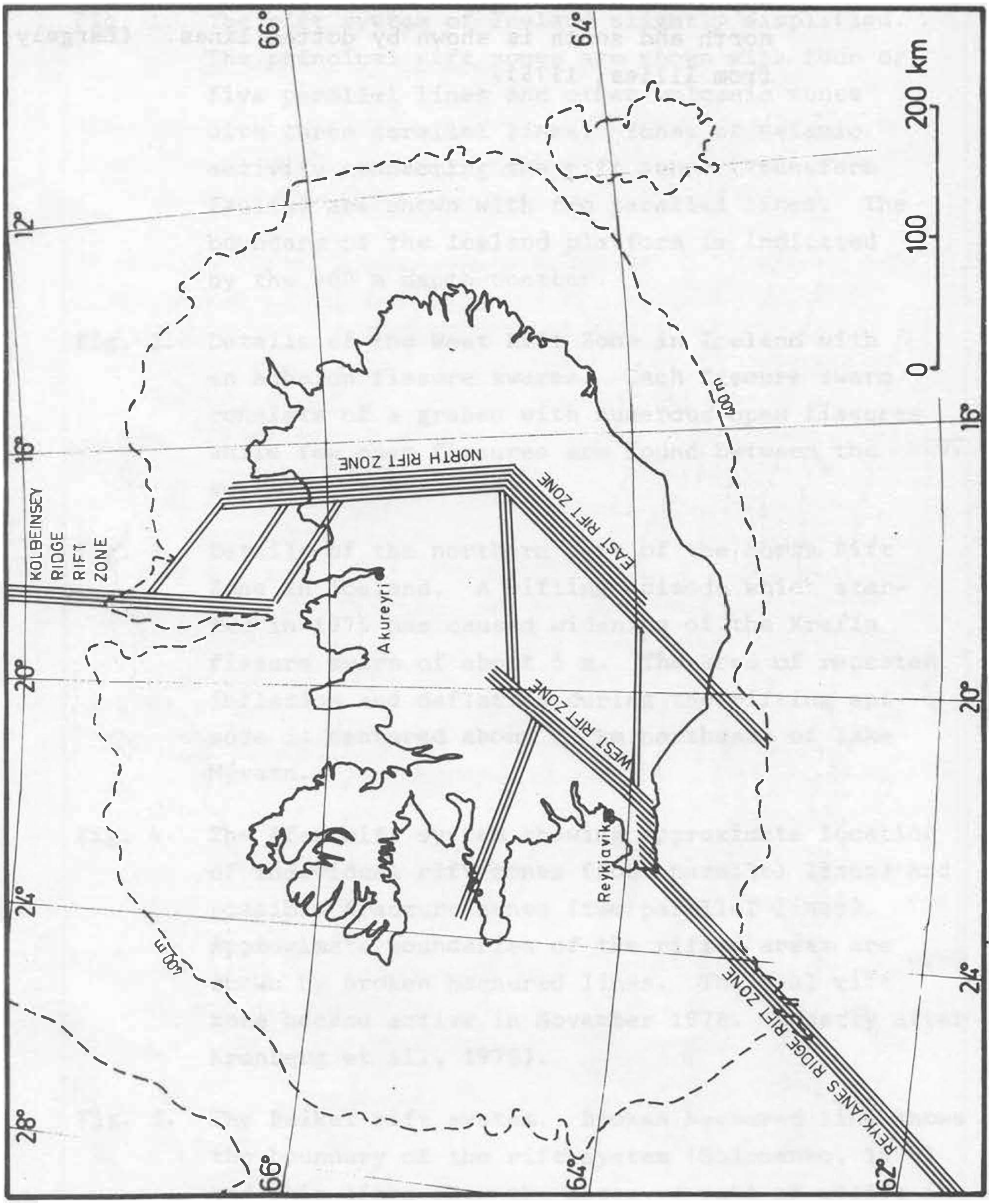

KOLBEINSEY RIDGE RIFT ZONE
NORTH RIFT ZONE
EAST RIFT ZONE
WEST RIFT ZONE
REYKJANES RIDGE RIFT ZONE
Akureyri
Reykjavik
400 m
0
100
200 km
66°
64°
62°
12°
16°
20°
24°
28°

Fig. 1

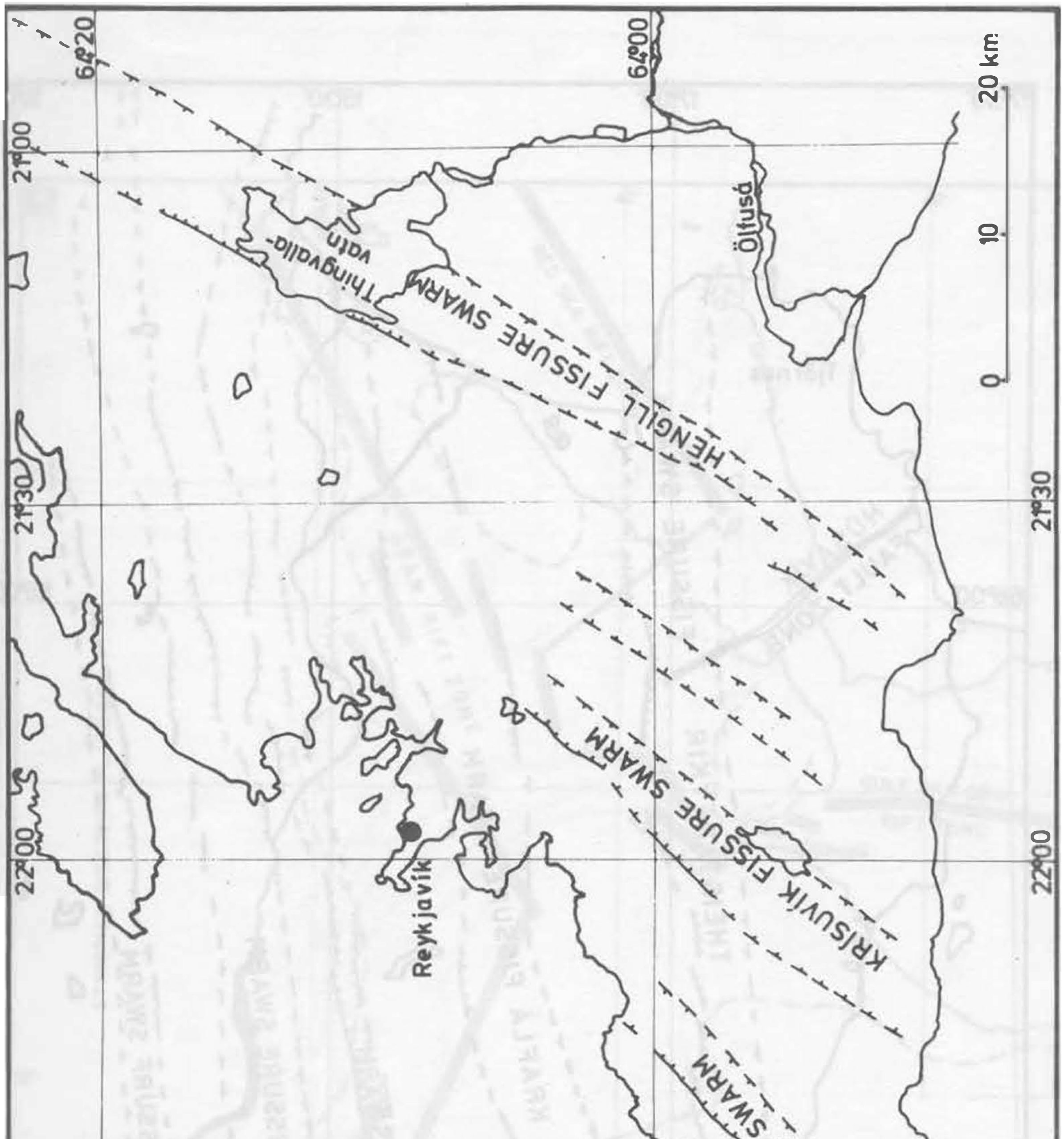
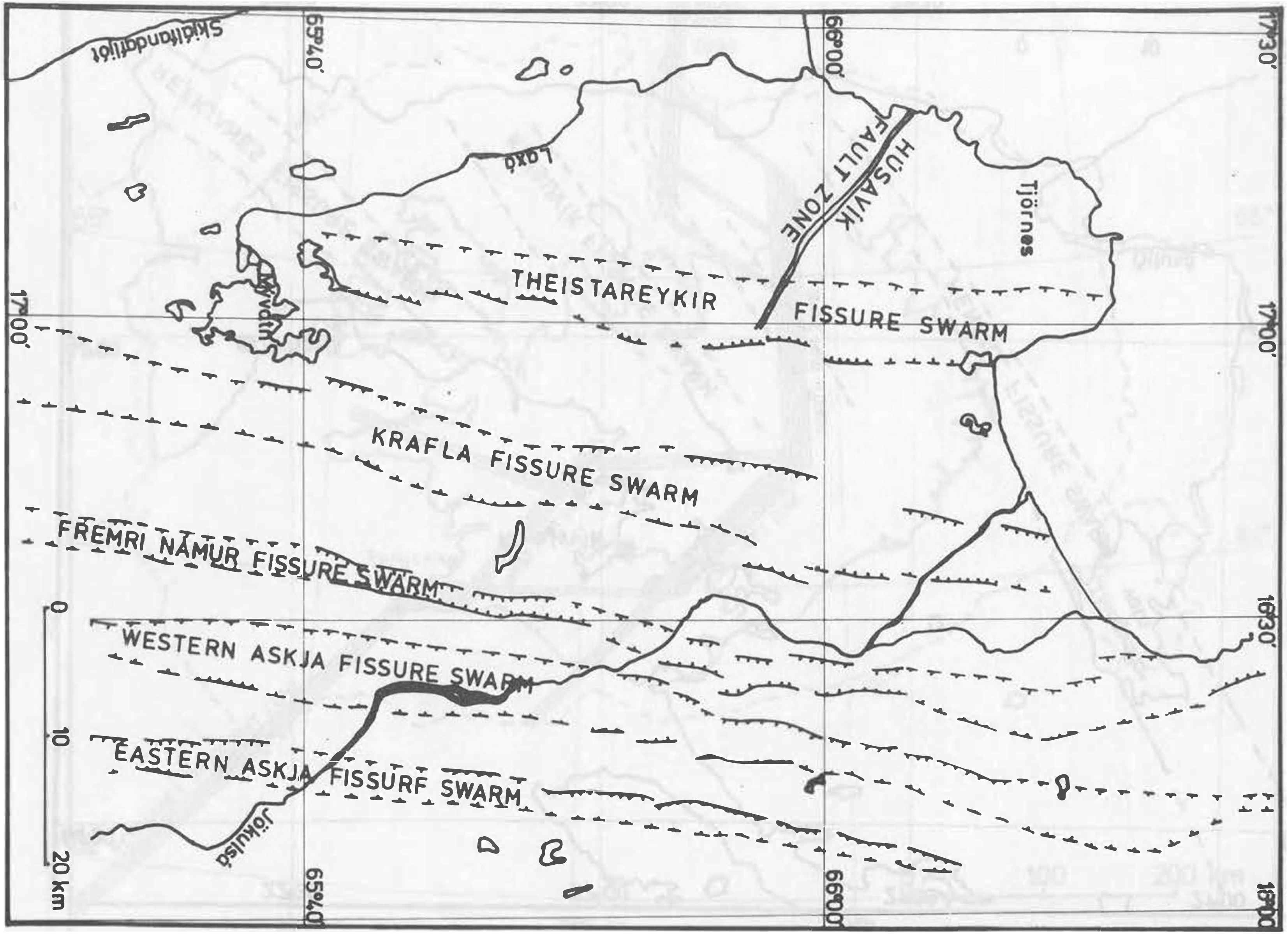

64°20
64°00
21°00
21°30
22°00
22°30
HENGILL FISSURE SWARM
KRÍSUVÍK FISSURE SWARM
REYKJANES FISSURE SWARM
Thingvalla-
vatn
Reykjavík
Keflavík
Ölfusá
0
10
20 km

Fig. 2

Fig. 3


THEISTAREYKIR FISSURE SWARM
KRAFLA FISSURE SWARM
FREMRI NAMUR FISSURE SWARM
WESTERN ASKJA FISSURE SWARM
EASTERN ASKJA FISSURF SWARM
HÚSAVÍK FAULT ZONE
Tjörnes
Laxá
Mývatn
Jökulsá
Skjálfandafljót
0
10
20 km
65°40'
66°00'
17°30'
17°00'
16°30'
16°00'

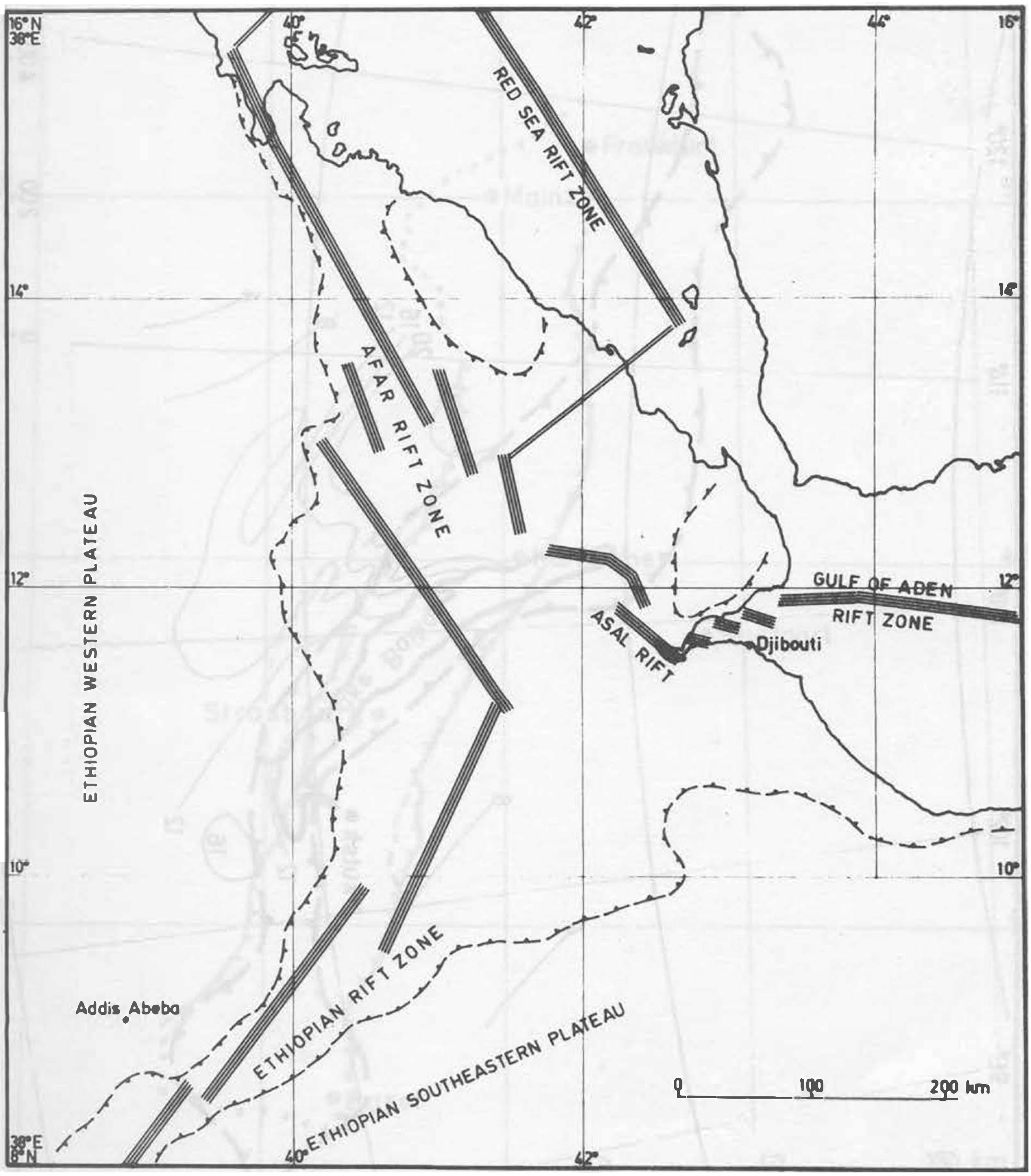

16° N
38°E
40°
42°
44°
16°
14°
14°
12°
12°
10°
10°
38°E
8°N
40°
42°
RED SEA RIFT ZONE
AFAR RIFT ZONE
ETHIOPIAN WESTERN PLATEAU
GULF OF ADEN
RIFT ZONE
ASAL RIFT
Djibouti
ETHIOPIAN RIFT ZONE
ETHIOPIAN SOUTHEASTERN PLATEAU
Addis Abeba
0
100
200 km

Fig. 4

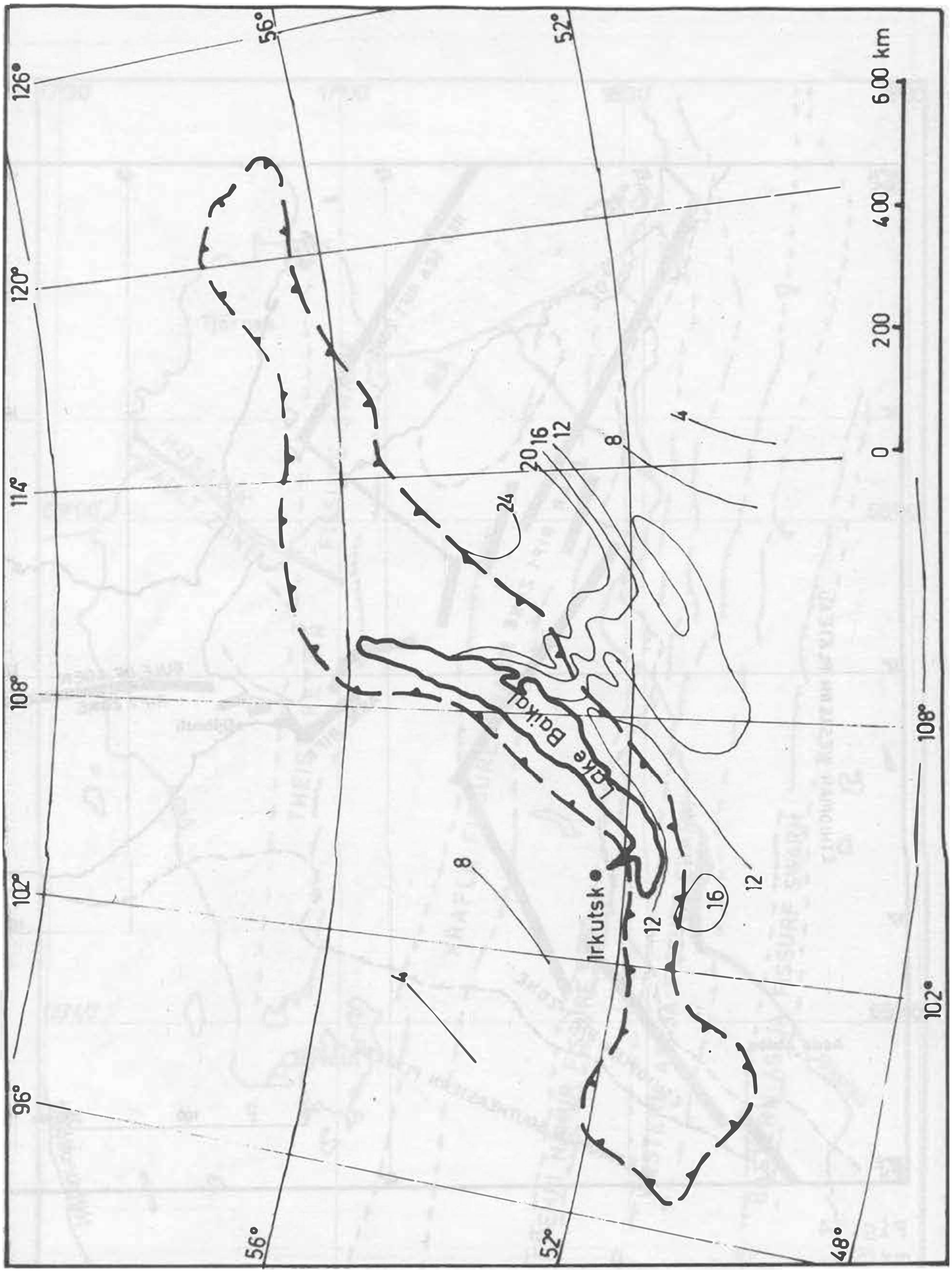

126°
120°
114°
108°
102°
96°
56°
52°
48°
Lake Baikal
Irkutsk
24
20
16
12
8
4
0
200
400
600 km

Fig. 5

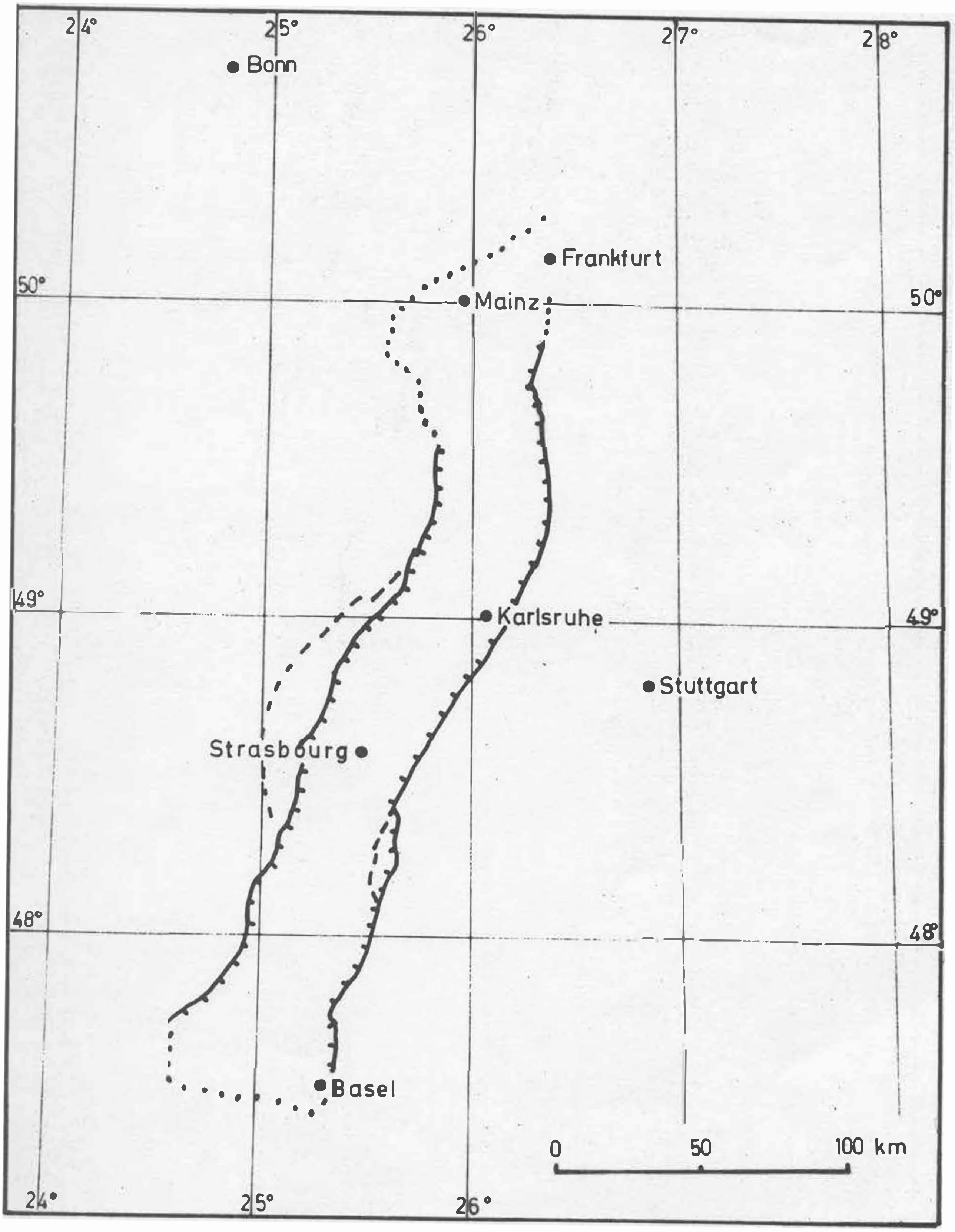

24°
25°
26°
27°
28°
Bonn
Frankfurt
Mainz
50°
50°
Karlsruhe
49°
49°
Stuttgart
Strasbourg
48°
48°
Basel
0
50
100 km
24°
25°
26°

Fig. 6