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RECENT VOLCANIC HISTORY OF THE VEIDIVÖTN FISSURE SWARM, SOUTHERN ICELAND

A basis for volcanic risk assessment

by

Gudrún Larsen

Appendix:

MONITORING AN ICELANDIC TYPE VOLCANIC SYSTEM

by

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Reykjavík 1984

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The appendix should not be referenced
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RECENT VOLCANIC HISTORY OF THE VEIDIVÖTN FISSURE SWARM SOUTHERN ICELAND

A basis for volcanic risk assessment

GUÐRÚN LARSEN

ABSTRACT

The recent volcanic history of the southwestern part of the Veidivötn fissure swarm, S-Iceland, provides a basis for assessment of volcanic risk in an area of large hydropower potential. Local tephrastratigraphy and regional tephrochronology provide relative and absolute dating of individual eruptions as well as information on the volume and distribution of the products formed in each eruption.

Three large eruptions took place in this area in ~ 1480 A.D., ~ 900 A.D. and ~ 150 A.D., respectively. Each eruption produced approx. 1 km^3 (DRE) of basaltic, and minor amounts of silicic lava and tephra on fissures up to 42 km long. No evidence is found of smaller eruptions during this period. The estimated eruption frequency, one eruption every 600-800 years, implies that this part of the Veidivötn fissure swarm is inactive for long periods between relatively large volcanic events.

A change in the mode of eruption from effusive to explosive took place during this period. The hazards posed by this area include far reaching lava flows, widespread

heavy tephra fall and damming of a large glacial river with the consequent formation of unstable lakes.

A volcano-tectonic model, which explains the observed eruption frequency and provides a basis for a long term monitoring program, is proposed. Eruptions on the Veidivötn fissure swarm are interpreted as corollaries of rifting episodes initiated in the Bárdarbunga central volcano. Volcano-tectonic episodes affect the fissure swarm at an average interval of 100 years. Minor episodes are limited to the central volcano and adjacents parts of the fissure swarm. During the less frequent major episodes, rifting and volcanic activity extends to the extreme southwestern part of the fissure swarm.

Seismic monitoring of the Bárdarbunga central volcano could provide an early warning of renewed activity on the Veidivötn fissure swarm. According to the proposed model, a major rifting episode resulting in eruption on its southwestern part can be expected during the next 100 to 300 years.

INTRODUCTION

The Veidivötn fissure swarm (Fig. 1) within the Eastern Volcanic Zone of Iceland is one of the most productive volcanic areas of postglacial time in Iceland (Vilmundardóttir 1977, Jakobsson 1979). It is probably part of a volcanic system up to 150 km long, centered upon the Bárdarbunga volcano under Vatnajökull's icecap (Saemundsson 1979). The fissure swarm consists of a number of volcanic fissures more or less parallel with the general trend of the swarm, N45°E The products are tholeiitic basalts, mostly lava flows but considerable amounts of basaltic tephra have been erupted as well (Kjartansson 1961, Vilmundardóttir 1977, Jakobsson 1979, Larsen 1982).

In the extreme southwest the Veidivötn fissure swarm cuts into a tectonic and petrological boundary where the Eastern Volcanic Zone changes from an axial rift zone into a practically nonrifting flank zone (Saemundsson 1979, Óskarsson et al. 1982). Silicic lavas with alkalic affinities are erupted on the apparent continuation of the fissure swarm within the flank zone where a mature central volcano, Torfajökull, lies in its track (Saemundsson 1972, Grönvold 1972), indicating that two genetically unrelated magma systems, the tholeiitic Veidivötn system on the rift zone and the alkalic Torfajökull system on the flank zone are responding to a common tectonic process (Jakobsson 1979). Silicic lavas on the Torfajökull system are contaminated by the tholeiitic basalt of the Veidivötn system, indicating that the eruptions may have been triggered by injection of magma from the latter system (Mörk

1984, Blake 1984).

The river Tungnaá flows across the southwestern part of the fissure swarm and ground water level is high along its path. Lavas erupted on the fissure swarm have followed the course of the river, causing gradual rise in ground water level and consequently increasing hydrovolcanic (explosive) activity. Future eruptions in this area may cause considerable disturbance to the country's energy production as major hydropower plants on the Tungnaá river can be affected by lava flows and tephra fall. The postglacial volcanic history and possible future behavior are therefore of economic as well as volcanological interest.

This study is concerned with the youngest eruptions on the southwestern part of the Veidivötn fissure swarm (Fig. 2). For assessment of volcanic risk, information is needed about eruption frequency and magnitude, mode of eruption and the processes that set off eruptions in this area. The last aspects requires the recent volcanic history of the entire volcanic system to be considered as well.

Previous work in the research area (Fig. 2) includes mapping of eruption sites and lava flows (Kjartansson 1962, Saemundsson 1972, Vilmundardóttir 1977, Jakobsson 1979), dating of several lava flows by C14 method or by tephrochronology (Kjartansson 1961, Thorarinsson 1954, 1967, Vilmundardóttir 1977) and preliminary mapping of silicic tephra deposits (Thorarinsson 1970). The extensive basaltic tephra deposits originating in this area have not, however, been studied or mapped previously, with the exception that mapping of historical tephra layers in Southern Iceland revealed that two recent basaltic tephra layers had been erupted within the area (Larsen 1978).

Eruption frequency and magnitude could not be assessed until the basaltic tephra deposits had been mapped and dated. This was therefore the prime target of the study. The work was limited to the last 2700 years period after it became clear that almost all tephra deposits of local origin were younger than a regional marker tephra of that age.

Eruption frequency was found to be lower than indicated by previous work. Three large eruptions have taken place during the last 2700 years but up to nine smaller eruptions were formerly thought to have occurred during the same period. The two youngest eruptions were predominantly explosive and produced widespread basaltic tephra layers. The third youngest eruption, and the earlier eruptions as well, were predominantly effusive, producing far reaching lava flows. The prime cause for the change in mode of eruption from effusive to explosive is thought to be rise in ground water level within the volcanic area.

It will be argued below that eruptions on the Veidivötn fissure swarm are corollaries of rifting episodes initiated in the Bárdarbunga central volcano. The term Veidivötn fissure swarm is extended to include simultaneous eruptions caused by propagation of rifting into the Torfajökull central volcano on the flank zone.

THE TEPHRA DEPOSITS

High ground water level within the research area (Fig. 2) is reflected by numerous lakes, including a group of lakes named Veidivötn. Craters which produced basaltic tephra can be divided into two categories, tephra rings and maar type explosion craters, both types indicating hydromagmatic activity according to data summarized by Lorenz et al. (1970). Irregular crater formations interpretated as pseudocraters (Larsen in prep.), formed when lava flows enter wet environment (Thorarinsson 1953), also occur within the area. Craters which produced mainly lava are of two types, scoria cones and spatter cones.

Most of the basaltic tephra deposits have the characteristics of tephra produced by hydromagmatic explosions (Walker & Croasdale 1972, Walker 1973, Self et al. 1980). The deposits range from surtseyan ash to strombolian scoria deposits and, occasionally, spatter deposits. The hydromagmatic type contains abundant xenolithic material, which varies from one crater to another according to the underlying strata. A tephra deposit produced by an individual crater or a crater row often has its own macroscopic characteristics, such as color, grain type, grain size, xenolithic content and crystal contents, which distinguish it from the other deposits. Reversed, this also means that the tephra can be traced back to the crater/crater row that produced it.

CHRONOLOGY STUDIES

Data on the volcanic history was obtained through a combined study of the local tephrastratigraphy, i.e. tephra deposits produced within the Veidivötn fissure swarm, and the regional tephrastratigraphy, i.e. dated tephra layers from sources outside that area. The latter is mainly based on the work of Thorarinsson (1944, 1954, 1958, 1967, 1975) and the author's own research in Southern Iceland (Larsen 1978, 1979, 1981, Einarsson et al. 1980).

Within the Veidivötn area and areas adjacent to it more than 100 sections through tephra deposits, in tephra craters and in soil with dated tephra layers were inspected or measured in detail. Microprobe glass analyses were used to correlate deposits and to check identification of dated tephra layers (Larsen 1981), where field correlation was difficult. Additional 200 soil sections in the distal parts of the country were measured or consulted. These measurements were aimed at:

(1) Obtaining relative ages of deposits from the various tephra craters, that is find which craters had erupted at the same time or in what order they had been active.

(2) Obtaining relative ages between tephra deposits and lava flows, that is find whether or not any of the tephra deposits and lava flows belonged to the same eruption or in what order they had been formed.

(3) Obtaining absolute ages for tephra deposits and lava flows through the use of soil sections containing dated tephra layers.

(4) Defining the actual number of eruptions through combinations of (1)-(3).

(5) Mapping the distribution and volume of the tephra deposits to determine the magnitude of the eruptions that

produced them.

The results are summarized in Fig. 3 section 2, and in the following chapter.

Age determination of the prehistoric marker tephra UN, 2700 + - 100 years B.P., is based on a dated Hekla tephra layer found just below it (age 2660 + - 80 C14 years, Kjartansson et al. 1964, calibrated to 2800 + - 90 years B.P. after Ralph et al. 1973). It is preferred as a marker tephra over the dated Hekla layers of similar age, which are poorly defined within the research area.

VOLCANIC HISTORY

A combination of relative and absolute datings revealed that three eruptions occurred in the last 2700 years, at ~ 1480, ~ 900 and ~ 150 A.D. respectively, on three parallel fissures. Moreover, all the basaltic tephra deposits belong to the two youngest eruptions, which were predominantly explosive, whereas the third youngest eruption was predominantly effusive.

The Veidivötn eruption, ~ 1480 A.D.

The youngest eruption took place on the easternmost fissure in the Veidivötn area (Fig. 4a and b). The eruptive fissure is at least 40 km long, possibly extending farther to the NE than indicated here. It is not a single continuous fissure but consists of an array of smaller segments, a feature most pronounced at the SW end where it extends across the rift zone/flank zone boundary and into the Torfajökull central volcano.

Tephra produced by the craters and crater rows shown on Fig. 4b, was deposited during identical weather conditions and coalesces to form a single, widespread tephra layer to the N and E of the fissure (Fig. 5). All the fissure segments contributed to its formation during the early stages of the eruption and no extended breaks in the explosive activity can be inferred from the existing data. The activity changed from explosive to effusive on most segments before it died down, and small lava flows formed during the later stages of the eruption.

The bulk of the material produced by this eruption is basaltic tephra. Its volume, as calculated from the isopach map (Fig. 5), is 3.5 km^3. Assuming the bulk density of 0.9 measured in a laboratory as an average, this corresponds to 1.1 km^3 of lava. This volume estimate is likely to be conservative. Basaltic lavas add up to 0.4 km^3. Minor amounts of silicic tephra and lava were erupted at the SW end of the fissure, within the Torfajökull central volcano, totaling 0.05 km^3, or less.

The duration of the explosive phase of the eruption can be roughly estimated from average production rates of basaltic lava in recent eruptions (calculated as $m^3 sec^{-1}$ per unit length of fissure, Thorarinsson 1968). Craters and crater rows that produced the basaltic tephra add up to 20 km. Using the dense rock equivalent (DRE) of the tephra, 1.1 km^3, and assuming that all 20 km remained equally active during its production, duration of 69 hours was obtained for the explosive phase. The total length of the eruption cannot, however, be estimated from the existing data since there may have been breaks in the activity during the effusive phase of the eruption.

This eruption is nowhere mentioned in written sources. Documents from the latter half of the 15th century are scarce and even eruptions that damaged inhabited areas are left unreported (Thorarinsson 1967). The age of the Veidivötn eruption was calculated by extrapolation of soil thickening rates between dated tephra layers below and above the Veidivötn tephra in several soil sections (see also Fig. 3). The average value gives the year 1480 + - 11 years (Larsen in prep.)

The material produced by this eruption was formerly thought to belong to up to three individual eruptions (data summarized by Vilmundardóttir 1977).

The Vatnaöldur eruption, ~ 900 A.D.

The second youngest eruption took place on a discontinuous fissure parallel to that of the Veidivötn eruption (Fig. 4c). The eruptive fissure is at least 42 km long between the extreme ends but in the SW it discontinues near the rift zone/flank zone boundary and reappears 12-13 km farther SW within the Torfajökull central volcano.

Tephra deposits produced by the craters and crater rows shown on Fig. 4c coalesce to form a single widespread tephra layer, distributed almost peripherally around the fissure (Figs. 6 and 7) All the fissure segments were active in the early stages of the eruption, during which silicic tephra was erupted on the SW end simultaneously with basaltic tephra from the NW part of the fissure. The silicic tephra is found either as a fairly well defined unit at the bottom of the tephra layer or as thin interbeds in the lowermost part of the basaltic tephra. Wind blew from the south during the early stages of the eruption but changed counterclockwise, allowing the silicic tephra to be deposited prior to the basaltic tephra in most localities to the northwest and west of the eruptive fissure. This produced the effect shown on Fig. 7: the axes of thickness formed by the basaltic and silicic tephra layer are parallel but 15-20 km apart, corresponding to the distance separating the crater rows that produced them. Westerly wind prevailed after eruption of silicic tephra ceased. No signs of extended breaks in the explosive activity have been found so far.

The eruption was almost purely explosive and the bulk of the material produced is basaltic tephra. Its volume as calculated from the isopach map (Fig. 6) is 3.3 km^3, corresponding to 1.1 km^3 of lava. Basaltic lava is negligible, less than 0.01 km^3. Silicic tephra and lava add up to 0.1 km^3, calculated as lava.

The time needed to produce the basaltic tephra was estimated in the same way as for the Veidivötn eruption and was found to be 122 hours (5 days).

The composite part of the Vatnaöldur tephra layer (Fig. 7) was originally dated and mapped by Thorarinsson (1944, 1967, 1970) as an independent tephra layer, VIIa+b, deposited in the 9th century, near simultaneously with the early settlement in Iceland. Pollen-analytical studies indicate that its depositon took place during the landnám period, i.e. the period between 870 and 930 A.D. (Einarsson 1963), most likely around ~ 900 A.D. (Thorarinsson 1967). The dating is still valid, now possibly supported by the Greenland ice core chronology which lists an eruption in 897 or 898 A.D. (Hammer et al. 1980)

The material produced by this eruption was previously thought to belong to three eruptions (data summarized by Vilmundardóttir 1977).

Dómadalshraun-Tjörvahraun eruption, ~ 150 A.D.

The third youngest eruption took place on a ≥ 8 km long fissure, parallel to the other two (Fig. 4d). Its northeastward extension is not known, since it may be buried below > 20 m thick tephra deposits from the two younger eruptions. The SW end extends into the Torfajökull central volcano.

Lava flows and tephra deposits produced by the craters shown on Fig. 4d are contemporaneous formations according to the local and regional tephra stratigraphy (Fig. 3). The eruption was predominantly effusive and produced large lava flows and a small tephra layer (Fig. 8). The bulk of the material produced is basaltic lava, Tjörvahraun and Hnausahraun. The volume is estimated to be 0.8 km^3 (Vilmundardóttir 1977). Basaltic tephra is negligible. A significant amount of silicic lava, Dómadalshraun, was produced at the SW end of the fissure, estimated to be 0.05 km^3 (Blake 1982). A small silicic tephra layer was erupted during the extrusion of Dómadalshraun, its volume is estimated to be ~ 0.05 km^3, corresponding to ~ 0.01 km^3 of lava.

Basaltic and silicic material must have been erupted simultaneously from different parts of the fissure because the silicic tephra erupted at the SW end has been mixed into the scoriaceous top of the basaltic lava erupted farther NE. Silicic clasts, often crushed or deformed, are found down to 1.5 m depth in the rubbly top layer of the lava in several pits excavated for power line foundations. The most plausible explanation is that the silicic tephra was deposited on the moving lava flow, a condition met only by simultaneous eruption of basaltic lava and silicic tephra.

The time needed to produce the basaltic lava was estimated in the same way as for the Veidivötn eruption. A duration of 200 hours (8 days) was obtained, assuming that no breaks occurred in the eruptive activity.

The age of the eruption was estimated from the existing tephrochronological data and the average accumulation rate of tephra layers for the periods present to 2700 B.P., present to 1100 B.P. and 1100 to 2700 B.P., in the area represented by section 1 on Fig. 3. Dates obtained through these averages lie between 1730 and 1950 B.P. An approximate date has been set at 1840 + - 100 years B.P or 150 + - 100 years A.D. (Larsen in prep.).

The material produced by this eruption was previously thought to belong to three smaller eruptions (Vilmundardóttir 1977).

Notes on eruptions older than 2700 years

It was found, during the field work on the three eruptions described above, that one or more craters on each of the three fissures were older than 2700 years (compare Fig. 4a and Fig. 4b, c and d). In other words, all three fissures had been channels for earlier eruptions.

Vilmundardóttir (1977) noted that the sources of at least four basaltic lavas erupted on the southwestern part of the fissure swarm before 2700 B.P. could not be located. If several eruptions take place on the same fissure, each new eruption is bound to destroy older craters to some extent. Such repeated activity will leave only a few craters from each eruption relatively intact, but the lava and tephra from each eruption can almost certainly be identified and dated through careful field studies. A few older generation craters are found among the craters active in the Dómadalshraun-Tjörvahraun eruption, representing at least one older eruption on that fissure. The age of two craters, one at the SW end of the fissure producing a small silicic lava and another on the NE half producing basaltic scoria (indicated by arrows on Fig. 4a), was estimated by the method described for the Dómadalshraun-Tjörvahraun eruption. An approximate dating of 3100 + - 100 years B.P. was obtained. This age is in good agreement with a basaltic lava flow previously dated at ~ 3000 years B.P. by Vilmundardóttir (1977). The volume of this lava flow is estimated to be 3.9 km^3

An eruption took place on this fissure at ~ 3100 B.P., but it is not known whether this eruption represents the fourth youngest eruption in this area, since older generations of craters on the other fissures have only been roughly dated as yet. It can be stated, however, that at least six eruptions have taken place on these three fissures during postglacial time (last 10.000 years).

Changes in ground water level and in the eruption mechanism of the basalt

Shorelines of a large lake, within and in the vicinity of the southwestern part of the fissure swarm, have been found in the basaltic tephra deposits. A large glacial river, Tungnaá, crosses the fissure swarm from SE to NW in this area. The existence of a temporary lake, Langalón, in its riverbed had already been pointed out (Kjartansson 1961). Reconnaissance mapping of shorelines revealed evidence of a much larger lake, that formed after the deposition of the Vatnaöldur tephra in ~ 900 A.D. (Fig. 9). Older shorelines have not been identified because of extensive covering tephra and lava. A lake, however, began to form earlier, at the latest as a consequence of the third youngest eruption. That eruption took place on the northwesternmost of the three fissures (Fig. 4d) which crosses the riverbed of Tungnaá where the river leaves the fissure swarm. A lava barrier there traps the river within the volcanically active area. The ensuing lava flow did not accumulate within the fissure swarm itself (Fig. 8) but dammed the river effectively. As a result, ground water elevation exceeded surface elevation within the fissure swarm and a lake was formed there.

The two youngest eruptions occurred on fissures along the edge and in the middle of the lake basin (compare Fig. 9 and Fig. 2 or 4). The xenolithic material thrown out by some of the craters consists of waterworn pebbles and lumps of lacustrine sediment. The explosivity of the basaltic magma in these eruptions is therefore readily explained as a result of effective interaction with water or watersaturated sediments. This is also in accordance with the morphology of the tephra craters and tephra deposits described above (p. 5-6).

Each of the two youngest eruptions dammed the Tungnaá river where it crossed the fissure swarm and raised the lake level temporarily until the tephra dams were breached and the lake was drained down to the level controlled by the lava dam. Remnants of this lake are seen in the present Veidivötn lakes.

General characteristics of the three youngest eruptions and the potential hazards involved

The three eruptions have several things in common that may be typical for eruptions in this area and are likely to be repeated in future eruptions.

Disregarding the different eruption mechanism of the basalt, the general characteristics of these three eruptions are the following:

The eruptions took place on discontinuous fissures, up to 42 km in length. All extend across the rift zone/flank zone boundary, up to 15 km into the flank zone.

Each of these three eruptions produced a dense rock equivalent (DRE) of about 1 km^3 or more of basaltic material and minor amounts of silicic material.

During the peak of each eruption, the whole length of the fissure was active. Basaltic and silicic magma was extruded simultaneously from each fissure.

Calculations based on average production rates in recent eruptions indicate that the bulk of the material produced in each eruption was extruded in a relatively short time, possibly as short as 60-70 hours.

All three eruption fissures lie across the riverbed of Tungnaá and caused temporary disturbance to the flow of the Tungnaá river.

The potential hazards posed by these eruptions are the following:

Widespread heavy tephra fall with thicknesses in excess of 2 m at distances of 10 km if the eruptions are predominantly of explosive (hydromagmatic) character (Fig. 5 and 6).

Lava flows extending 20 km or more from the source if the eruptions are predominantly of effusive character (Fig. 8).

Damming of a large glacial river with consequent formation of unstable lakes (Fig. 9).

The damage caused by these eruptions cannot be discussed unless a utilization of the affected areas is postulated. Evaluation of the effects of such eruptions on the present utilization of hydropower should be subject to a separate study. A more detailed description of each of the three youngest eruptions will be presented in other reports and could serve as a basis for such a study. At present, their consequences are best demonstrated by Figs. 5 to 9. The basaltic tephra layers produced in the two youngest eruptions are the most voluminous tephra layers of their kind known so far in Iceland. However, it must be borne in mind that larger eruptions than the three discussed here have taken place in this area, cf.p. 14. The consequences of a future eruption, whether an explosive or an effusive eruption, can therefore be more severe than indicated by Figs. 5 to 9.

The effects of these eruptions on the Tungnaá river can be discussed only in general terms. The consequences can be divided into temporary disturbances and permanent changes. The effects of the explosive eruptions (two youngest eruptions) belong mostly to the first category. The river was temporarily dammed by rows of tephra craters built across the river bed. Its flow may also have been disturbed elsewhere by deposition of tephra in the river bed. Its course, however, was permanently altered only where it crossed the fissure swarm. The effects of the effusive eruptions (third youngest and older eruptions) were of more permanent nature. In addition to the damming of the river where it crossed the fissure swarm, the lava flows followed its course downstream and forced the river out of its channel, thus permanently altering large parts of its course.

INTERPRETATION OF THE VOLCANIC HISTORY

The volcanic activity described above took place simultaneously on two petrologically and tectonically different parts of the Eastern volcanic zone, the tholeiitic rift zone and the transitional to alkalic flank zone. This is best demonstrated by the two youngest eruptions, where the eruption sites and the eruption products are still well exposed both on the rift zone and the flank zone. The eruption fissures become more discontinuous as they approach the rift zone/flank zone boundary but follow the trend of rift zone tectonics for up to 15 km into the flank zone. The volcanic activity is therefore best explained as a result of rifting on the Veidivötn fissure swarm that has extended across this boundary allowing different magmas to erupt to the surface in a single eruption.

Rifting and fissure propagation across a tectonic boundary

The above interpretation is supported by the petrology and geochemistry of the eruption products. In the two youngest eruptions, tholeiitic basalt belonging to the Veidivötn series of Jakobsson (1979) constitutes 90% or more of the total volume erupted. Tholeiitic basalt is also found as contaminant in the silicic lava and tephra erupted within the flank zone, both in the youngest eruption (Mörk 1984) and the second youngest eruption (Mc Garvie, pers.comm. 1983). Evidence that the silicic magma was mobilized by injection of tholeiitic magma from the rift zone is presented by Mörk (1984).

For prediction and monitoring of future volcanic activity in this particular area, it is important to know whether the volcanism is, as a rule, the result of such rifting or whether processes operating within the flank zone must also be considered, as implied by the work of Jakobsson (1979).

This problem comes into consideration in the third youngest eruption. The main basaltic lava flow, Tjörvahraun, was classified by Jakobsson (1979) as transitional alkali basalt of the Torfajökull series. This would possibly imply that basaltic magma originating within the flank zone could open up a fissure in this area. More recently, however, Blake (1982) pointed out that this lava appears to be an approximately 50:50 hybrid of tholeiitic basalt of the Veidivötn series and transitional alkali basalt of the Torfajökull series. Tholeiitic basalt is also present as a contaminant in the silicic lava and as a distinct phase in the mixed silicic tephra erupted within the flank zone (Sigurdsson 1970, Blake 1982 and 1984). Blake concludes that the silicic and basaltic magma originating within the flank zone was mobilized by rifting and injection of tholeiitic magma from the NE. Consequently, the third youngest eruption should also be considered the result of a rifting on the Veidivötn fissure swarm. However, tholeiitic basalt may constitute somewhat less than 50% of the total volume erupted or approx 0.4 km^3

DRE. It is interesting to note that a previous eruption on this fissure produced ~ 3.9 km^3 of tholeiitic basalt (cf.p. 14).

The fissures active in the three youngest eruptions have all been channels for earlier postglacial eruptions. The basaltic lavas older than 2700 B.P. that have been erupted within the research area are all tholeiitic (Vilmundardóttir 1977) and at least some have been erupted along the trace of these fissures. Tholeiitic contamination has been found in several of the pre 2700 B.P. silicic lavas (Mc Garvie, pers.comm. 1983) but they have not yet been tied in with basaltic lavas to form dated eruptions, with the exception of the eruption - 3100 B.P.

It is tentatively concluded that all the known postglacial eruptions in the research area are the result of the same process, a periodic rifting of the Veidivötn fissure swarm. Future eruptions are consequently expected to be caused by such rifting while processes within the flank zone are considered unlikely to trigger an eruption. The research area (as outlined on Fig. 2) should be regarded as the southwesternmost part of the Veidivötn fissure swarm and that term is therefore extended to include the eruption sites within the Torfajökull central volcano on the flank zone as well.

The eruption frequency and magnitude indicated by the three youngest eruptions, a large (~ 1 km^3) eruption at intervals of 6-800 years, implies that this part of the fissure swarm is volcanically inactive for long periods between relatively large rifting events. The data presented above also purports that the rifting is propagating southwestwards into a different tectonic environment, the flank zone, which is in agreement with the suggested southwestwards propagation or transgression of the rift zone (Óskarsson et al. 1982, Meyer and Sigurdsson 1982). Rifting on the southwestern part of the Veidivötn fissure swarm may be affected by this situation, resulting in few and large eruptions, separated by long periods of quiescence.

THE VEIDIVÖTN FISSURE SWARM AS PART OF LARGER VOLCANIC SYSTEM

Renewed activity on the southwestern part of the Veidivötn fissure swarm is possibly preceded by precursory symptoms that can be detected by instrumental monitoring. An important question is how the earliest possible warning signals of renewed activity can be detected and where to look for them.

The mechanism of rifting as well as the relationship between fissure swarms and their associated central volcanoes, where high level magma reservoirs are located, has been clarified during the present (1975-   ) episode of rifting and magmatic activity on the Krafla volcanic system in N-Iceland (Björnsson et al. 1977, 1979; Saemundsson 1979, Tryggvason in press). The tensional strain accumulated as a result of crustal spreading is released during rifting episodes of the various fissure swarms within the axial rift zones. During rifting episodes the central volcanoes appear to play an active role by supplying magma from magma reservoirs into the fissure swarms. Inflow of magma from below into a reservoir at a depth of $\sim$ 3 km below the Krafla central volcano was indicated by ground deformation, inflation, at the central volcano. From time to time during the present Krafla rifting episode, outflow of magma from the reservoir into the fissure swarm was indicated by deflation of the central volcano and sudden widening of the fissure swarm. The Krafla rifting episode has thus consisted of about 20 events of active rifting, apparently initiated at the central volcano when pressure within the magma reservoir reached certain critical level. During several of the rifting events, part of the mobilized magma escaped to the surface in volcanic eruptions at the central volcano or on the fissure swarm. The rifting episode was preceded by increased seismic activity and detectable ground deformation at the Krafla central volcano.

It is considered justified to make use of the knowledge obtained during the Krafla rifting episode on the mechanism of rifting and the relationship between fissure swarm and central volcano for a better understanding of the eruptive history of the Veidivötn fissure swarm and the possibilities of long term surveillance. Experience from the Krafla area indicates that detectable increase in seismic activity may begin at the central volcano several months in advance of any visible rifting or magmatic activity (Björnsson et al. 1977) and detectable inflation may begin earlier still (Björnsson et al. 1979). By analogy to the Krafla fissure swarm, rifting episodes on the Veidivötn fissure swarm are likely to be preceded by similar activity. The logical likely to be preceded by similar activity. The logical first step of long term surveillance would therefore involve monitoring of its central volcano.

<u>Location of the central volcano</u>

Two areas have been suggested as a possible central volcano associated with the Veidivötn fissure swarm, the icecovered Bárdarbunga in the NW part of the Vatnajökull icecap (Saemundsson 1979) and the Klofnafell area (Jakobsson 1979) immediately NE of the present study area (Fig. 1). The characteristics that make central volcanoes stand apart from the rest of the fissure swarm are their higher eruption frequency and productivity, the appearance of silicic rocks during later stages of their evolution, and in many cases, caldera development (Saemundsson 1979).

The Bárdarbunga area has many of these characteristics. It is a topographic height with rocks exposed up to 1800 m.a.s.l. indicating high productivity. A depression in its center is attributed to caldera collapse (Thorarinsson et al. 1974). Eruption frequency on the icecovered part of the fissure swarm, where the Bárdarbunga area lies, is high, close to one eruption every 100 years on the average: At least 10 subglacial eruptions have spread basaltic tephra beyond the limits of the Vatnajökull glacier during the last 1200 years (Larsen 1982, Thorarinsson 1974). One of them took place in 1477 A.D., near simultaneously with the Veidivötn eruption - 1480 A.D. (Larsen 1982, Thorarinsson 1958). The youngest eruption dates back to the year 1910 (Thorarinsson 1974). The known interval between eruptions varies from 50 to more than 150 years, but there may be additional ones that are only recorded in the ice itself (Steinthorsson 1977).

The Klofnafell area has not significantly higher eruption frequency than the southwesternmost part of the fissure swarm during the last 1100 years (Larsen unpubl. data). The elevation is 700-800 m.a.s.l. No data exist on the productivity of the two areas in relation to each other or other parts of the fissure swarm. Silicic rocks have not been found in either area. At present, these areas can only be compared by means of eruption frequency, and their elevation taken as a measure of bulk productivity. The comparison is definitely in favor of the Bárdarbunga area.

The term volcanic system includes both fissure swarm and central volcano. Usually volcanic systems and fissure swarms are named after the central volcanoes. Bárdarbunga fissure swarm would have been more appropriate than Veidivötn fissure swarm once a decision has been made in favour of the Bárdarbunga central volcano. The latter name will, however, be retained throughout the paper to avoid confusion and to emphasize that Bárdarbunga has yet to be firmly established as the central volcano on this particular fissure swarm.

A simplified model

If Bárdarbunga is the active central volcano on the Veidivötn fissure swarm, large scale rifting affecting a 100 km long segment from Bárdarbunga southwestwards, and consequent lateral transport of magma has been taking place at intervals of 6-800 years during the last 2700 years.

The near simultaneous eruptions on the southwestern and northeastern part of the fissure swarm in ~ 1480 and in 1477 A.D., strongly suggests that a 100 km segment of the fissure swarm was activated in a major rifting episode around 1480. No such data exists for the older eruptions. For comparison, an 80 km long segment of the Krafla fissure swarm was activated during the present rifting episode (Björnsson et al. 1977, Tryggvason 1980).

Eruptions on the icecovered northeastern part of the volcanic system could either be caused by rifting episodes or by volcano-tectonic activity at the central volcano, where other fault systems such as calderas may be superimposed on the fissure swarm. Data on eruptions on the icecovered part is not specific enough to distinguish between such eruptions but an analog of the latter is found in the 1961 eruption of Askja (Thorarinsson and Sigvaldason 1962). It is, however, known that some of the eruptions that are confined to the northeastern part, icefree areas included, are caused by rifting episodes, e.g. the 1862-4 Tröllahraun eruption (Thorarinsson and Sigvaldason 1972, Jónsson 1945).

Volcanic activity can apparently result from: (1) major rifting episodes activating the whole fissure swarm, (2) minor rifting episodes activating only the northeastern part and (3) magmatic activity confined to the central volcano. At this stage it must be assumed that the precursory symptoms of all three are similar. The long term monitoring efforts will therefore have to be aimed at the volcanic activity in general, using empirical data to estimate whether a rifting episode is likely to extend into the southwestern part of the fissure swarm or not. The postglacial volcanic history as a whole is still incompletely known. It is, however, possible to construct a simple model of the fissure swarm from the limited data available at present, which could serve as a basis for the monitoring and prediction work until a detailed postglacial volcanic history has been recorded.

A simplified volcano-tectonic model of a periodically rifting Veidivötn fissure swarm, based on the data presented in this paper but independent of time, would be as follows: Episodes of rifting and magmatic activity affect the fissure swarm at an average interval of 100 years, resulting in volcanic activity at the Bárdarbunga central volcano and the proximal (northeastern) part of the fissure swarm. In every sixth or eight episode, rifting extends southwestwards along the fissure swarm, activating its whole length and resulting in large fissure eruptions on the southwestern part as well.

DISCUSSION

Evaluation of the postglacial eruption history of southwestern part of the Veidivötn fissure swarm indicates possible eruption sites and eruption behaviour of future eruptions and the resulting volcanic hazards. The data presented here is mostly limited to the volcanic activity of the last 2700 years, or about one quarter of the postglacial time. Conclusions regarding future activity in this area, drawn from this data, will necessarily assume that the pattern observed for this period continues in the future. Such an assumption can be questioned because (1) it is known that some of the basaltic lava flows erupted in the period prior to 2700 B.P. are larger than the ~ 1 km^3 volumes obtained for the last three eruptions, (2) there are indications that both longer and somewhat shorter intervals than the 6-800 years intervals between the three youngest eruptions may have occurred between some earlier eruptions (Vilmundardóttir 1977 and pers. inform. 1982), and (3) the data is limited to volcano-tectonic fissures on the east side of the fissure swarm, which were active in the three youngest eruptions. Volcano-tectonic fissures on the west side were active prior to 2700 B.P. and have not been studied in similar detail. It can be argued, however, that if there has been a change in pattern with time, the present pattern is more likely to continue in the near future then is a previous one to be resumed.

The next eruption on the southwestern part of the fissure swarm is likely to take place on one of the preexisting volcano-tectonic fissures. If it takes place on one of the three fissures active during the last 2700 years some aspects of the volcanic activity can be predicted. (1) The fissure will be long (~ 10 km or more). (2) The whole length of it will be active during the peak of eruption. (3) Large amounts (~ 1 km^3 DRE) of basaltic magma and minor amounts of silicic magma will be erupted. (4) The eruption will cause temporary disturbances to the river that crosses the fissure swarm. Less certain aspects of a future eruption concern the magnitude of the eruption, and the eruption mechanism of the basalt. The only conclusion on the magnitude that can be drawn from the existing data (including Vilmundardóttir 1977) is that - 1 km^3 DRE of basalt appears to be a minimum value. The eruption mechanism of the basalt will almost certainly be affected by the high groundwater table but to a different degree depending on which fissure erupts. Eruption on the easternmost fissure (active in the youngest eruption) will be most explosive because it cuts through the present lake area and the bulk of the material produced could be basaltic tepra.

The volcanic hazards resulting from eruptions on the southwesternmost part of the Veidivötn fissure swarm are (1) far reaching lava flows, (2) widespread heavy tephra fall and (3) damming of a large glacial river with consequent formation of unstable lakes.

The proposed volcano-tectonic model of the Veidivötn fissure swarm indicates where the precursory symptoms of renewed volcanic activity are likely to appear. The model is, however, patterned after the Krafla fissure swarm and assumes that data from one fissure swarm ca be applied to another. It is tentatively suggested as a working model for seismic monitoring of the fissure swarm until further data on the volcanic history has been obtained.

Assuming that the model is representative, interpretation of an eventual increase in seismic activity in the Bárdarbunga area should consider at least four possibilities. It could be the precursor of (1) tectonic activity at or near the Bárdarbunga central volcano without any magmatic activity, e.g. the 1975 to 1980 seismic episode in the Bárdarbunga area (Einarsson 1983), (2) tectonic activity within a caldera structure, with subsequent magmatic activity, analog to the 1961 Askja eruption (Thorarinsson and Sigvaldason 1962), (3) minor rifting episode affecting only the northeastern part of the fissure swarm, e.g. the 1862-4 Tröllahraun episode (Thorarinsson and Sigvaldason 1972, Jónsson 1945) and (4) a major rifting episode affecting the whole fissure swarm, resulting in eruptions on the southwestern part as well as elsewhere on the fissure swarm, e.g. the Veidivötn episode around 1480.

The present period of quiescence on the southwestern part of the fissure swarm has lasted for ~ 500 years. The last interval was significantly longer or ~ 580 years and the previous one was estimated to be 750 (+ - 100) years. It is not possible to predict whether next rifting episode will be a minor or a major one. A major rifting episode can, however, be expected during the next 100 to 300 years.

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FIGURE CAPTIONS

Fig.1 The Veidivötn fissure swarm (ruled area) on the Eastern Volcanic Zone, Southern Iceland. B: Bárdarbunga central volcano, below the Vatnajökull ice cap, T: Torfajökull central volcano, both shown as black areas, Kl: Klofnafell area, H: Hekla central volcano, K: Katla central volcano, Ö: Öræfajökull central volcano. Adapted from Saemundsson (1979, Fig. 1).

Fig.2 The southwestern part of the Veidivötn fissure swarm. Craters which produced mainly tephra are indicated by bold lines, those which produced mainly lava are indicated by closed or open circles and thin lines. Approximate boundary between rift zone and flank zone indicated by broad arrows.

Fig.3 Composite soilsections and profiles from the study area and adjacent regions. 1. Composite soil section dominated by tephra layers from the Hekla area (southwest corner of the study area and areas immediately west of it). 2. Tephra and lava stratigraphy within the study area. 3. Composite soil section showing tephra stratigraphy in the Katla area (southeast of the study area). Age determinations of historical tephra layers after Thorarinsson (1958, 1967) and Larsen (1978, 1981 and unpubl. data). Age determination of marker tephra UN based on 14C dating of a Hekla tephra layer found just below it in the Hekla area (Kjartansson et al. 1964). H: Hekla, K: Katla, G: Grímsvötn, L: Lakagígar, E: Eldgjá. Asterisk: Source checked by chemical composition of the glass.

Fig.4a Craters and crater rows in the research area (legend as on Fig. 2) and the present course of the Tungnaá river (ruled).

4b The Veidivötn eruptive fissure, ~ 1480 A.D. Craters active during the explosive phase indicated by bold lines (tephra rings, tephra ramparts, maars). Craters active during the effusive phase indicated by dots or thin lines (spatter cones, spatter ramparts) and open circles (scoria cones). Outlines of lava flows are traced by thin lines. Those smaller than 1 km^2 are not shown.

4c The Vatnaöldur eruptive fissure ~ 900 A.D. Same legend as on b.

4d The Dómadalur-Hnausar eruption, ~ 150 A.D. Legend as on b. Possible NE extension could not be determinated due to excessive tephra cover of the Vatnaöldur Fremri crater row.

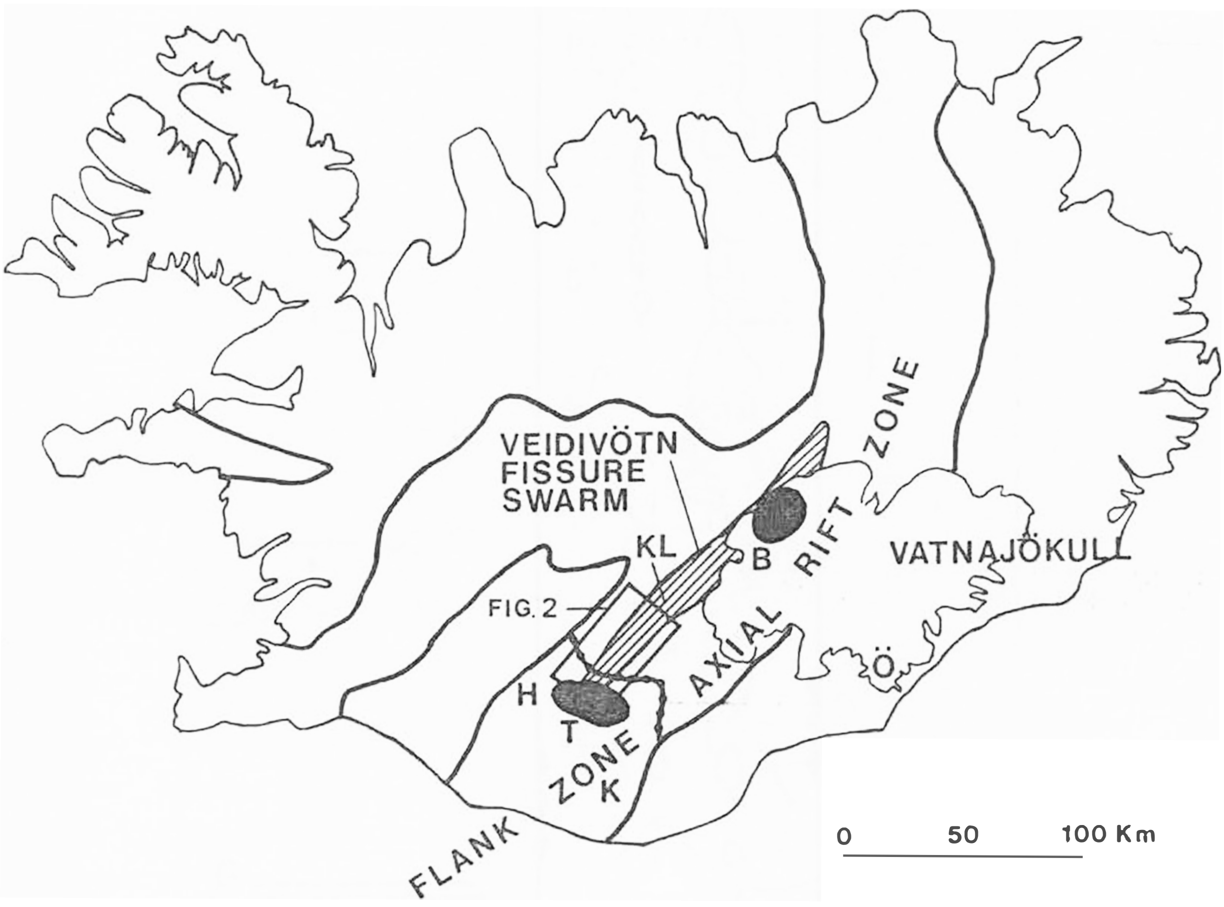
Fig.5 Isopach map of the ~ 1480 Veidivötn tephra layer. Distribution of sub-units (not shown here) was considered when the map was compiled. Inset map shows thickest part of the tephra layer and the most productive craters/crater rows. Numbers ending in two zeroes indicate unfavourable conditions for thickness determinations.

Fig.6 Isopach map of the tephra layer from the Vatnaöldur eruption ~ 900 A.D. Inset map shows thickest part of the basaltic tephra and the most productive craters/crater rows.

Fig.7 Isopachs of lower silicic part, originating in Hrafntinnuhraun crater row, are shown by thin lines. Isopachs of the upper, basaltic part, originating in Vatnaöldur crater rows and Hnausapollur crater, are shown by bold lines.

Fig.8 Lava flows and tephra produced in the Dómadalshraun-Tjörvahraun eruption ~ 150 A.D. Dotted line indicates position of power transmission line.

Fig.9 Langalón lake, maximum extension after the Vatnaöldur eruption of ~ 900 A.D assuming that no tilting has occurred in the area covered by the lake since that time. The submerged area is about 140 km^2.



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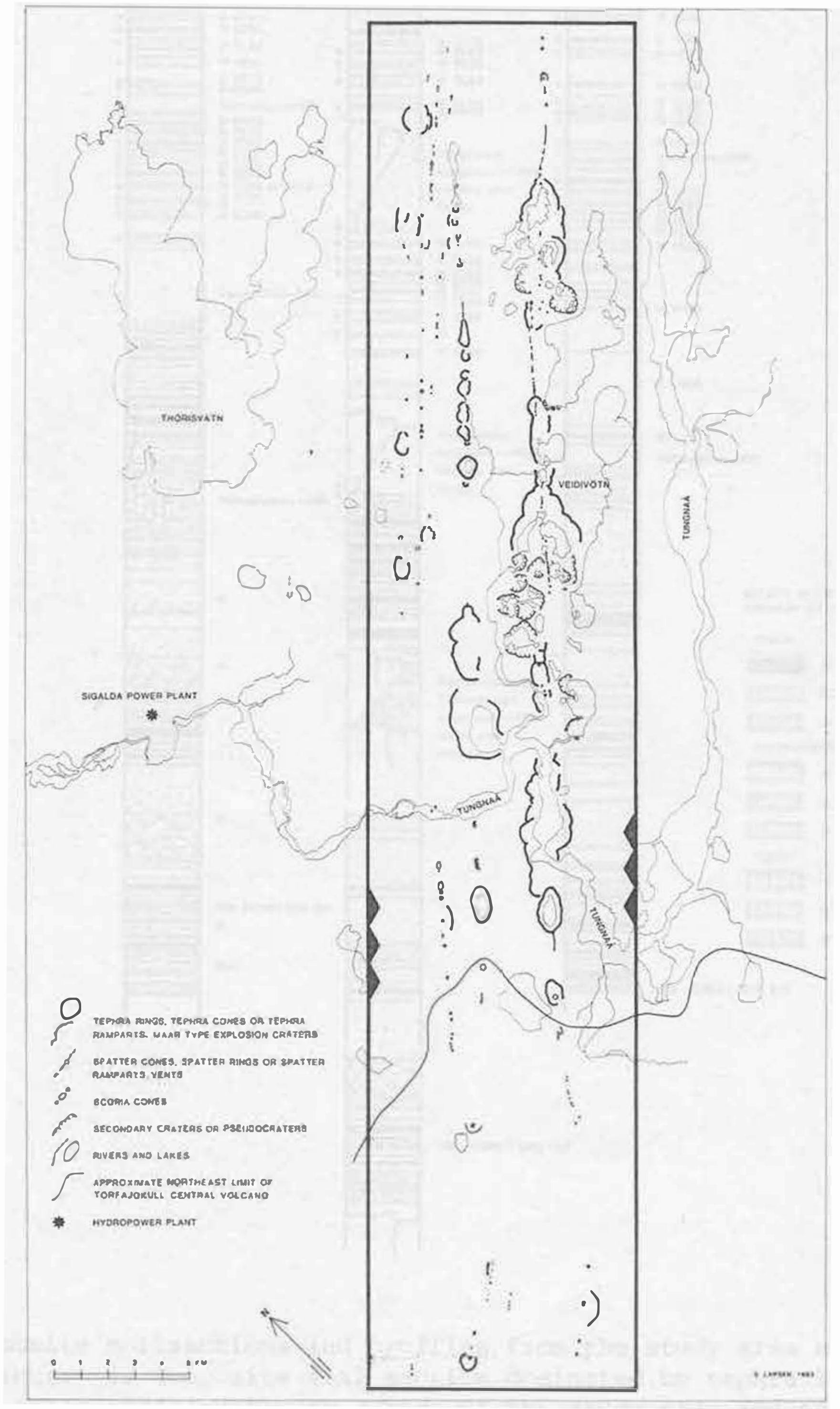

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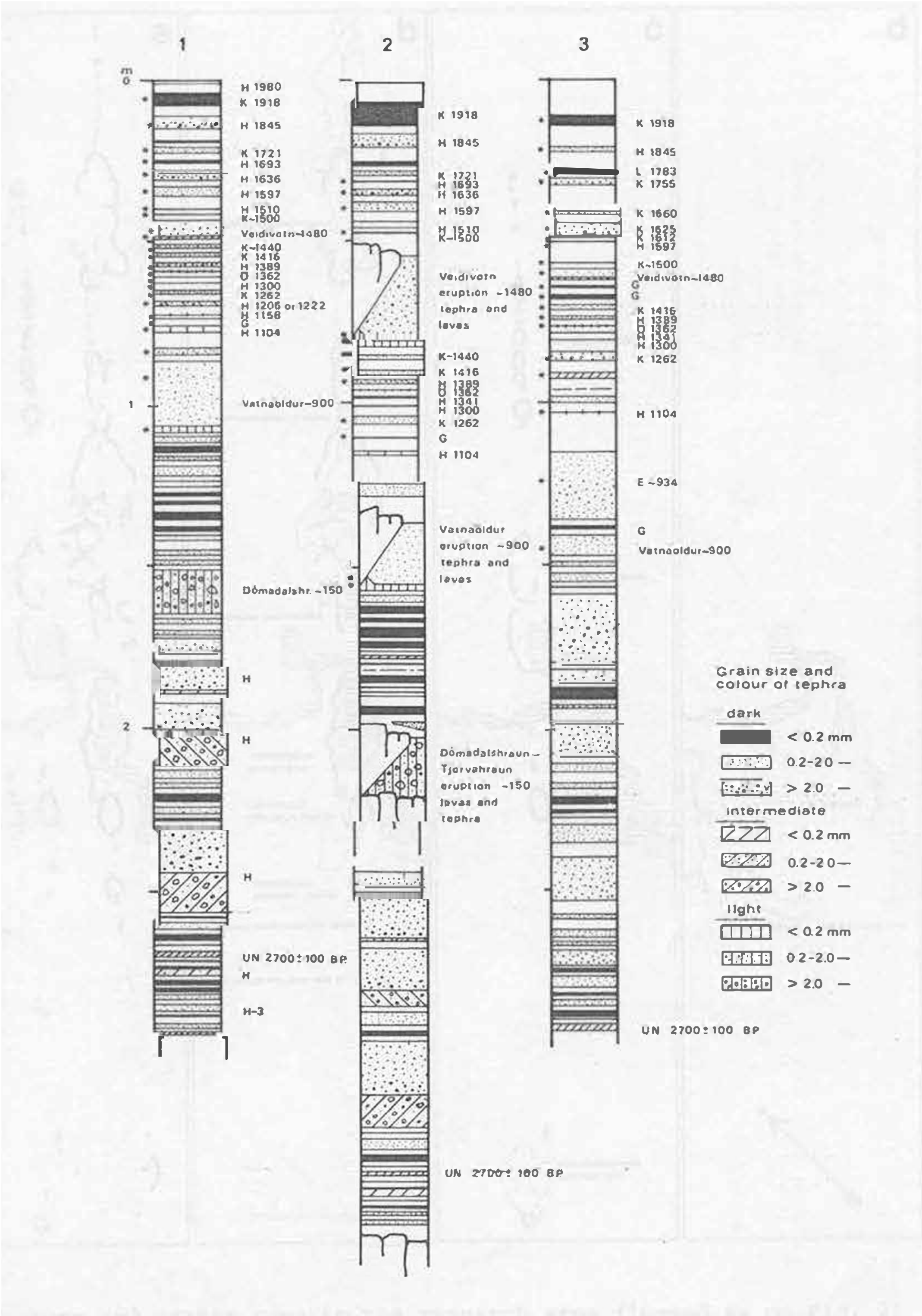

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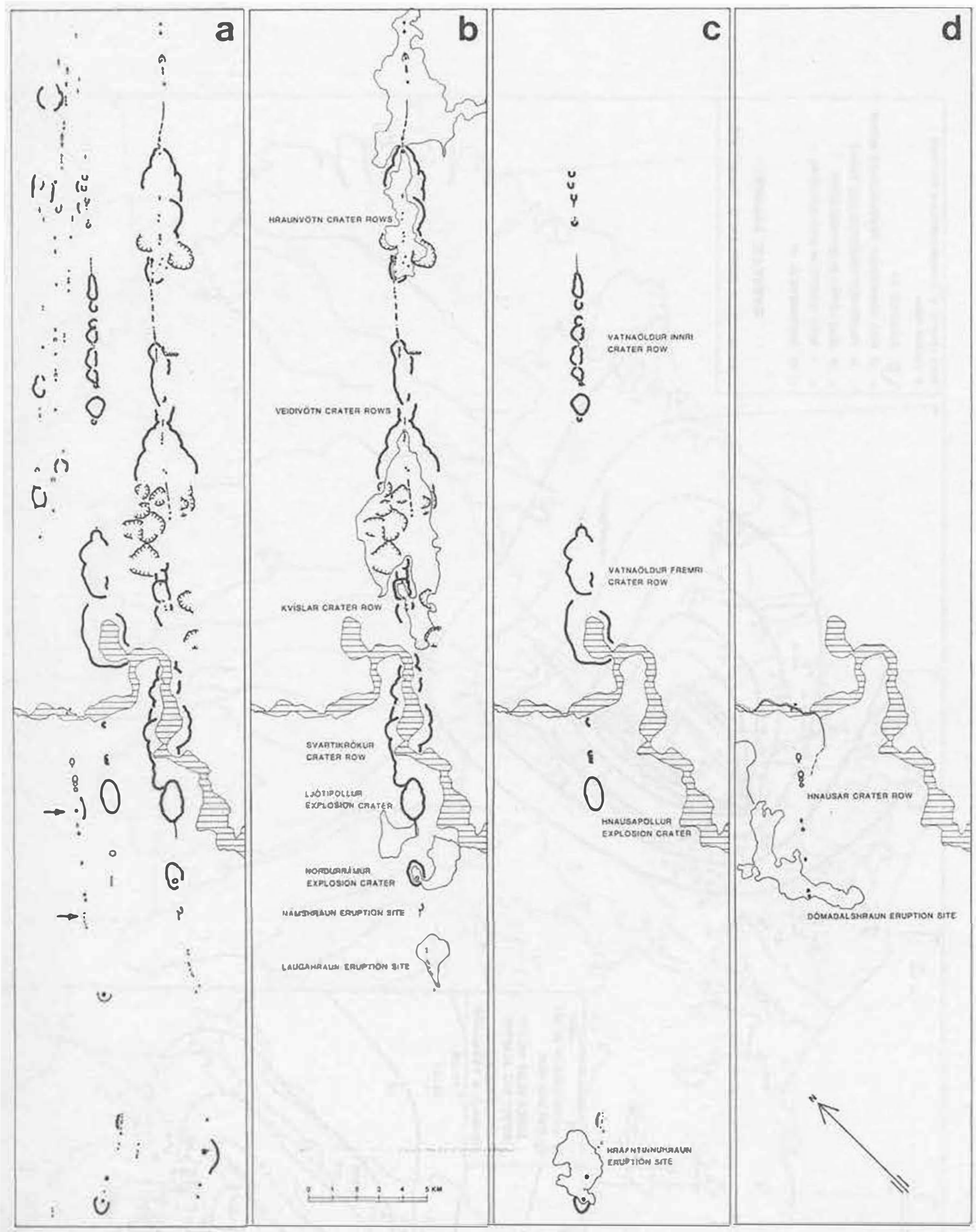

Fig.4(a) Craters and crater rows in the research area (legend as on Fig. 2) and the present course of the Tungnaá river (ruled).

(b) The Veidivötn eruptive fissure, ~1480 A.D. Craters active during the explosive phase indicated by bold lines (tephra rings, tephra ramparts, maars). Craters active during the effusive phase indicated by dots or thin lines (spatter cones, spatter ramparts) and open circles (scoria cones). Outlines of lava flows are traced by thin lines. Those smaller than 1 km^2 are not shown.

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(d) The Dómadalur-Hnausar eruption, ~150 A.D. Legend as on b. Possible NE extension could not be determinated due to excessive tephra cover of the Vatnaöldur Fremri crater row.

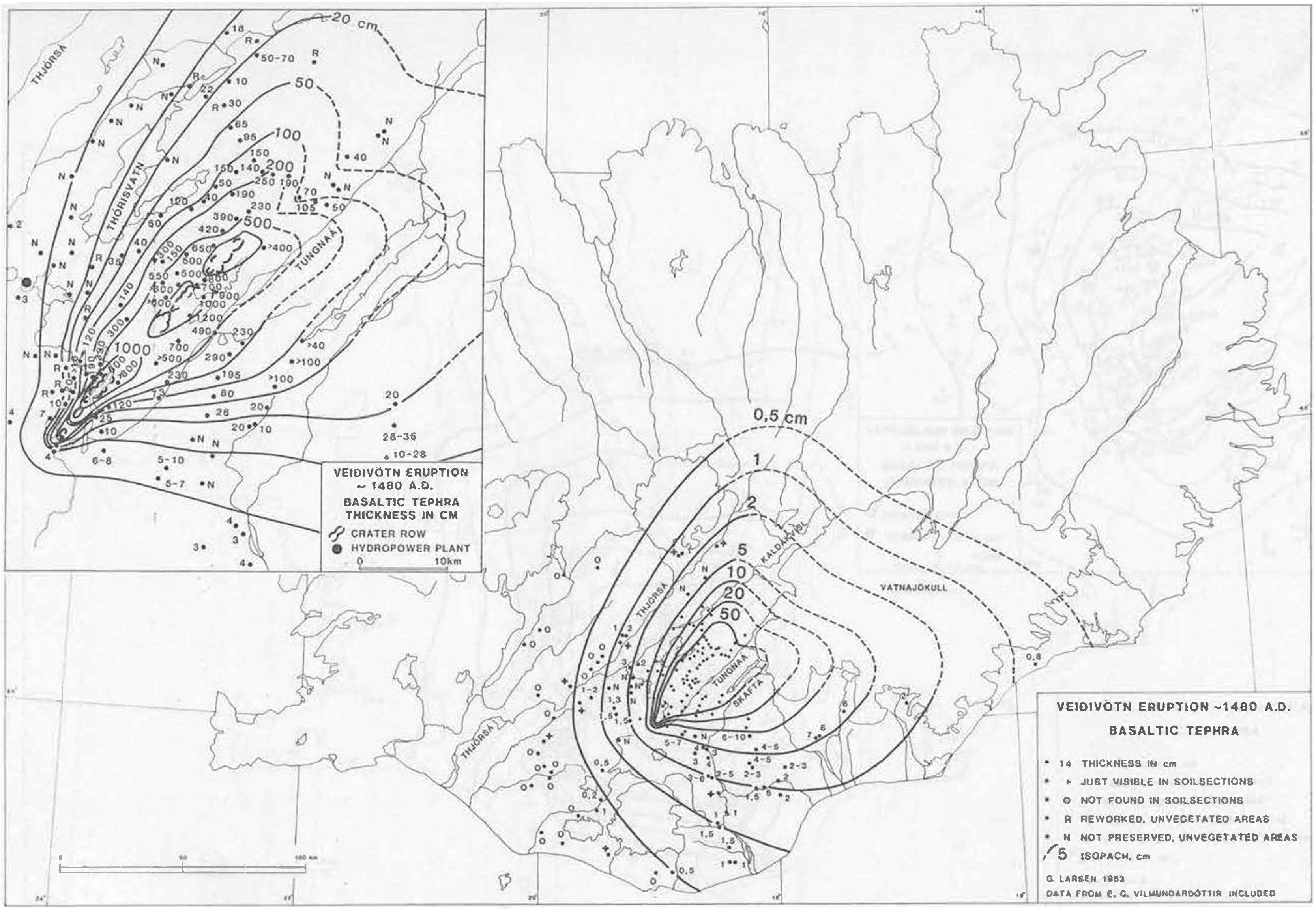


Fig. 5 Isopach map of the ~1480 Veidivötn tephra layer. Distribution of sub-units (not shown here) was considered when the map was compiled. Inset map shows thickest part of the tephra layer and the most productive crater/crater rows. Numbers ending in two zeroes indicate unfavourable conditions for thickness determinations.

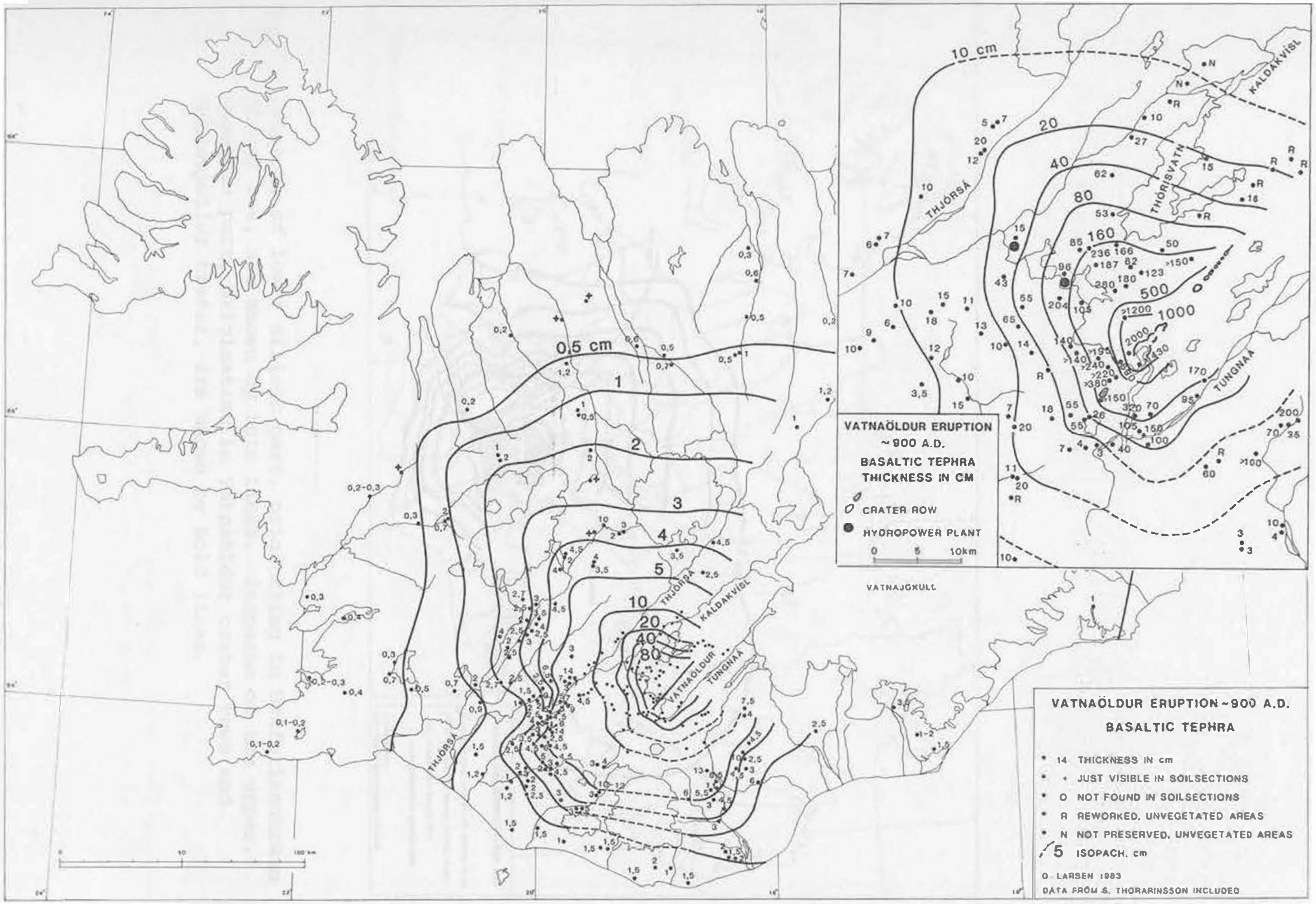
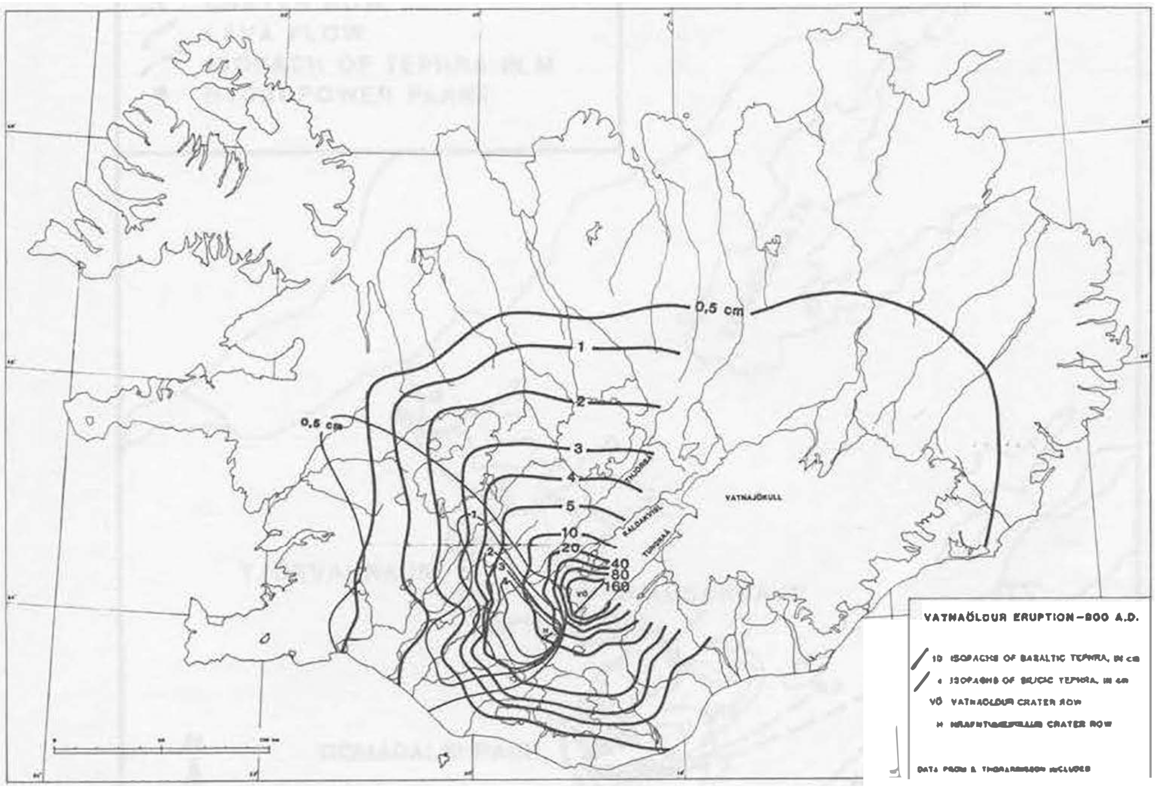


Fig. 6 Isopach map of the tephra layer from the Vatnaöldur eruption ~ 900 A.D. Inset map shows thickest part of the basaltic tephra and the most productive craters/crater rows.



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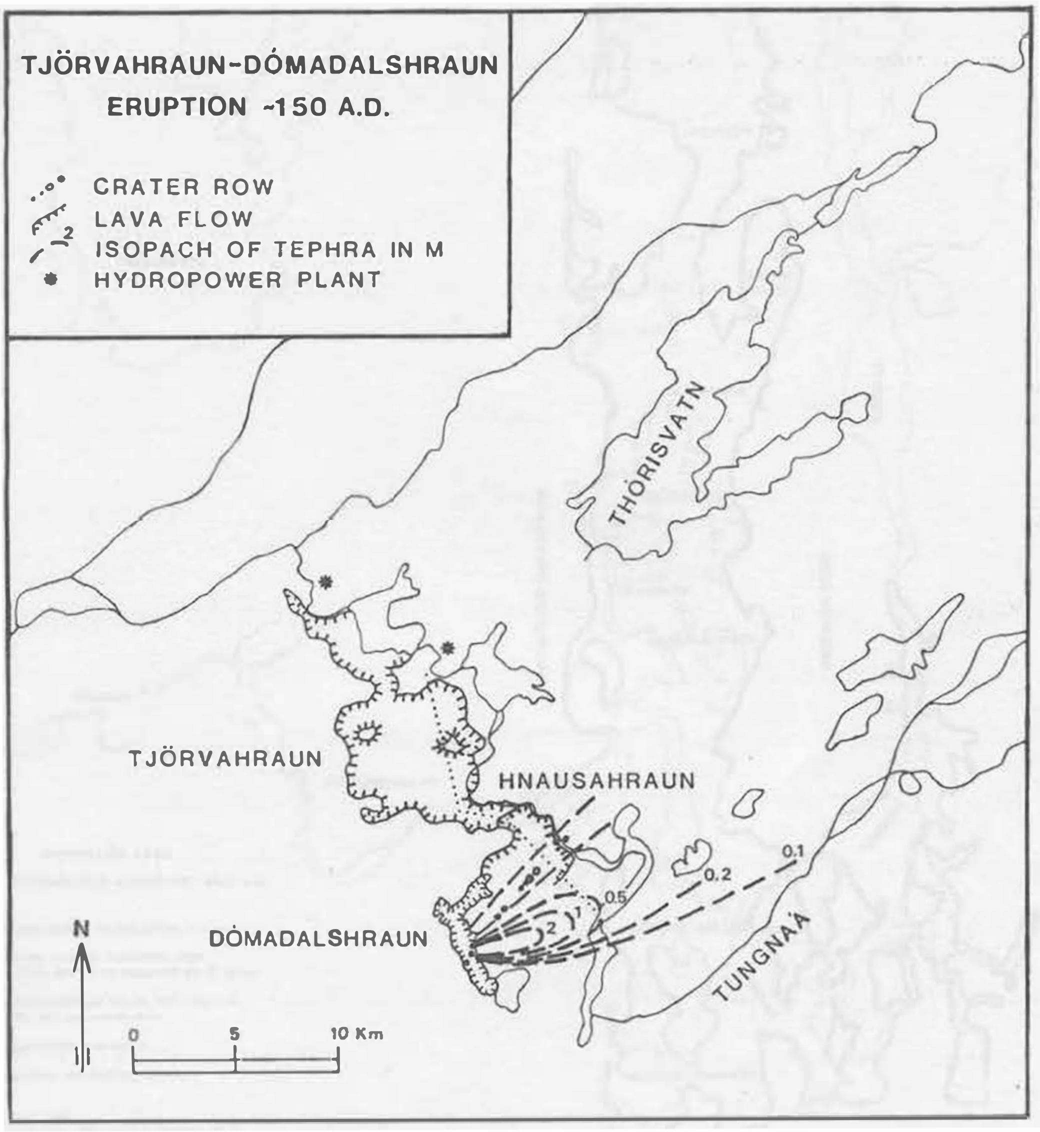

Fig. 8 Lava flows and tephra produced in the Dómadalshraun-Tjörvahraun eruption ~150 A.D. Dotted line indicates position of power transmission line.

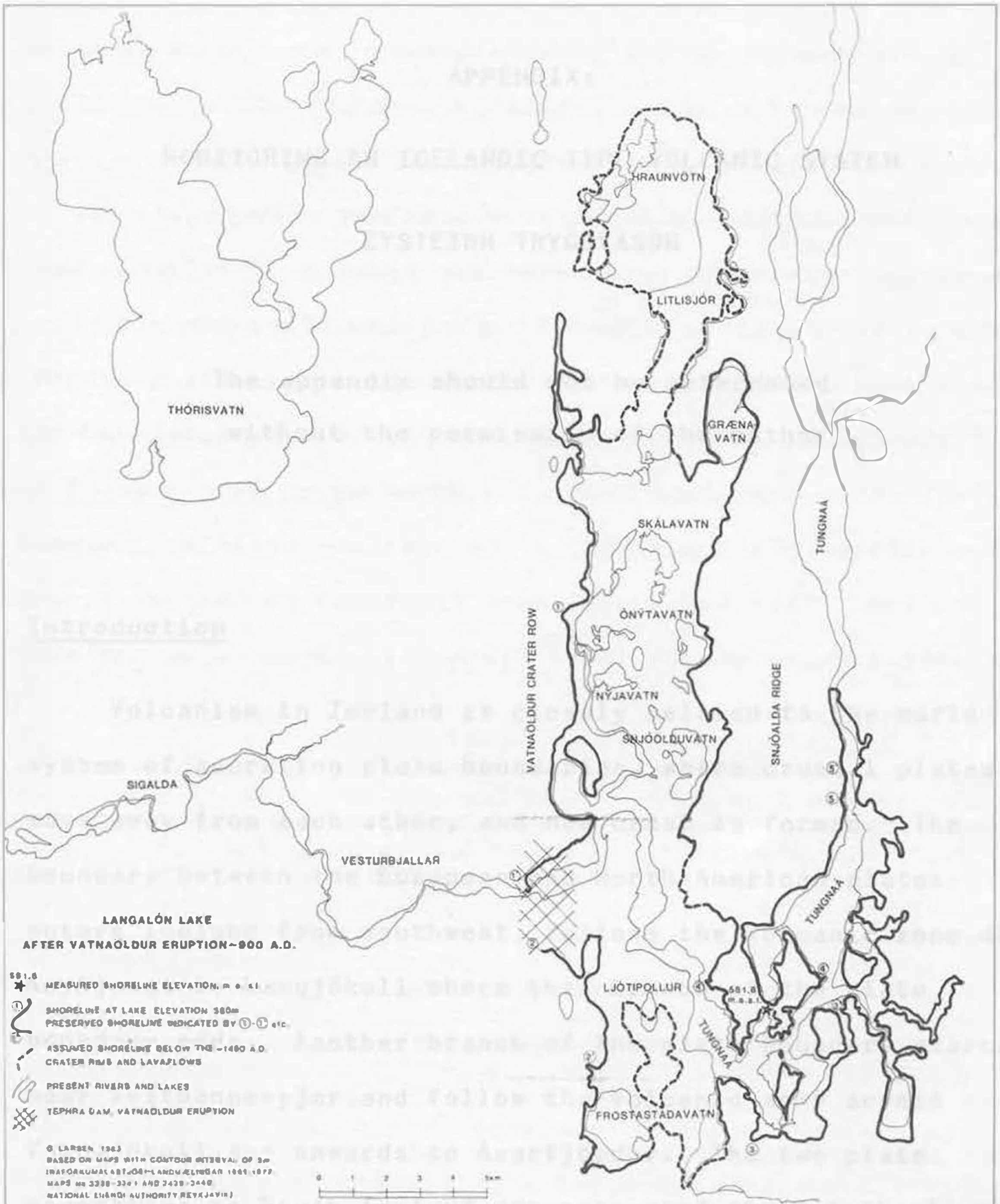

Fig. 9 Langalón lake, maximum extension after the Vatnaöldur eruption of ~ 900 A.D. assuming that no tilting has occurred in the area covered by the lake since that time. The submerged area is about 140 km^2.

APPENDIX:

MONITORING AN ICELANDIC TYPE VOLCANIC SYSTEM

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The appendix should not be referenced
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Introduction

Volcanism in Iceland is closely related to the world system of accreting plate boundaries, where crustal plates move away from each other, and new crust is formed. The boundary between the European and North-American plates enters Iceland from southwest, follows the volcanic zone of Reykjanes to Langjökull where this branch of the plate boundary ends. Another branch of the plate boundary starts near Vestmannaeyjar and follow the volcanic zone across Vatnajökull and onwards to Axarfjördur. The two plate boundaries in South Iceland are connected through the South Iceland seismic zone from Ölfus to Rangárvellir.

The long time average movement of the crustal plates in Iceland has been determined from magnetic signatures on the ocean bottom southwest and north of Iceland. The average velocity of one plate, relative to another is about 2 cm per year. The eastern plate moves towards ESE relative to the western plate.

The opening of the plate boundary is not a constant process and takes place during periods of rifting while the plate velocity at some distance, say 100 km, from the boundary is believed to be near constant. The plate boundary appears to heal after each period of rifting, but the continued plate movement causes the plate edges to be stretched until the tensile stress approaches the strength of the crust. Then the plate boundary breaks again and the plate edges move away from each other by an amount equal the accumulated plate movement since previous break at the same location. This break will open fractures in the crust, and basaltic magma enters these fractures. Some magma may erupt to form basalt lava.

The relationship between opening of the plate boundary and eruptions is not well understood, but eruptions may be a consequence of rather than cause of the rifting on the plate boundary.

The plate boundaries in Iceland are not a single line of fissures, but several zones of fissures may lie parallel to form a wide and complicated plate boundary. An example is the Veidivötn fissure swarm, and the Laki eruptive fissure in South Iceland.

Icelandic type volcanic system

An Icelandic type volcanic system is here defined as a central volcano intersected by a fissure swarm. Eruptions coincide with rifting along the fissure swarm. Known "Icelandic type volcanic systems" include the Krafla-

Gjástykki volcanic system and the Askja-Sveinagjá volcanic system. Suspected volcanic system of this type are: the Ketildyngja-Búrfellshraun volcanic system, Bárdarbunga and the Veidivötn fissure swarm, Grímsvötn and the Laki eruptive fissure, Katla and the Eldgjá fissure, Kverkfjöll and associated fissure swarm and also several volcanic systems on the western volcanic zone of Iceland.

Active volcanoes in Iceland which appear not to belong to the above group of volcanic systems include Hekla, Öræfajökull, Eyjafjallajökull and the volcanoes on Snæfellsnes.

Monitoring of volcanic system

This is the act of observing phenomena which may be used to determine how the volcanic system will behave in near or distant future, and which may improve our understanding of the processes which are at work within the volcanic system. If monitoring is to be used to estimate variations in the behaviour of a volcanic system, the observations must concentrate on variable phenomena. These may include seismicity, deformation of the surface, variations in hydrothermal activity and in magnetic and electric properties. Also chemistry of emitted gas, groundwater and volcanic products may be observed.

Monitoring of volcanoes is primarily based on continuously observed and recorded data, but may be supported by intermittent observations of various kind.

Behaviour of Icelandic type of volcanic systems

Knowledge on behaviour of Icelandic volcanic systems during and before eruptive periods is very scant, and largely confined to one system, the Krafla-Gjástykki volcanic system. Limited information exists on the Askja-Sveinagjá volcanic system, and still less information on other volcanic system, as Grímsvötn, Bárdarbunga and Katla. Hekla will not be considered, as it is apparently a different kind of a volcanic system, and further, no or very scant knowledge exists on the processes leading to eruptions of Hekla.

Pre-eruption observations of the Krafla volcanic system include (1) repeated precision leveling 3 to 9 years prior to the 1975 Krafla eruption, (2) repeated distance measurements 0.5 to 8 years prior to the same eruption and (3) seismic recordings over extended period. The leveling measurements near the Krafla fissure swarm, some 20 km north of the center of volcanic activity, showed 0.4 +- 0.2 microradian per year tilt towards the fissure swarm. It was not clearly observed if this tilt changed with time. The distance measurements across the Krafla central volcano showed significant lengthening of measured lines between 1971 and 1975 while no lengthening and even indication of shortening was observed between 1967 and 1971. The seismic observations showed marked increase in earthquake frecuency within the Krafla central volcano in the year 1975, beginning at least 6 months before the first volcanic event.

Earthquakes were strongly felt near Askja for some weeks before the Askja-Sveinagjá eruption of 1875, where earthquakes are very rare. Also, earthquakes were noticeable before the Laki fissure eruption of 1783.

No earthquakes were reported before the beginning of the 1724-1729 volcanic period of the Krafla volcano.

Increased seismic activity was recorded in Askja for some time, prior to the 1961 Askja eruption, and also in Grímsvötn before the 1983 Grímsvötn eruption.

Monitoring of the hypothetical Bárdarbunga-Veidivötn volcanic system

With reference to the limited knowledge of pre-eruptive behaviour of Icelandic type volcanic system, several measurable changes can be expected before a future eruptive activity of this system.

1. Seismicity

Observations show that increased seismicity precedes eruptions of several volcanic systems in Iceland, and this is likely to happen on the Bárdarbunga-Veidivötn volcanic system. According to the observations at Krafla, the pre-eruption earthquakes are located within the central volcano itself, and no pre-eruption seismicity was observed along the associated fissure swarm. The pre-eruption earthquakes of Askja 1961 and Grímsvötn 1983 were apparently located within respective central volcanoes, but the eruptions were also confined to the central volcano.

These observations indicate that pre-eruption seismicity of Icelandic type volcanic system is confined to the central volcano, possibly to the roof of a magma reservoir. Focal mechamism of pre-eruption earthquakes has never been determined in Iceland, but it is to be expected that these are normal fault (tensional) type earthquakes.

If seismicity is used to monitor the Bárdarbunga-Veidivötn volcanic system, then the earthquakes need to be located accurately and focal mechanism should be determined for a number of earthquakes.

2. Vertical displacement of the fissure swarm

If similar vertical displacements occur as were observed near the Krafla fissure swarm before the 1975-1981 eruptive period, then repeated precision leveling of lines oriented perpendicular to the fissure swarm will show some tilt. However the tilt rate of approximately 0.5 microradian per year is so small that recording tiltmeters will not detect it. It is probable that the tilt rate (or subsidence rate) will increase shortly before volcanic activity because of nonelastic deformation as breaking point is approached, but such increase has never been observed, and therefore, cannot be assumed as a certainity.

Tilt observations near the central volcano are expected to show uplift of the volcano prior to eruption. Comparison with distance observations at the Krafla central volcano indicate that a tilt of some tens of microradians may be expected on the flanks of the volcano over a period of one or more years prior to eruption, but earlier, no uplift is expected, and even subsidence of the central volcano is probable, as of the fissure swarm.

3. Horizontal component of deformation

It is expected that the fissure swarm and the immediate surroundings will stretch continuously before a volcanic event. This stretching is expected to be oriented perpendicular to the fissure swarm, but associated subsidence of the fissure swarm will bend the elastic crust to such an extent, that surface extension may not be easily observed. It seems probable that the stretching rate will increase shortly before rifting because of ductile behaviour as breaking strain is approached, but this has not been observed.

The central volcano will probably expand horizontally shortly before an eruption. This expansion is expected to be measurable by means of a geodimeter, if bench marks are located within 10 km of the central point of the expansion.

4. Volume-strain

A fairly simple method of measuring variations in volume-strain has been developed in recent years. Although no result exists on volume-strain variations in or near Icelandic type volcanic systems during or prior to eruptions, it is to be expected that significant and systematic strain variations precede eruptions. Above an inflating magma reservoir, as probably exists within the central volcano prior to eruptions, compressional strain will supposedly decrease at increasing rate because of increasing horizontal expansion. Outside the fissure swarm, the compressional strain can be expected to decrease more slowly, or even to increase immediately before an eruption as expansion of the central volcano creates compression in surrounding areas, when the boundaries of the magma chamber are rapidly yielding to the tensional stress.

5. Other phenomena

The ice cover of Bárdarbunga makes most observation difficult. This includes various types of electrical and magnetic observations, which under different condition might be worth while to consider. Also gravity observations are useless for pre-eruption monitoring because of the ice cover. Chemical monitoring of gases or groundwater is similarly difficult or not possible.

Suggested monitoring system for the Bárdarbunga-Veidivötn volcanic system.

1. Three seismometers, the minimum number of instruments for location of earthquakes, should be operated within 20 km distance from Bárdarbunga, one in Köldukvíslarbotnar, one in Vonarskard and one near Gæsavötn. Seismometers cannot easily be operated to the south or east of Bárdarbunga, and this three seismometer array is nearly linear and thus very unfavorable for the purpose of locating earthquakes. Therefore, one additioned station in Jökuldalur is suggested. The signals from these seismometers should be transmitted to a collecting station where continuous observation is possible (to Akureyri, Búrfell or Reykjavík).

2. Several lines of precision leveling, each 1 to 3 km in length, consisting of 10 to 30 bench marks, should be leveled every year or as frequently as deemed practical.

3. Several lines for distance measuring near Bárdarbunga, and across the fissure swarm, should be measured with geodimeter once each year.

4. Two-component tiltmeters should be located near each seismometer and the signals transmitted to the collecting station.

5. Volumetric strain meters should be placed at 100 to 400 m depth near each seismometer, and the signal transmitted to the same collecting station.

This monitoring system should be supported by occasional distance and leveling measurements which cover the whole area of the Bárdarbunga- Veidivötn volcanic system.