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EFFECTIVE SEALING BY SEDIMENT LOAD

HAUKUR TÓMASSON

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SESSION III, - Dams and Reservoirs

EFFECTIVE SEALING BY SEDIMENT LOAD

H. Tómasson
National Energy Authority, Dept. of Water Power, Reykjavík, ICELAND

ABSTRACT

Within the active volcanic zone of Iceland there are several large rivers originating in great ice caps. They carry a substantial sediment load. On their way through the volcanic zone the rivers flow in seemingly sealed channels sometimes fairly high above the regional groundwater table although the bedrock is composed of highly permeable moberg (hyaloclastite) and lava.

Permeability tests in boreholes using silt-laden water from these rivers showed definite decrease in the permeability of the rock during the test. This was due to the sediment load in the water. It led to the conclusion that the selfsealing process could be of engineering importance, effective and rapid enough to seal man-made lakes. Additional tests were made by pumping continually into one hole for two weeks during which time the leakage decreased to 2% of the original value.

Further tests on a larger scale were then made by diverting water from a river onto the permeable lava formation. The initial leakage proved to be 40 m^3/sec per km^2 of flooded area being of two types, uniform leakage over the whole area and localized leakage through swallow holes. The former type initially sealed rapidly and then in a linear manner corresponding to the increase in thickness of the impervious silt layer.

The leakage through swallow holes decreased wery slowly. These holes are most common at lava fronts and hillocks in the lava. Studies have been made to plug swallow holes with some result. After six years of operation about ten per cent of the original leakage remains.

EFFECTIVE SEALING BY SEDIMENT LOAD

The majority of water power potentials in Iceland is in glacier rivers which are constantly muddy and carry a substantial amount of sediment load, mainly silt and sand. Many of these rivers flow through young highly permeable volcanic formations and have sealed their beds by the sediment.

It was early realized that this sealing effect of the silt-laden water could be an asset in connection with the operation of proposed reservoirs and intake ponds on the young pervious formations. Some are now partly built. The main problem is to determine the speed of the process; is it fast enough to be of engineering significiance? The idea that this could be the case was awaken when it was observed that the graphs from Lugeon permeability tests, using silty water, showed a tendancy to decreasing leakage as the test went on. A graph of that type is shown in fig. 1, test 1.

The first test run to obtain knowledge of the speed of such a sealing (tightening) effect was initiated in 1963 (Tómasson 1964). The method used was based on pumping water into a borehole almost continuously for 17 days. The hole, DI-3 at Búrfell, was drilled in 1962 into a post-glacial lava flow, about 4000 year old, and a routine Lugeon test performed. A graphic core log of this hole is shown in fig. 2. The test was performed in the following manner:

1) Permeability test I

2) Sealing test I
   Pumping of water from Thjórsá river into the hole for 17 days.
   Samples taken from the water and its sediment load analyzed.
   The results are shown in fig. 3.

3) Permeability test II

4) Sealing test II
   Pumping water as prviously for three days.

The result of sealing test I shows that the water take of the hole decreased to 1/100th part of the maximum. By then 3500 m^3 of water had been pumped into the hole, containing approximately 950 kg of sediment load. In permeability test II the sediment fillings were washed out at pressure closely corresponding to the stress built up by the pumping of sediments into the joints.

In sealing test II the leakage continuously decreased after a start at a level similar to 11 days of pumping in sealing test I. The average sediment concentration was 300 mg/l whereof 14% was sand, 55% silt and 31% clay.

Comparison of the sealing of this drillhole to the sealing of a usual lake bottom with leakage paths through a lava flow to an underlying very open aquifer in the bottom layer of the lava flow indicates that this process can be very fast, fast enough to be of engineering significance. Certainly, the sediment concentration in the test was higher than would be expected in a real lake and also better graded with larger grain sizes acting as a filter for the smaller ones. But even with this in mind the very rapid decrease of leakage is promising as a process worth taken into consideration in connection with building of dams in geological setting as that described above.

In 1965 it was decided to broaden the scope of the test, see Tómasson (1976) and Tómasson et.al. (1976). The new test, called Langalda Diversion, was begun in 1966 with the diversion of a branch of river Tungnaá on to the highly pervious postglacial lava flows surrounding the river. In the course of the diversion small, shallow ponds were created where leakage could be calculated. The total size of these ponds was 0,17 km^2, general depth 1-2 m and the inflow 1-2 m^3/s. Observations on these small ponds showed an initial leakage of 30-40 $m^3/s/km^2$ decreasing in a few months to 10 $m^3/s/km^2$. The initial sealing was mainly due to formation of a thin layer of silt and clay on top of eolian sand and loess covering the lava flow. The remaining leakage was confined to swallow holes at the lava margin, which were too open for the sediment to seal. The swallow holes had to be closed with a material having filter criterion, well graded sand and gravel, to start the self-sealing mechanism. Positive results were obtained and in 1968 the leakage had been reduced to only 2 $m^3/s/km^2$. An analysis by Elíasson (1969) of the properties of carpet sealing using data from this test described it mathematically by the following aquation:

$$1) \quad \frac{Q_L \cdot t}{D \cdot A} = C \text{ or } Q_L = \frac{C \cdot D \cdot A}{t}$$

where Q is the leakage through the bottom of area A, t is time, D is some characteristic depth and C a constant characteristic for the particular reservoir found experimentally at the test site to be about 50. It can also be calculated when the characteristic of suspended sediment load and the permeability of the relatively impervious carpet can be measured.

To imitate more closely the circumstances at proposed hydro-power sites, the diversion was further extended in 1969 to a so-to-say full scale test, by building a dam, 10 m high, farther downstream on the diversion route creating a lake of 8 m maximum depth and 1,5 km^2 in area. In the following two years the inflow was gradually increased to 6-12 m^3/s. The intake into this lake has only been open during summer and the lake has only been at maximum level occasionally. The graph in fig. 4 shows the average inflow and lake elevation for every summer. In winter the basin is usually dry.

The sealing process in this lake is more complicated than the small lakes partly due to the fact that tectonic fissures opened in the bottom of the lake forming very large swallow holes. Clusters of such holes also formed elsewhere on the lake bottom, especially at small hillocks which are probably pseudocraters, and also at lava margins. Fig. 5 shows the average leakage per month during the last few summers. It is obvious that drying of the silty sediment on the bottom during winter and spring causes much damage to the impervious carpet. The same effect can be seen during summer when the lake has been emptied while repair was carried out.

Extensive experiments were carried out at the Langalda reservoir on methods to seal swallow holes. The use of natural filters as in the small scale test was partly used in the extended diversion, but often proved difficult because of driving problems created by the silt/clay layer on the lake bottom. Impervious plastic sheets were also tried, but usually with poor results as the high hydrostatic gradient around the edge of the sheet caused piping. Artificial filters, some sort of cloth, used together with the loose surface material on the bottom around the swallow holes proved least expensive. Most of the sealing work on swallow holes did not yield obvious results in hydrographs because the damage done to the impervious carpet by drying-out and traffic on the lake bottom did more than offset the possible benefit of the repair. On the other hand inspection of the lake bottom frequently showed that repair of swallow holes had endured well, but often new swallow holes had opened up beside the old ones. The largest single swallow hole, at the shore in an open fissure swallowed about 5 m^3/s. It was filtered by dumping some truck loads of natural filters without emptying the lake. This had a very obvious positive result.

The alternative to put filter material in swallow holes without emptying the lake has obvious benefits. Therefore, experiments were carried out in order to find swallow holes with the water in. Searching for leakage by listening with geophones was tried and some results obtained. This method was very difficult to use due to almost constant windnoise. Pumping of filter material at suspected leakage spots was also tried but obviously the location of the suspected swallow holes was not accurate enough.

Another way to find open swallow holes is to perform current measurements in the lake. By this method the greatest single swallow hole was found. The most promising method to find swallow holes with the water in seems to be the measuring of the electric self-potential in traverses in the lake. This method has not been fully tested but theoretically a water current should give anomaly in electric self-petential in swallow holes and has actually been proved to do so. But other unknown conditions in the ground can also give anomalies. The accuracy in location is fair but hardly good enough to allow concentrated action against swallow holes.

This method is much less weather-sensitive than other proposed methods so it can be used in normal weather conditions. Some repair work was done in the springtime during 1971 to 1975. Swallow holes on open fractures absorbed greatest quantity of filling material. The largest of the six fractures was closed by dumping in some 200 m^3 of material, but much less was used for the other fractures. About 200 swallow holes outside fractures were repaired by various methods. The total material handling in the repair work amounts to only about 500 m^3, which is less than 5% of the volume of the Langalda dam. As to cost this volume was more expensive per m^3 than the material composing the dam, especially natural filters which were transported a considerable distance. In fig. 5 the result of the sealing efforts, natural and man-made, can be seen. The initial leakage was very high, more than 50 $m^3/s/km^2$, but in 1977 the leakage had been reduced to less than 3 $m^3/s/km^2$. Still, a substantial number of swallow holes remained open, especially at the highest lake level.

The methods which have been used for sealing swallow holes are presumably not the most effective. They have tended to minimize the amount of material handled. A method retaining the water in the lake during repairing would yield much quicker results and be more durable against wave and wind action. We must now recall the results from the pumping test in the borehole. In a usual lake the concentration of sediments leaking through the bottom is much lower than in the water pumped into the hole. Also both sand and even coarse silt fractions are mostly lacking in the leakage water. The method to use dredging pumps to move sediments from one place to another in a lake can make the sediment concentration in leakage water many hundred of even thousand times higher than in natural conditions and much higher than in the borehole test and include coarser grain sizes.

A special method to find leakage areas in a lake, an electrical self-potential survey, has been introduced. Although not very accurate spatially it is probably good enough to allow the pumping to be concentrated at suspected leakage areas where swallow holes can be sealed at a similar pressure to what they have to withstand in the future operating of the lake. Although this method would include more material handling than the methods hitherto experimented with in the Langalda test reservoir, it would cost so much less per m^3 that the method in fact would be less expensive and more reliable in the long run.

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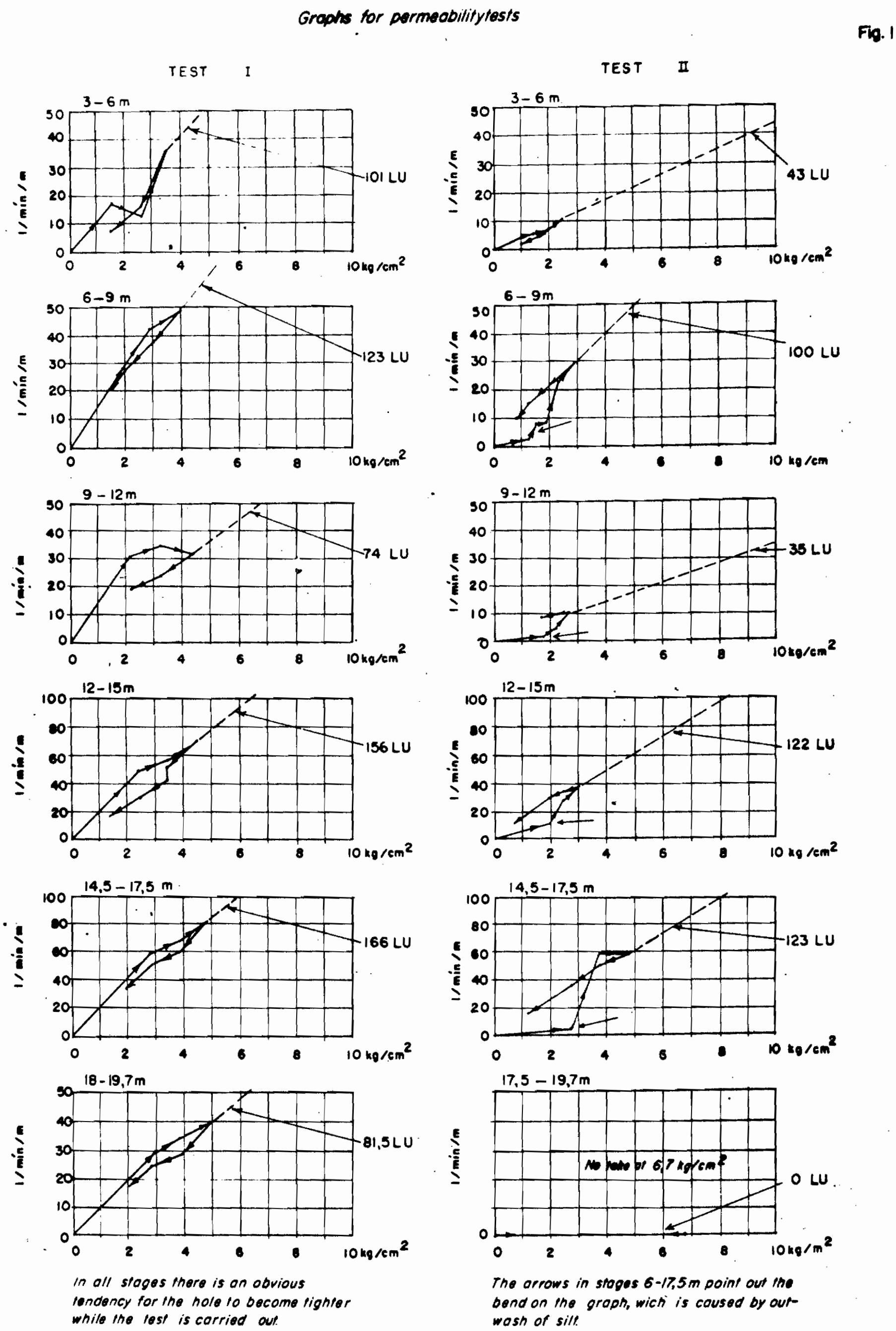


Fig. 1. Graphs of permeability tests I and II in borhole DI-3.

Fig. 2

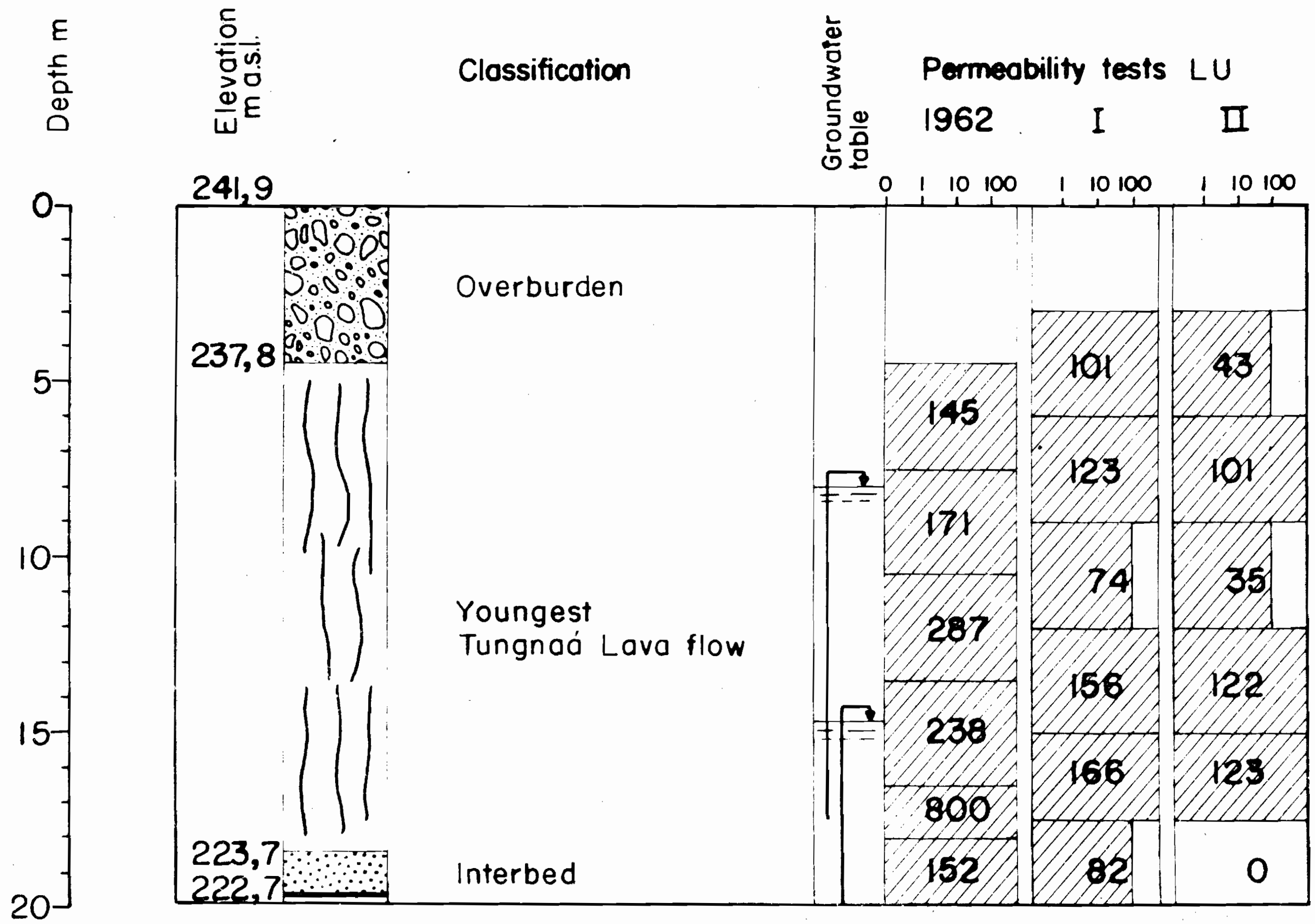


Fig. 2. Graphic log of borhole DI-3.

Fig. 3

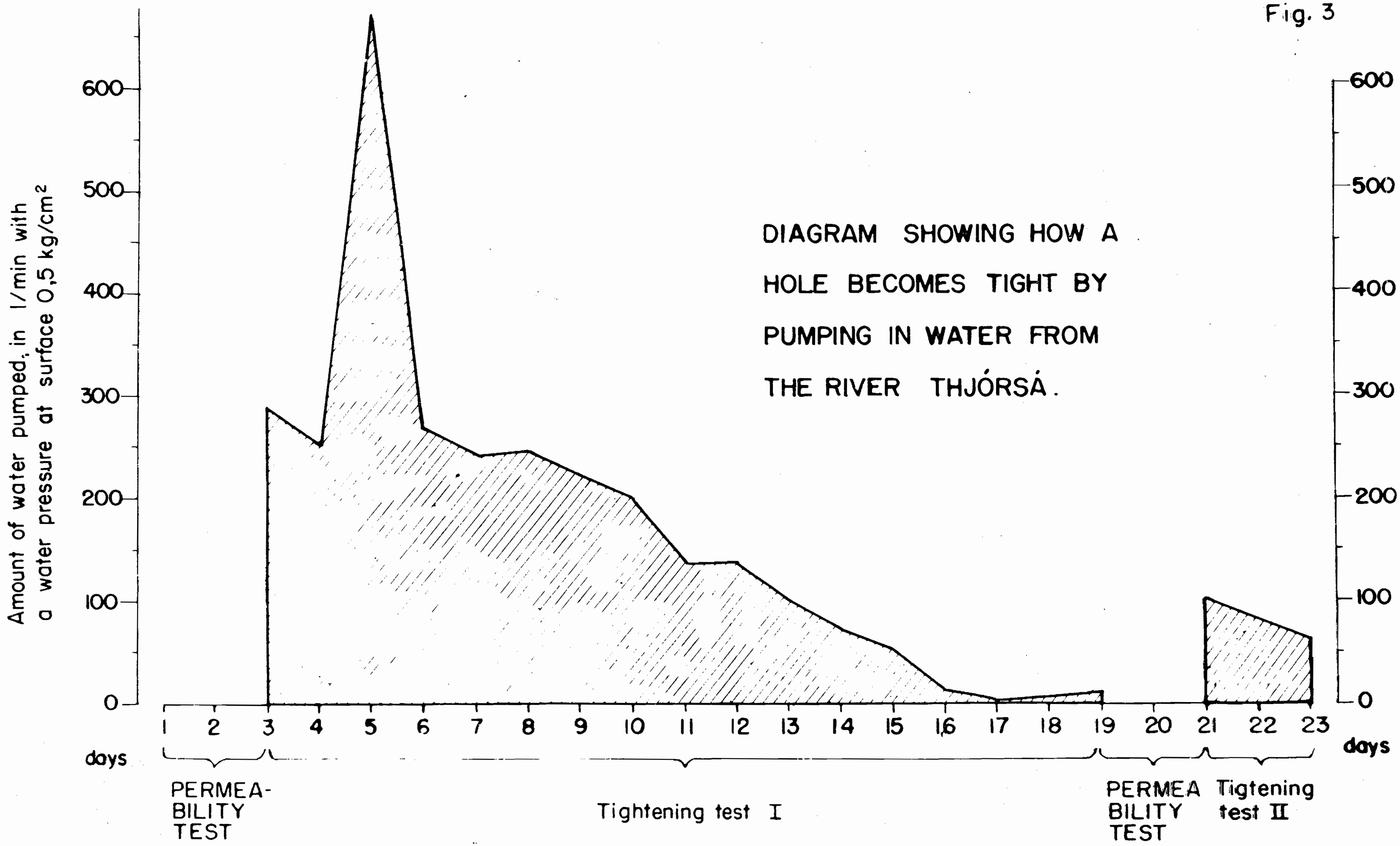


Fig. 3. Diagram showing the result of the tightening (sealing) tests in borhole DI-3.

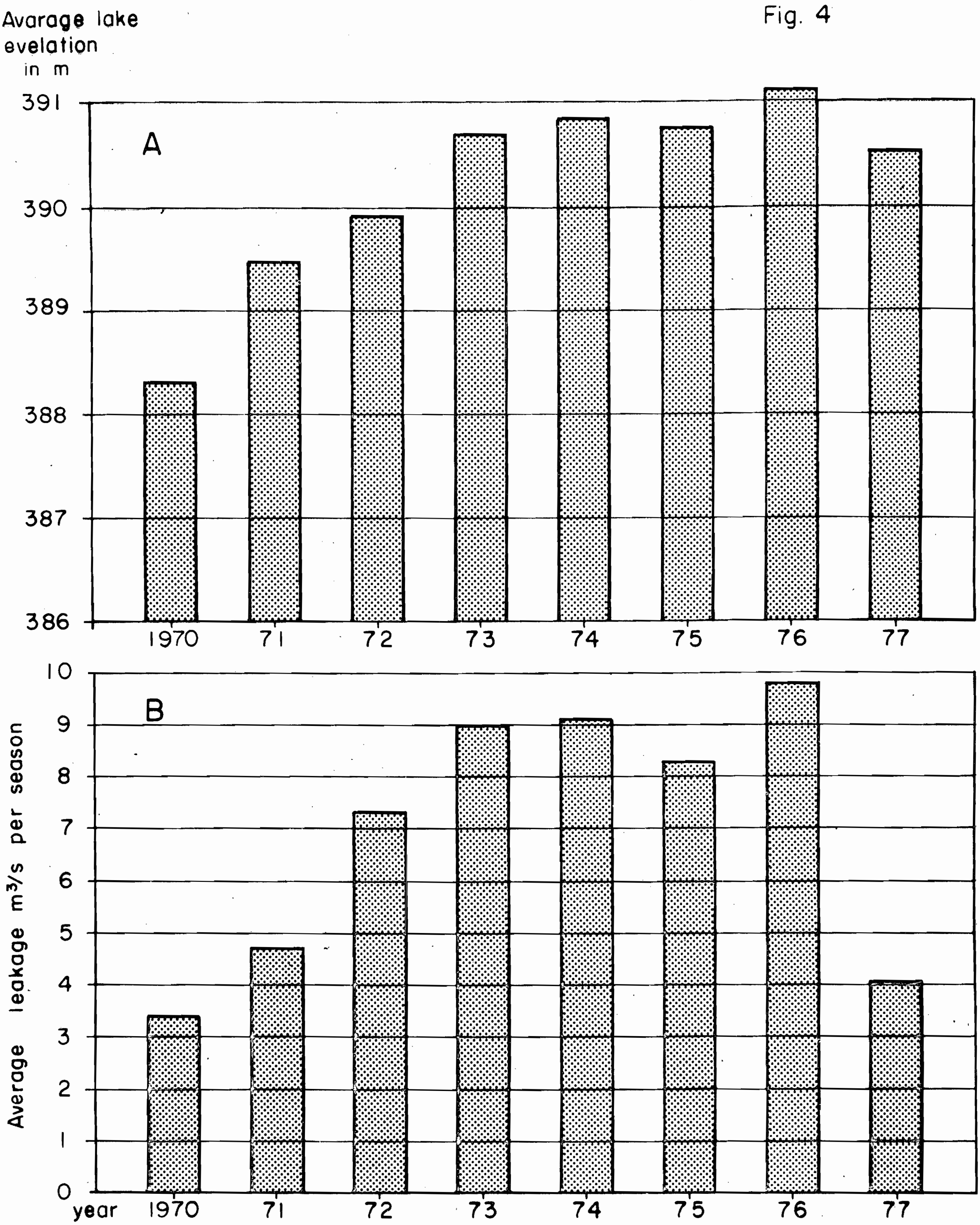


Fig. 4. A: Average elevation of the Langalda lake each season.
B: Average inflow into the Langalda lake each season.

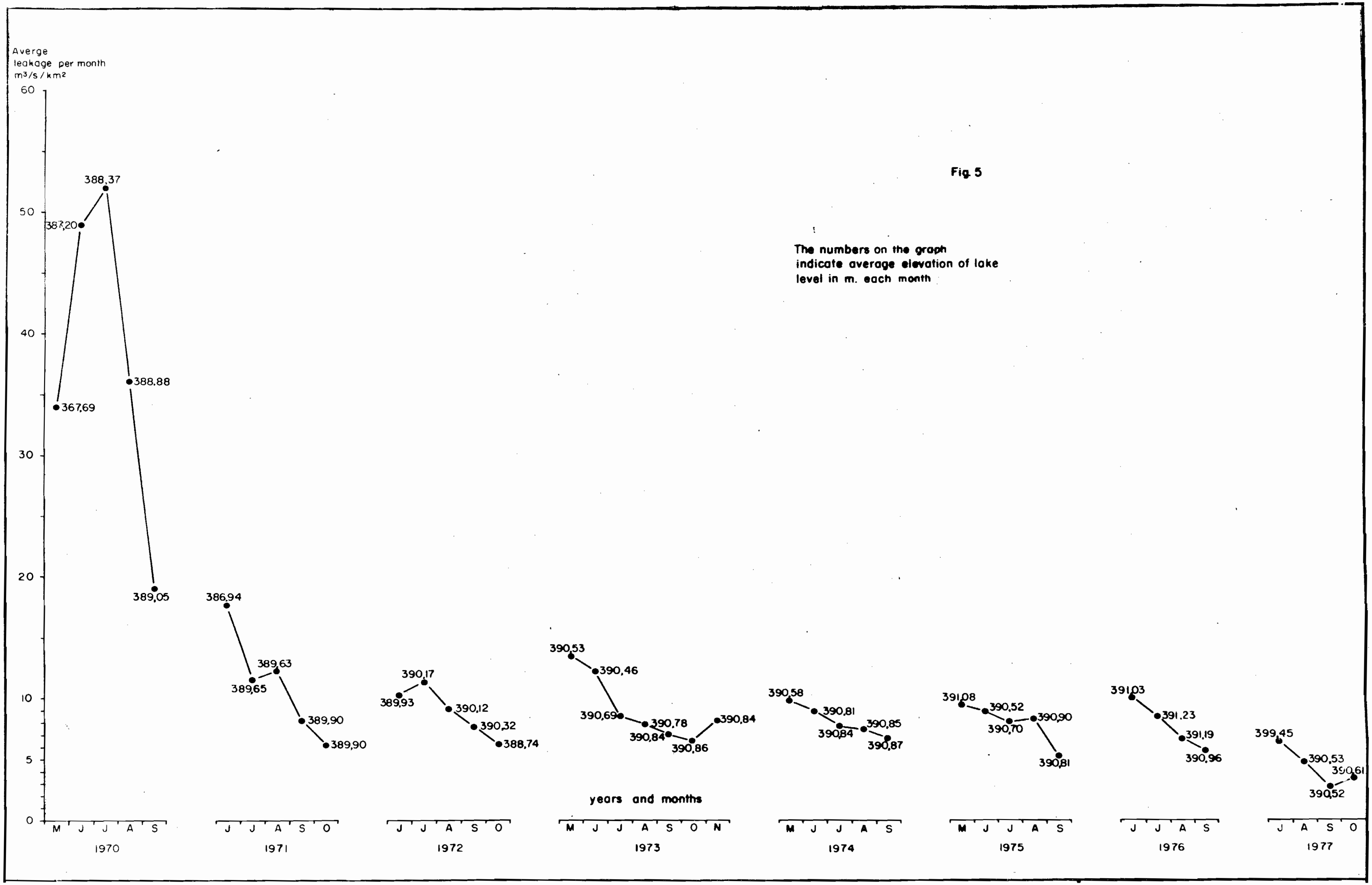


Fig. 5. Average leakage each month plotted against the corresponding average lake elevation.

Additional notes on effective sealing....

In my paper on effective sealing by sediment load it is proposed that the most efficient method to seal swallow holes would be to pump in sandy material with the water retained in the lake so that the swallow holes would be active during pumping.

This summer (1978) this theory was tested by pumping the sand of an already formed delta into a concentrated area of swallow holes connected mostly to fissure no. 6 but others at lava hillocks assumed to be pseudocraters. The pump used had a pumping capacity of 40 m^3 of solid material per hour. Pumping lasted for about 50 hours. The actual concentration of sand was lower than pumping capacity indicated, but activation of sandy material on surface near the swallow holes by the water jet may have compensated for this so that the 40 m^3/hour quantity of sealing material may actually have been reached.

The results of the pumping test are shown in the two graphs following. The first one shows the relation between lake level and ground water level in the near by drillhole HR-2. It shows the gradual tightening of the lake from 1972 to 1974. In 1975 fracture no. 6 opened up and a setback in the tightening process is indicated. After filling of the main swallow hole on fracture 6 with filter material in 1975 at a high lake level there was a very well marked decrease in leakage. Since then a gradual tightening has taken place, but during the pumping test a sudden decrease in leakage occurred.

The other graph shows lake level plotted against leakage for each day from shortly before, during and after the pumping. The result is very obvious, a decrease in leakage by 3 to 4 m^3/sec. This result is in fact much better than I had expected. The decrease in leakage is similar to what was obtained at Sigalda reservoir last autumn by putting on a sealing blanket at about 200 times higher cost.

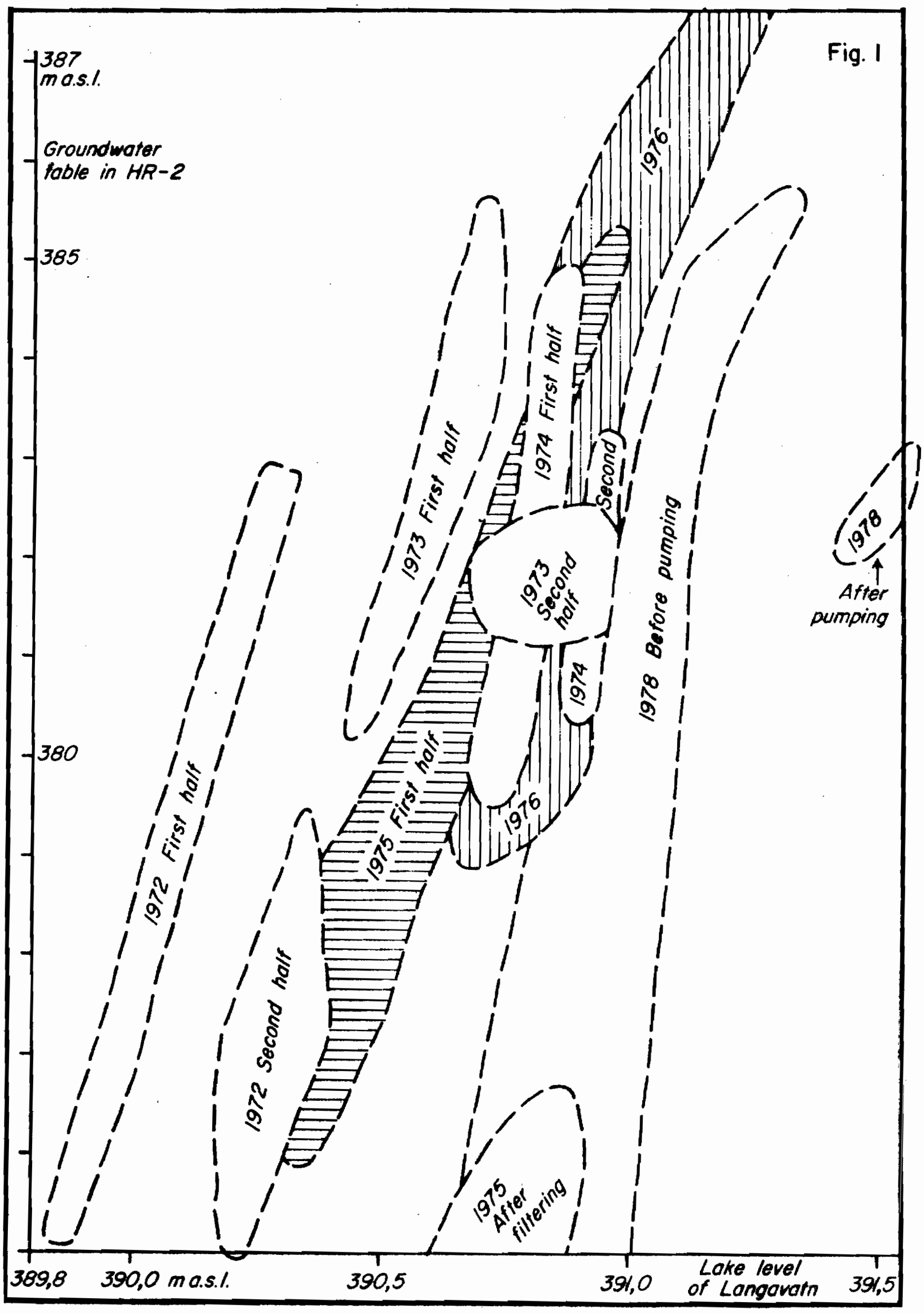
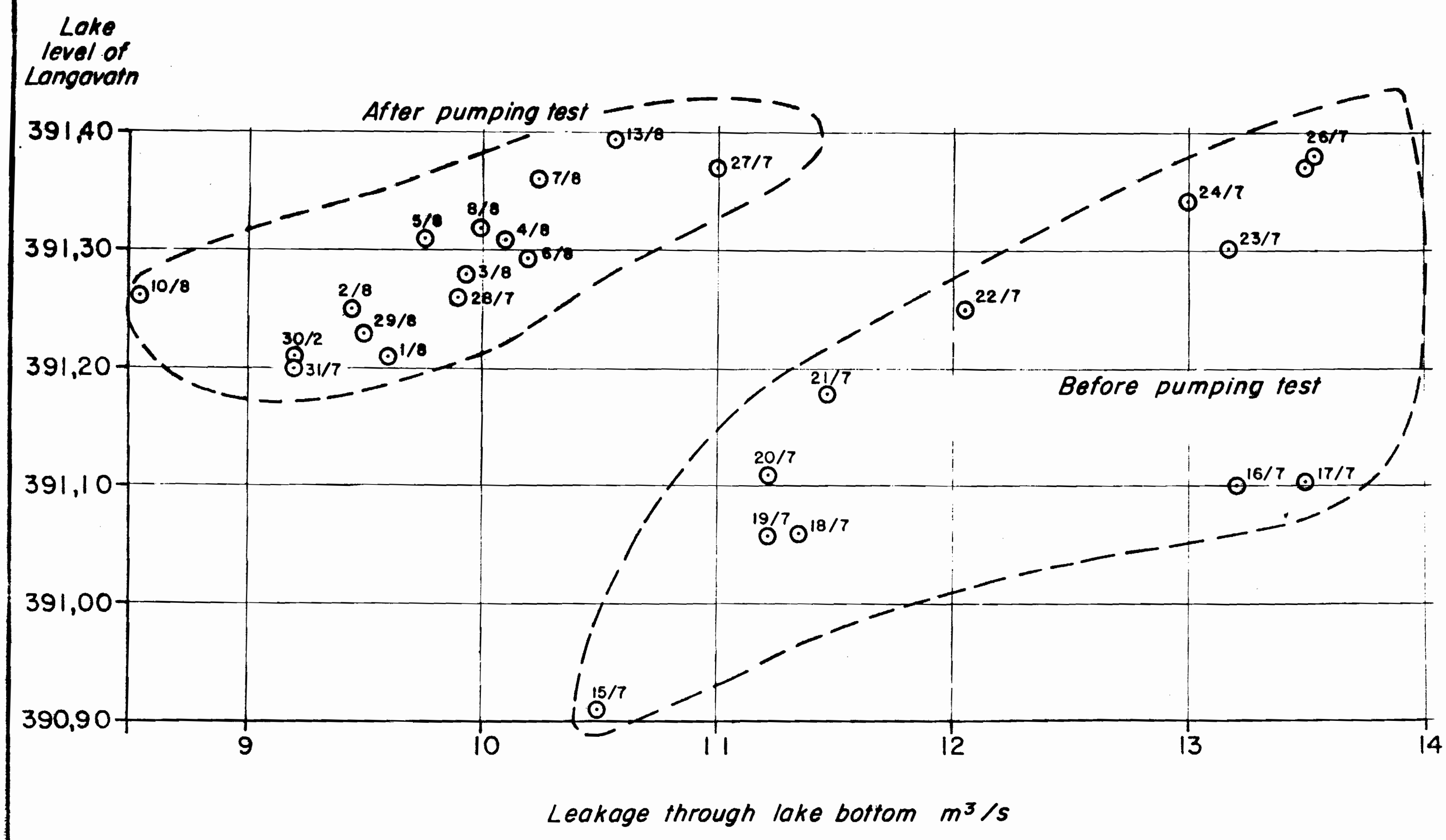


Fig. 1 Relation between groundwater level and lake level of Langavatn.

Fig. 2 Lake level of Langavatn plotted against leakage through lake bottom.



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THE INFLUENCE OF LOW HORIZONTAL STRESS AT RESRVOIR SITES

HAUKUR TÓMASSON

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THE INFLUENCE OF LOW HORIZONTAL STRESS AT RESERVOIR SITES

H. Tómasson
National Energy Authority, Dept. of Water Power, Reykjavík, ICELAND.

ABSTRACT

The Mid-Atlantic Ridge runs through Iceland as an active volcanic zone with crustal spreading taking place away from the zone on both sides. The rock formations in the active zone are very permeable, but some of the largest rivers in Iceland, with many topographically favourable hydropower sites, flow within the zone.

At such geological settings very low horizontal stresses can be expected, at least in the direction perpendicular to the faultlines. Direct measurements of stress are difficult as the rocks are very heterogeneous and badly cemented.

A large scale test on reservoir leakage at Langalda in the eastern volcanic zone of Southern Iceland proved to be an indirect measure of the horizontal stress, as hidden fissures opened up on the bottom of the reservoir due to the hydrostatic pressure formed inside the fissures, strong enough to jack the fissure walls apart. At the test site the depth to the ground water table was some 20-30 m and this is a measure of the necessary pressure needed to exceed the minimum horizontal stress.

Such conditions are of considerable concern as they exist at several potential hydro power sites in Iceland. A possible way to countermeasure movements of this type is by pumping of material into boreholes or directly into fissures and thus gradually increase the horizontal stress in the rock. Experiments have shown that in Iceland the cheapest material for pumping is silty sand, often abundant close by. The cost of pumping should not prohibit the development of an otherwise promising hydro power site in spite of the probability of reopening of fissures.

THE INFLUENCE OF LOW HORIZONTAL STRESS AT RESERVOIR SITES

The worldwide pattern of plate boundaries, which are supposed to be the axes for seafloor spreading, is usually connected to the mid-oceanic ridges. Iceland is a part of the Mid-Atlantic ridge. To the southwest it joins the island as the Reykjanes ridge, but north of Iceland the Kolbeinsey ridge extends north as a continuation of the mid-oceanic ridge. The ridge runs through the country as zones of fissure swarms and graben tectonics (fig. 1). In southern Iceland and off the coast of northern Iceland it is offset by transform faults.

The tectonically active zones are very young geologically and most of the active volcanoes in Iceland are within their limits. The rock formations of lava flows, pillow-lavas, breccias and tuffs are mostly of basaltic composition. Their permeability is high but some of the largest glacier rivers flow through these areas. In several places the young topography offers favourable sites for hydropower development. These sites are certainly somewhat hazardous as both tectonic activity and volcanism can interfere with power developments. But with regard to the relatively long intervals between possibly destructive events power developments are considered feasible and in fact already partly developed.

As to stress conditions in the tectonic zones low horizontal stress is to be expected, at least perpendicular to the lines of graben tectonics. In the transform fault zone on the other hand much higher horizontal stress is anticipated. Direct measurements of stress is difficult to make due to the very heterogeneous character and limited consolidation of the rocks. Of the few stress measurements done in Iceland (Hast 1967) none is from within the volcanic zone. Lugeoun permeability tests in boreholes often indicate the lowest stress component as at a specific pressure sudden increase in water loss (fig. 2) occurs indicating fracturing or rupturing of the walls of the hole. In the shallow exploration holes we have tested this stress component is usually substantially lower than the rock load.

The Langalda test reservoir is located at the outskirts of the active tectonic/volcanic zones (fig. 1). This test lake, having potential maximum depth of 8 m and an area of 1,5 km^2, is mostly situated on postglacial lava flows. A ridge of pillow lava and breccia, named Langalda, covered by tillite constitutes the northern shore. On this ridge many fractures show up topographically, but no trace of them was seen in the postglacial lava flows prior to impounding of the lake. At the test site the regional groundwater level is low, at 20-40 m below the ground surface.

Water was first diverted into the Langalda lake in summer 1970. During winter 1970-1971 there was constantly some water in the lake basin. In a thawing flood on March 8-9 1971 the lake reached its highest possible level. The bulk of the water was snow-melt from the lava fields upstream from the diversion where in summer time there is no run-off. On April 17 1971 voluminous springs were issuing out downstream of the Langalda dam. During the follwing 4 days the lake was completely drained. Then the author observed a rift in the lake bottom just upstream of the dam. Obviously the springs issuing out at the toe of the dam were directly connected to this fracturing (figs. 3 and 4). From weather records and other observations of the dam it is obvious that the fracture opened up on April 15 or 16. Some days after the rifting was observed the main spring flow started and lasted until May 10. At that time the intake gates had been repaired and the lake was soon completely emptied. A distinct fracture pattern extending for 1 km along the lake bottom was now visible, the main trend being paralell with Langalda in this reach while each separate fracture had a more northerly direction.

All these fractures are in moberg (pillow lava or breccia) or overlying tillite. They can neither be detected on the surface of the young lava flows nor higher up in the Langalda hill, above lake level. On the other hand a fracture was observed downstream of the dam in direct continuation of the one upstream of it. The water thus plays an evident role in making this phenomenon so distinct. When the fractures open up the water washes into them all loose material from the banks leaving the fractures clear as far down as can be seen, between 10 and 20 m. Each individual fracture seems to extend for almost 100 m, the width amounting to as much as 20 cm near the middle. Some of the fractures are evidently old, with fillings on their inside walls. When loosing their support the fillings more or less cave in but what remains of them often indicates a divergence of 20 cm. In the tillite the fracture planes frequently match accurately, but strike-slip or strike-dip movements amounting to a few cm can also be detected widely. The movement, either vertical or horizontal, seems to be at random.

Immediately after the fracture system was discovered the meteorological office in charge of the seismometer network in Iceland was requested to check whether any earthquakes had occurred in this area. No tremor exceeding 2 on Richter scale had been observed, but this is the lowest level of seismic activity the set up of seismometers could detect in this part of the country. A portable micro-earthquake station was therefore installed on Langalda in the beginning of May and glass plates concreted across the fissures in 10 places. Some of the plates had bad anchorage on the fracture rims but 5 of them were anchored on sound tillite. While the lake was empty no movements could be observed, neither with the seismometer nor the glass plates.

The fractures were repaired by various methods but the one running under the dam was sealed by pumping in a mixture of sand and bentonite. At the latest stage a cement bentonite mixture was used until the fracture had been filled. Shortly after reimpounding of the lake at about 4 m water depth minor leakage was observed at the fracture downstream of the dam. The lake was emptied again and the water disappeared in 3 days. It was then seen that a part of the fracture system had reopened. The glass plates indicated compression amounting to a millimeter or slightly more. This fracture was again repaired and since then no water has appeared at surface downstream of the dam.

In 1971 no further movements were detected, but in the spring of 1972 the glass plates downstream of the dam broke and the fracture was extended several tens of metres further downstream. A widening of about 3 mm was observed. Again, new glass plates were concreted across the fracture.

In 1973 some minor movements were recorded; about 4-5 mm widening of the fracture in spring and then contraction in the autumn when lake level was falling. Small components of normal faulting and strike-slip faults could be discerned. The results of these measurements are shown in figure 5. From 1974 on the measurements were carried out with an invar rod and measuring clock whereby the accuracy was very much increased. This year the movements were much smaller than before, but showed the same seasonal trend as in the previous year.

Several other faults formed in the Langalda lake bottom. The biggest one, no. 2 on the map figure 6, opened up in September 1972. It extended about 100 m up on dry land making visual observation possible. Sudden increase in leakage recorded in continuous stage recorders on lake and inflow indicates that it was found 1 or 2 days after it opened up. These later faults were formed both in moberg and postglacial lava. They are probably new in the postglacial lavas as old fracture fillings were not observed there. But in the moberg underneath these are certainly old faults in most cases. Faults no. 3, 4 and 5 were found when lake level was lowered in 1972 for repairing swallow holes and fault no. 2. At this time it was obvious that fault no. 1 was practically tight as the level did not fall much below the lowest point of fracture no. 2 although no inflow was allowed for several days. Figure 7 shows fault no. 2.

Fracture 6 was never observed as a continuous rupture. It was first detected in August 1975 as a line of swallow holes in the lava. In spring 1976 a trench was excavated in the moberg hill south of the lake in a continuation of this line to try to find the fracture there and it was certainly found, a large open fracture as seen on figure 8. This fracture was bridged by moraine and loessy soil and had not been opened at this place for at least several thousand years. Fractures no. 1, 2 and 6 ahve been instrumented with strain meters and all show the same tendency in reaction to the groundwater level, the higher the groundwater level the wider the fractures.

The micro-earthquake seismometer installed at Langalda after the initial rifting has since been in operation every now and then. In 1971 it occasionally showed very small movements and once an earthquake was actually heard by people on location just after the second emptying of the lake. Such small quakes occurred approximately every second day. Correlation with lake level was faint if existing at all. These local earthquakes seem to have decreased with time and were hardly noticed in 1974. The seismometers do indicate that the movement should be classified as creep but not as tectonic fracturing. Unfortunately the seismometer was not operating when fracture no. 2 opened up.

An explanation of the phenomena at Langalda has to take into account the geological facts as described at the beginning of this paper. We are dealing with a low horizontal stress field. The lower principal stress is perpendicular to the rift axes, often tension; the higher principal stress along the rift axis. In this stressfield a very small additional force created by water pressure in fault planes can cause rifting. This happens at a very shallow depth in the ground or the uppermost few hundred metres or even less.

In figure 9 an effort is made to explain this further. The fault has lower principal horizontal stress perpendicular to the fault-plane but higher principal stress along the faultplane. The fault is an old normal fault. At the time of study the lower stress was tension. The lower stress is still very small or of the order of 1-2 kp/cm^2. The geological condition is such that groundwater level is far below surface, or 20-30 m. For some reason an opening is formed in the fault filling, where it is weakest. This opening can start as piping but when contact is made with the lake the hydrostatic pressure at the faultplanes exceeds the horizontal stress and the fault opens up.

In litterature very few records exist of phenomena such as those described here. Still there is one from New Zealand which I know of: i.e. the Arapuni hydroelectric scheme on the Waikato River descrived by William Furkert, 1935. The problem there and the geological conditions seem to be identical to those I have described above. In New Zealand they fought this problem for 4 years at an enermous cost.

The means by which to repair and counteract initial and/or further opening of fissures have in common the necessity to build up enough stress within the fractures to withstand the expected water pressure. This can be done in two ways:

One is to put on water and let the fracture open up. Then the fracture should be filled with the cheapest available granular material preferably with the water at high level. In Iceland this is usually silty/sandy material which can be pumped into place. Each fracture may need to be filled more than once. In this manner the lava bottom can gradually be stressed to a level withstanding the water pressure. An equilibrium obtained in this way would probably be offset should a tectonic event occur in the neighbourhood. Such events are rare and, in such a case, the repairs should not be very different from what has been described above.

The other way is to counteract movements by creating stress in the ground by pumping down material around or into suspected fractures under pressure higher that which will be in the lake. In this manner the bottom can be prestressed. Here again the main concern is the quantity, but not the quality, of material pumped down. The cost of the material pumped down must be low. Yet the prestressing procedure can hardly be applied except where fractures cross dam axes as this must be much more expensive than filling open fractures.

It is likely that similar events to those at Langalda can happen at any location where the same or similar geological conditions exist. At some hydropower sites in Iceland such is the case. This does not necessarily stop the construction on any otherwise good power site, as it would presumably occur during the first years after construction and would usually be repairable at a low cost. But such fracturing can be dangerous for dams if it is not noticed in time. Also the higher the dam the more dangerous this is. Therefore high dams should not be built in a geological setting of the obove type.

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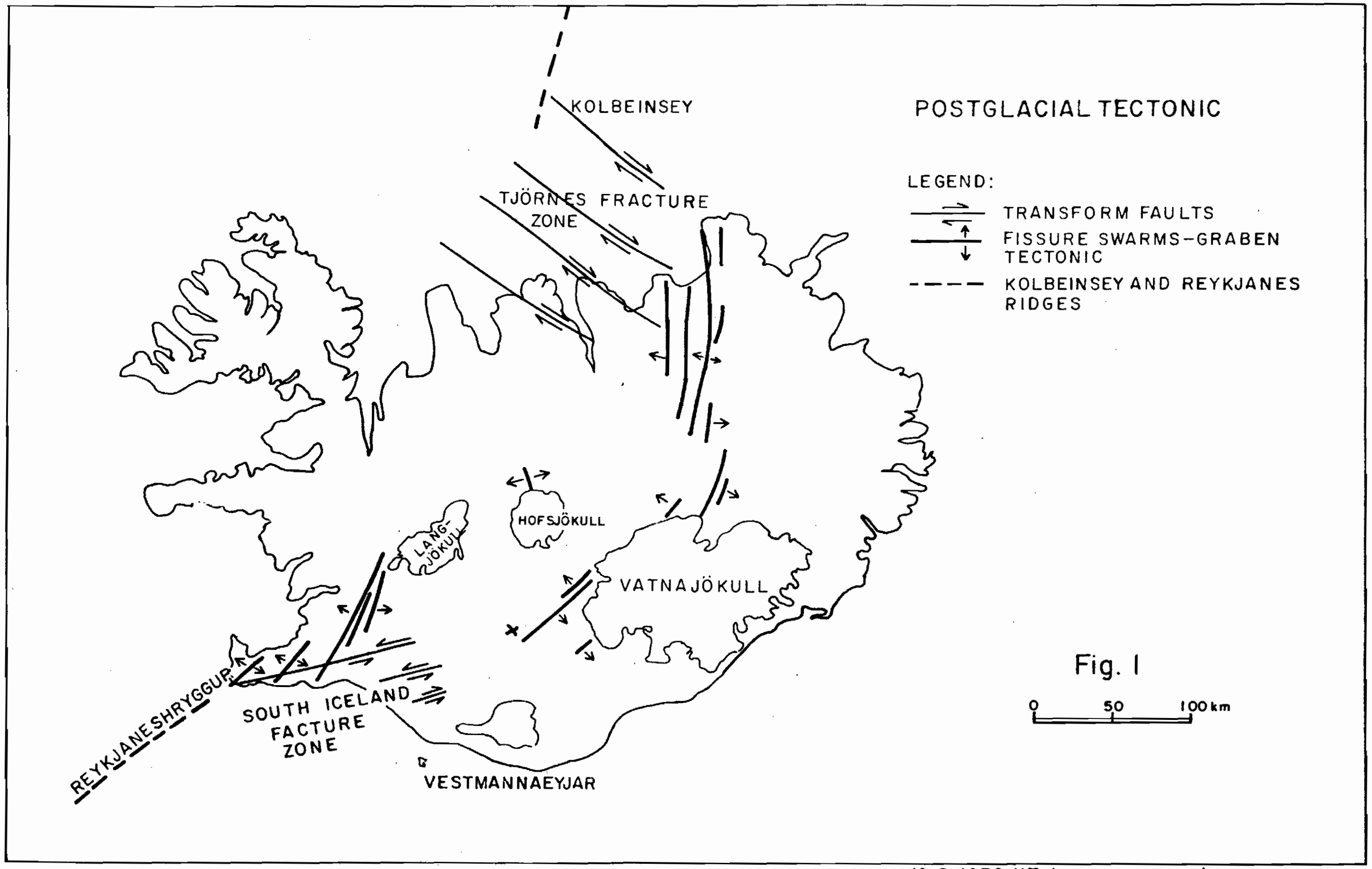


19.2.1976 H.T./IS Tnr. 383 B-Ým Fnr. 13946

Fig. 1 Map of Iceland showing the zone of fissure swarms and graben tectonics.

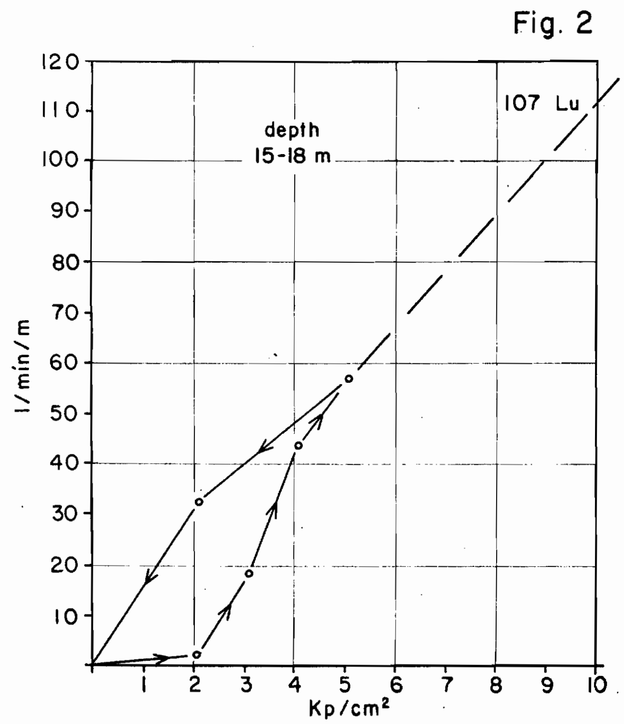


Fig. 2 Typical graph for permeability test.

Fig. 3
Fracture 1 where it disappears under the upstream toe of the dam.

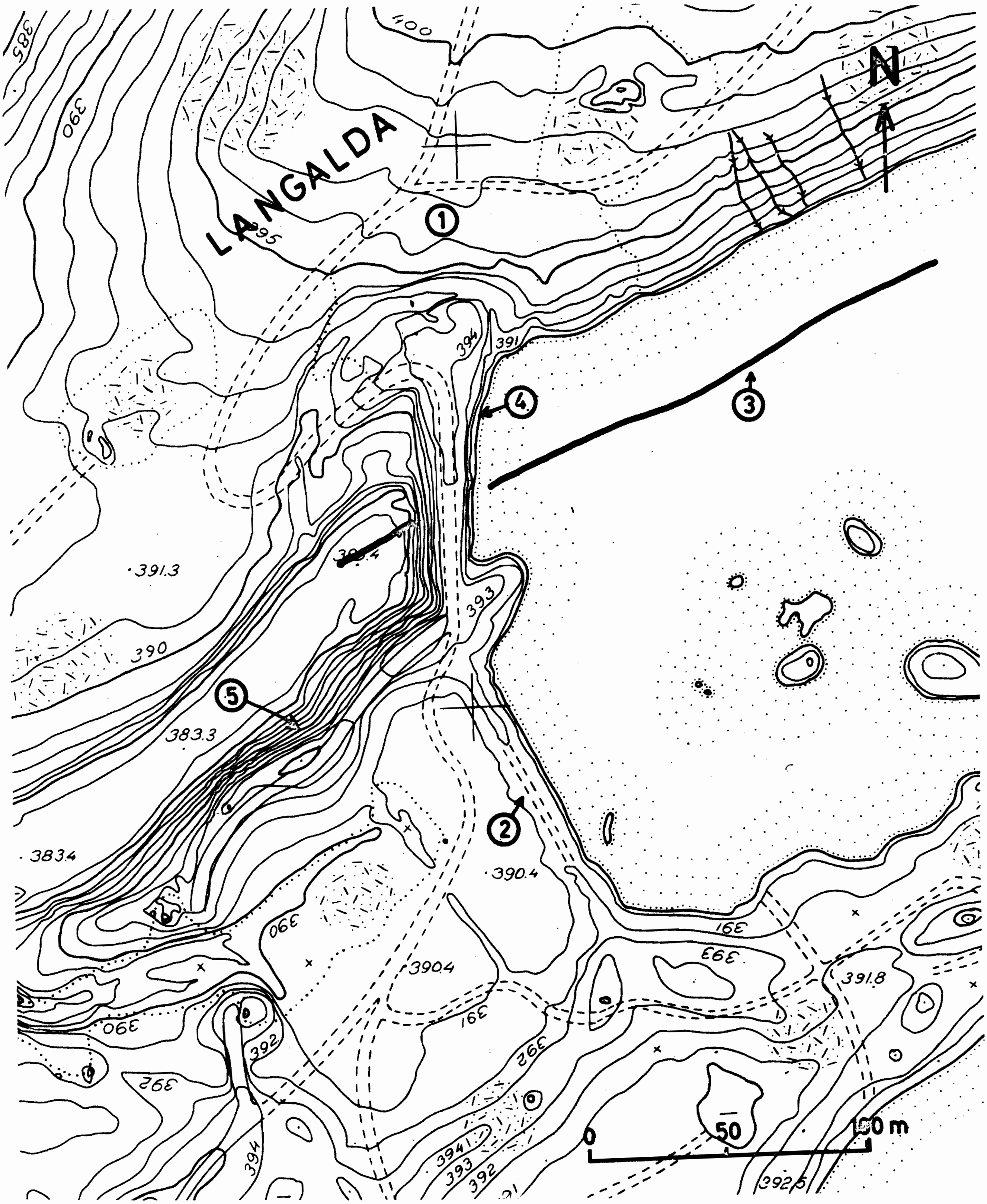
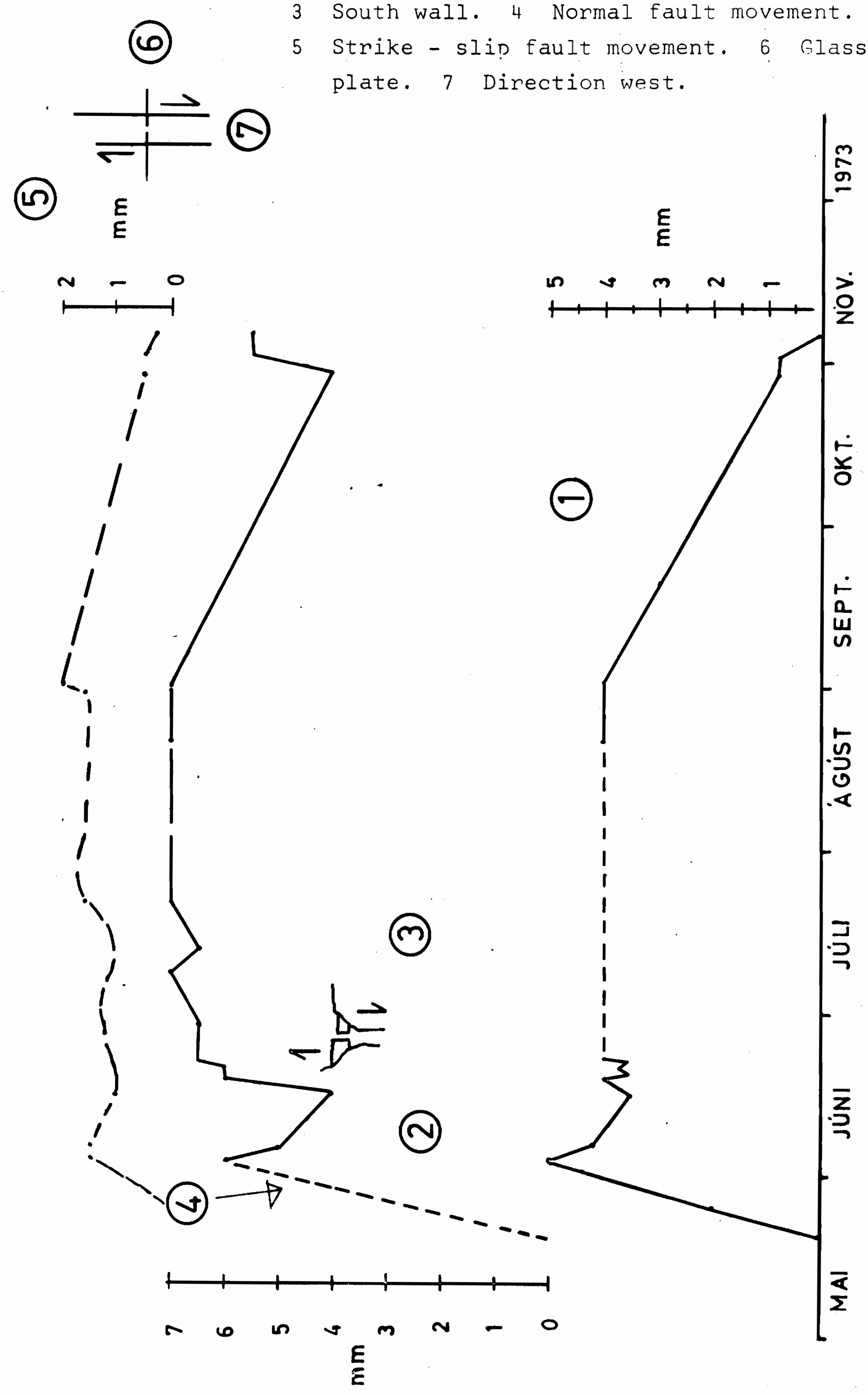


Figure 4

Map with 1 m contour lines showing the dam and the lake approximately 7.5 m deep and fault under the dam. 1 Borrow area in Langalda. 2 Spillway on postglacial lava flows. 3 The fracture. 4 The main dam. 5 Lava front.

Figure 5 The movement of the fault downstream of the dam and changes in positions of glass plates concreted across it in 1972.

1 Widening of fault, 2 North wall.
3 South wall. 4 Normal fault movement.
5 Strike - slip fault movement. 6 Glass plate. 7 Direction west.



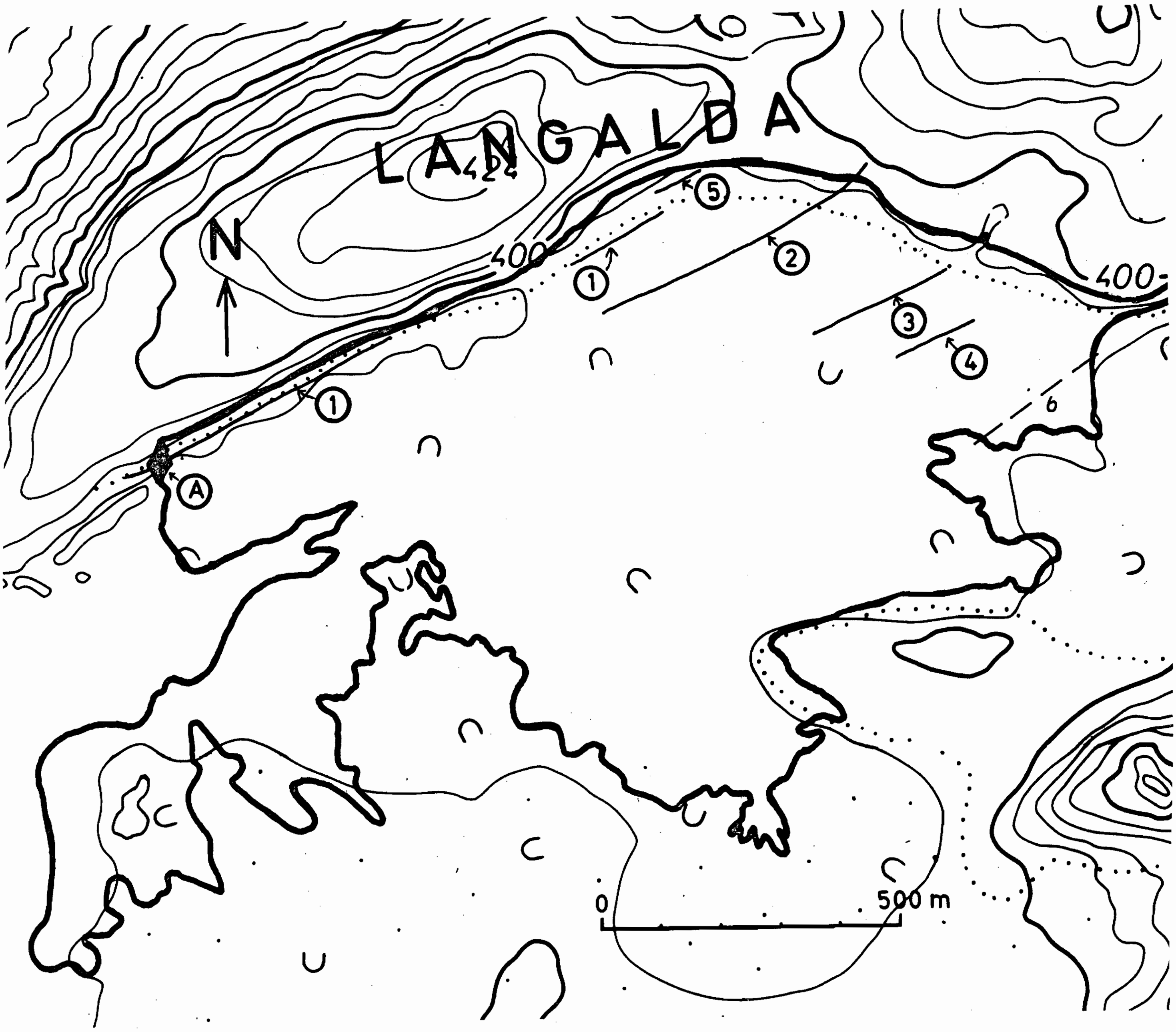


Figure 6

The Langalda test reservoir 7,5 m deep A The dam, 1 The first fracture found in April 1971; 2 The fracture found in September 1972; 3 and 4 were found when lake level was lowered in September 1972; 5 was found at a low lake level in May 1972.

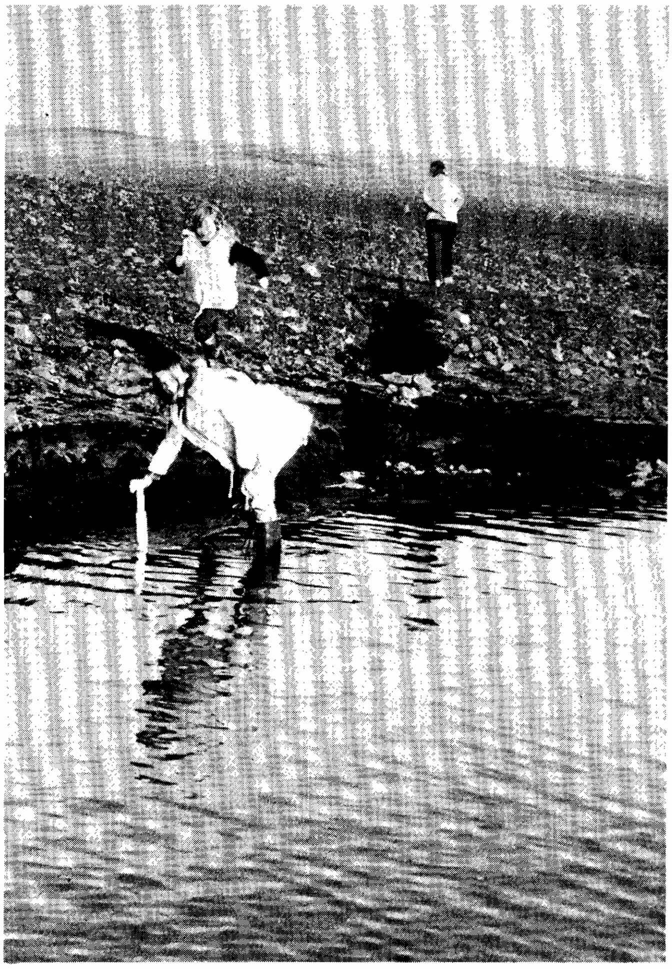


Fig. 7
Fracture 2 which opened up
in September 1972.
Photograph teken where it
extends up to dry land.

Fig. 8
In fracture no. 6 where it was opened up by a bulldozer trench.

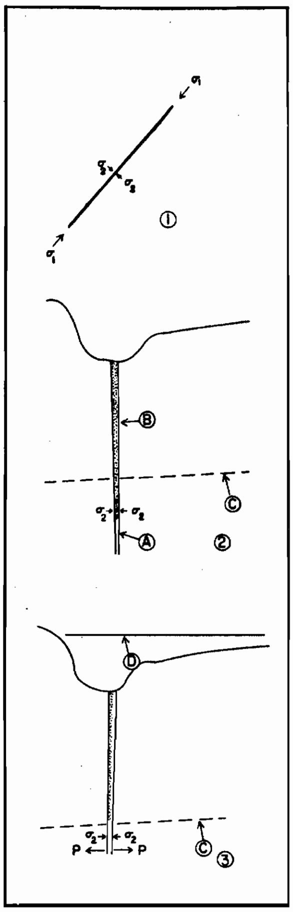


Figure 9

1 Plan sketch showing a fault, probably an old normal fault, with stress condition as shown. σ are the principal horizontal stresses.

2 Cross section across the fault before water is put on. A is relatively open fault below B, a fault filling which has been washed into the fault when it was an open fracture. C ground water table.

3 Shows the same as above after water is put on. D is lake level. P is hydrostatic pressure in the relatively open fault. This pressure is the same as the head from lake level down to ground water level. It is greater than the minimum horizontal stress. The result is widening of the fault.

ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY
DEPARTMENT OF WATER POWER

GROUND WATER AND LEAKAGE STUDIES FOR THE SIGALDA PROJECT SOUTHERN CENTRAL ICELAND

BJÖRN JÓNASSON
DAVÍÐ EGILSON
JÓSEF HÓLMJÁRN

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C O N T E N T S

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B. Jónasson, D. Egilson and J. Hólmjárn
National Energy Authority, Dept. of Water Power, Reykjavík, ICELAND.

ABSTRACT

The area discussed is on the western margin of the so-called Eastern Volcanic Zone in Southern Iceland. The goelogical setting is one of SW-NE running moberg (hyaloclastite) ridges dating from the last glaciation with postglacial lavas flowing down the valleys in between. The moberg is widely covered with moraine and tillite. Sediment deposits mainly varved clay, diatomaceous earth and alluvial silty sand cover the greatest part of the reservoir basin. Superficial deposits of tephra and eolian soil are common on the lavas. Interbeds of similar composition are frequent.

In Tungnaá river, which flows through the area there are several favourable hydro power sites and presently the 150 MW Sigalda power plant is starting operation.

The dam at Sigalda is located on postglacial lava and the headrace canal runs through the Sigalda moberg ridge.

Due to the highly pervious nature of the lavas and tectonic fractures in the moberg on the canal site a program of intensive studies of groundwater behaviour and leakage was undertaken in connection with the impounding of the reservoir and headrace canal. Various investigation techniques are applied, such as measurements of groundwater level, temperature, discharge of springs, chemical analysis, electrical resistivity and self-potential surveys etc.

1 INTRODUCTION

The Sigalda Project, which is still under construction, is located in the Tungnaá river in South-Central Iceland about 170 km by road east of the capital Reykjavík. The powerplant will be operated on a head of 74 m at maximum reservoir level of 498 m and active storage capacity of 142 Gl. The generating capacity of the plant will then be 150 MW.

After completion of the main civil works in 1976 the first impounding of the reservoir was started. It caused significiant rising of the groundwater level in the reservoir basin and dam area and increasing spring flow downstream of the dam.

The paper describes the geology of the project site and its vicinity, the initial geohydrological conditions there and last but not least the effect of the impoundings, as determined by the geohydrological observations made. The reservoir has been impounded four times, each time to a higher water level than before, but the headrace canal only twice. At present the fourth impounding is under way.

2 PROJECT DESCRIPTION

The main features of the project are a 33 m high rockfill dam (max. height 44 m) of $1,5 \cdot 10^6$ m^3 volume with an impervious asphaltic coating on the watered side, a 1100 m long partially cut and cover headrace canal and powerhouse and tailrace canal excavated into moberg. The active storage of the reservoir, between 498 m and 485 m elevation, will be 142 Gl. The dam is situated on postglacial lava flows, so-called Tungnaárhraun, adjoining the Sigalda moberg ridge at its right abutment, see photograph, Exh. 1. The bottom outlet, located in the river canyon, was used for diversion during the last phase of the dam construction. The headrace is a 450 m long cut and cover gallery running through the higher upstream part of the Sigalda ridge followed by a 580 m long open canal leading to the intake structures. In the powerhouse three 50 MW units are installed. The tailrace canal returns the utilized water to the river at el. 423 m. The headrace, powerhouse and tailrace are all situated within a moberg formation. The owner of the project is Landsvirkjun (The National Power Company). Consulting Engineering is a joint venture of the Swiss firm Elctro-Watt Engineering Services Ltd. and the Icelandic firm Virkir Consulting Group Ltd.

3 GEOLOGY AND HYDROLOGICAL CHARACTERISTICS

3.1 General Geology

Iceland is situated on the Mid-Atlantic Ridge. Two separate volcanic zones run through the country, one branch extending from the Reykjanes peninsula to the north of the Langjökull and the other from the Vestmannaeyjar Islands off the south coast to the north coast at Axarfjördur, see Exh. 2.

During the major glaciations of the Ice Age at the beginning of the Quaternary the whole country was covered with ice. The last glaciation ended some 10.000 years ago. During this time active volcanism continued below the glaciers, but the ice cover prevented the formation of lava flows, instead it caused the formation of moberg hills and ridges, which are therefore the main formation types within the volcanic zones of Iceland. They are partly covered with lava flows from recent time. Sigalda is situated near the western margin of the eastern volcanic zone of Iceland, Exh. 2.

3.2 Geological history

During the last glaciation, which lasted from 70.000 to 10.000 before present, the moberg ridges and hills of the Sigalda area were formed. At the end of it Tungnaá river had a more southerly and straighter course than its present one. Postglacial volcanic activity soon produced the enormous Tungnaá lava flows which flowed towards the Sigalda ridge, successively diverting the river course. Each lava flow is likely to have had appreciable influence on the course of Tungnaá. When finding a new course the river has most likely been in the habit of choosing the boundary between the moberg and the lava margin, often forming lakes, which existed over longer or shorter periods of time. The biggest of these lakes was probably the ancient lake Krókslón, now re-created by the Sigalda project. During the lifespan of the ancient lake enormous lava flows flowed into the lake and raised the water level.

A well defined shoreline at elevation 500 m marks the highest remains of the ancient lake. The sediments accumulated in this lake basin were mainly varved clay, diatomaceous earth and alluvial sand. The varved clay being of greatest quantity. Ash and tephra layers are often sandwiched in between the clay varves. The rock barrier at Sigalda which caused the existence of the lake was finally eroded away in the 9th century A.C. Lake Króksvatn was then, in all likelihood, emptied in a single immence flood. After that time Tungnaá river has eroded a channel, at least partly, through the lake sediments and down to the lava flows and moberg.

3.3 Moberg

Stratigraphy Sigalda hill is a chain of NE-SW trending moberg ridges built up in sub-glacial eruptions during the last glaciation. The hill is composed of at least three formations (ridges), S_1, S_2 and S_3 where S_1 is the youngest and S_3 the oldest one respectively. The moberg formations are intercalated by a very dense and hard tillite.

The headrace canal, which has the direction WNW-ESE, is excavated almost straight across formation (ridge) S_1, but the powerhouse and tailrace canal are situated in S_3.

The moberg ridges were piled up over active volcanic fissures while the area was still covered by glaciers of the last glaciation. Due to the warying interaction of water pressure (external pressure) and gas pressure (internal pressure in the magma) the different facies of the moberg are developed, ranging from tuff (the finest) to sills, intrusives, cube-jointed basalt and pillow lava as the roughest. The following classification of moberg facies is common: tuff, tuffbreccia (tuff>50%), breccia, pillow lava breccia (pillow lava fragments>50%), pillow lava, cupe-jointed basalt and sills or intrusives often irregular in shape and always jointed.

The headrace canal cut into formation S_1 shows in an up to 55 m deep section very clearly the structure of this moberg formation, see Exh. 3. The geological section of the Headrace canal and the cut and cover for the penstocks is divided in three parts with regard to the structure of the formation from the east to the west:

The eastern rim,	approximately	400	m	of	the geological	section
The crater	"	450	"	"	"	"
The western rim	"	400	"	"	"	"

It can also be seen in Exhibit 3 that all the moberg facies occur in the section and facies contacts are common, especially in the eastern rim. The pillow lava is dominant, but so-called tephra (scoriaceaous) breccia on either side in the crater and an irregular intrusive in the eastern rim are very prominent. The tephra (scoriaceous) breccia is similar in character to the scoria commonly found in so-called pseudocraters. It primarily consists of tephra but pillow lava fragments are also common. The irregular intrusive is jointed but at contacts with other moberg facies it becomes cube-jointed. Furthermore the irregular contacts are vitreous as is the case with each pillow in the pillow lava.

Leakage paths As mentioned above and is clearly demonstrated on the geological section, Exh. 3, the moberg formation is very heterogeneous. The more rough facies such as intrusives, cube jointed basalt, pillow lava, pillow lava breccia and tephra or scoriaceous breccia as well as their contacts (irregular contacts) have the highest permeability coefficients and thus constitute the main leakage paths. As the facies have very differently uniform distribution the permeability of the formation in general must be highly variable. Tectonic fractures are very common in the moberg formation. Often they are open for a few cm but filled with clay and sand. In such cases they conduct water better than the surrounding rock. Under conditions of rising groundwater level (e.g. during lake or reservoir impounding) and consequent increase in pore pressure the fillings can be washed out. Tectonic movements along fault planes often produce a relatively water tight curtain by grinding of the rock. The headrace canal route and its vicinity is quite clearly traversed by fractures and/or faults of E-W orientation, most likely with such a curtain.

As mentioned above each moberg formation is overlain by very hard and dense tillite. Such a tillite cover considerably reduces groundwater seepage or leakage between the formations. The main flow is therefore primarily horizontal. Vertical seepage (leakage) within individual formations is probably restricted to fractures, mainly open ones.

Under natural and actually also the present conditions the groundwater level is some tens of meters lower in the moberg formations than in the lava field in the vicinity of the dam. This can to a great degree be related to the watertight tillite covering the moberg.

Permeability measurements have been carried out in almost every borehole that penetrates the Sigalda moberg formation. The permeability values obtained are too low as the suspended load in the pumped-in water which is taken from the glacier-fed river Tungnaá tends to seal (tighten) the walls of the boreholes. Groundwater was also pumped up from two boreholes in the vicinity of the powerhouse drilled into the moberg formation S_3. Calculations of permeability coefficients on basis of those tests showed the pumping-up method to be more accurate. It gave the coefficient, or k-value, $2{,}6\text{-}3{,}1 \times 10^{-2}$ cm/sec.

3.4 Postglacial lava flows

Six major postglacial lava flows are found in the vicinity of the Sigalda area. They surround the moberg formations and cover them partly. Their average thickness ranges from 22 m to 15 m. Each lava flow can be divided into three zones, even if the contacts are diffuse:

1) Top scoriaceous zone
2) Middle dense zone
3) Bottom scoria

The top zone can be of two main types, i.e. the so-called aa lava (Icelandic: apalhraun) with a rough surface and pahoehoe lava (Icelandic: helluhraun) with smooth surface.

The pahoehoe lava type is often in the form of broken tabular blocks, thus creating a rough and uneven surface. The top zone is always vesicular and with cavities reaching a depth of a few metres. The cavities and vesicles in the top zone are usually filled up with surfacial material, since there are often thousands of years until the old lava flows are covered with new ones. Therefore, the top zone is often not as effective horizontal aquifer as the bottom zone.

The middle zone usually constitutes the main bulk of a lava flow. It´s contact with the top zone is both irregular and often diffuse as they often merge into each other. The jointing of the middle dense zone is due to contraction of the basalt during cooling and can be of two main kinds, regular hexagonal columnar jointing (studlaberg) or the close and irregular blocky jointing (kubbaberg).

The columns vary most frequently between 0,5-1,0 m in diameter. The length of the columns depends on the thickness of the flow. The maximum length is the same as the total thickness of the middle dense zone. Two zones of columnar jointing are common, one at the top and one at the bottom of the flow, separated by a zone of irregular jointing. Since the joints are usually empty, they are the main paths of vertical leakage through the flows.

The bottom zone is similar to the top zone, but thinner. It usually constitutes a brecciated zone from a few decimeters in thickness up to 2 og 3 meters. The bottom layer is the main aquifer for horizontal leakage in lava flows.

There are exceptions from the rule of three zones in a lava flow. For example, many lavas flow over water-saturated surfaces or into lakes. The water trapped under the molten lava can get overheated and cause eruptions resulting in small crater-like hills of scoriaceous basalt, the so-called pseudocraters, which are often found in clusters covering extensive areas. In these areas, the top zone is usually thick and scoriaceous and scoria can reach all through the lava flow. The lava front is usually very broken and scoriaceous, especially if the lava has flown into water saturated surfaced or into lakes. The lava fronts and pseudocraters can therefore be very effective paths for vertical leakage.

3.5 Superficial deposits in the lake basin

The sediments in the reservoir basin can be divided into the following units:

The varved clay deposits cover the greatest part of the former Króksvatn basin. They vary in thickness, and are even absent at the downstream end near the Sigalda canyon and in some watercourses in the basin, but increase in thickness upstream. The maximum thickness known is over 13 m. Vertical permeability of the clay is very low. It can be regarded as almost watertight.

The varved clay consists mainly of particles of clay, such as montmorillonite and kaolinite and a large amount of diatomaceous earth. There are also many layers of tephra sandwiched in between the varves (tephra is a term, which includes airborne volcanic products, such as ash and pumice).

Diatomaceous earth is found in the lake basin, contrary to the varved clay, it is unbedded and is yellowish/white in colour and the main constitutents are siliceous diatoms. Irregularly distributed lenses of sand and tephra are frequent.

Alluvial silty sand is found covering the clay deposits. The thickest part of it is in the high banks along the river just downstream of the Hnubbafossar falls and between the tributaries, Blautakvísl and Útkvísl, Exh. 4. The sandbanks are up to 10 m thick. They consist mainly of black tephra.

The so-called beach and colluvial deposits are found along the northern shore of the Króksvatn in the drainage area of Blautalaena. They lie mostly in the region of the 500 m shore line, which is clearly marked in this area. The material is mainly composed of sand and gravel and the coarser material has been transported a short distance to the lake from the surrounding slopes.

3.6 Tectonics

Tectonically Sigalda is situated within a transitional area between the western volcanic zone which is dominated by NNE-SSW tectonic trend and the eastern volcanic zone of NE-SW striking trend. In both cases volcanic fissures and fault lines follow the above trends.

It is obvious on Exh. 4 that the tectonic lineations can only be shown in the moberg areas but neither in the postglacial lava fields nor in areas of sedimentary deposits. In the vicinity of the Headrace canal the main trends of the faults seems to be approximately E-W. Tectonic lineation of other directions are also present and NNW-SSE striking fractures seem to prevail in vicinity of the headrace canal. Further off, especially farther east, the trend of the faults approaches NE-SW. Here the orientation of the eastern volcanic zone is becoming dominant.

It proved to be easy to map tectonics in the Headrace canal where the excavation was sufficiently steep, see Exh. 3. Elsewhere it was impossible to see any fractures. However, there appear to be two main fracture zones present. One is found in the east part of the eastern rim where the trend of the fracture is from NNE-SSW to NE-SW, but the NE-SW direction seems to be more dominating. The other fracture zone is found in the west part of the western rim and has a NNE-SSW trend. These fractures are generally undulating, but vertical displacement could not be detected. In some places the fractures are a few centimeters wide and then the fractures are clay and sandfilled. When this is the case fractures are generally only partially open.

4 GEOHYDROLOGICAL OBSERVATIONS

4.1 Groundwater level

The groundwater table was recorded by measuring the depth to the groundwater in boreholes in this area. The known altitude of springs and spring horizons was also when drawing the contour map of the initial groundwater level, see Exh. 5.

Impounding of the reservoir causes a simultaneus and significant response of the groundwater level west of the reservoir, see Exh. 6. This happens even at very low reservoir level. For example when the first 3 m were impounded, it caused an almost simultaneous 28 cm rise in groundwater level at 2,5 km distance from the reservoir. The increase of the groundwater table due to impounding from empty reservoir (474) to 491 m a.s.l. is about 10 m in the vicinity of the western boundary of the reservoir, see Exh. 7. Backwater pressure increase east of the reservoir is of similar amplitude.

The raising of the groundwater table in the lava flows west of the reservoir forms new springs and new spring horizons downstream of the dam.

There are a number of piezometer holes downstream of the dam. Most of them are relatively shallow, approximately 10 m deep. They do not usually go beyond the uppermost lava flow, on which the dam is founded. The deepest hole, however, is 68 m deep and penetrates two lava flows down to moberg. During the impounding, the piezometric head in this hole was about 4 m higher than in the shallower ones. In order to detect where this high pressure originated, a single packer was installed at depth of 34 m, below the bottom layer of the uppermost lava flow. This procedure made it possible to measure the piezometer head of the two aquifers below and above the packer. The high pressure was found to originate from the moberg in the bottom of the hole. Furthermore, since the packer was installed below the scoriaceous part of the uppermost lava flow, it was possible to measure the piezometric head in this aquifer. It appeared true that this hole has higher piezometric head and responds much quicker to any elevation changes of the reservoir than any of the shallower holes in its vicinity.

In June 1977 the reservoir was emptied from 490 m a.s.l. rather quickly (in fortnight). An inspection throughout the reservoir bottom showed that new springs had developed where small overburden load (depressions) coincided with a very broken underlying lava flow (e.g. lava front). These springs had total outflow of over 1 m^3/s. The outflow did not decline at all during the two months when the reservoir was empty.

4.2 Temperature measurements

Intensive groundwater temperature measurements, especially in boreholes and springs, using thermistor and digital multimeter, were carried out before and during the impoundings of the reservoir and headrace canal.

The temperature measurements constituted the presence of two groundwater systems. On one hand a "warm flow" (4,5-5°C) in the moberg (headrace canal and vicinity) and the northern part of the lavas in the reservoir basin and on the damsite area, and secondly a "cool flow" (3-4°C) in the lavas to the south. Springs issuing into the Sigalda canyon downstream of the training dyke are derived from the cool flow but springs further upstream from the warm flow, see Exh. 8.

The main aim of the temperature measurements was to observe the flow paths and general behaviour of the reservoir water (leakage water) in the ground as it mixes with the groundwater. The difference in temperature between the groundwater and the reservoir water (leakage water) made this possible.

Measurements of the groundwater temperature, which were started in 1974, indicate that no seasonal temperature variations occur. On the other hand the temperature of the resrvoir water showed significant seasonal variations and during the summertime daily variation were also observed. The temperature of the reservoir water is very steady at 0°C during the 4-6 winter months.

Ideal conditions for leakage studies occured for the first time during the 2nd impounding (Nov. 9 to Dec., 1976). A comprehensive program for measuring the groundwater temperature in boreholes and springs in the lava field on the damsite and reservoir areas was then carried out. Similar conditions were present during the first months of the 3rd impounding when the headrace canal was impounded for the first time. Similar temperature measurements in boreholes and springs were also carried out.

The measurements have indicated definite leakage paths in the damsite area and lava field. A leakage path was discovered south and west of the southern abutment of the dam within the cool flow, being detectable in few piezometric holes. The temperature measurements also showed the former diversion canal to be a leakage path. After the reservoir level had been kept constant at approximately 487 m el. for a few days during the second impounding it became clear that the main leakage path from the reservoir was along the contact zone of the lavas TH_{f-h}, the interbed and scoria of these lavas.

Groundwater temperature measurements in piezometric holes and springs in the Sigalda moberg, especially in the vicinity of the headrace canal, indicate definite leakage paths. It is not certain whether this leakage is along the contacts of the moberg facies and/or directed by tectonic lineations.

Temperature measurements in springs, issuing from the moberg downward to the Tungnaá river showed very clear temperature variations. This change in temperature appeared to take place very near the gully that cuts the Sigalda hill at the southern bank of the headrace canal. The gully has an almost E-W direction.

The temperature of the spring water changed from 0,8°C to 3,3°C within a short distance. Thus, this change was clearly related to tectonic lineations which have an almost E-W direction in this area and it is believed to be the main trend of the faults. The gully is eroded along such a tectonic lineation.

4.3 Chemical analyses

The primary purpose of the chemical analyses was to detect and trace the spatial degree of mixing of the reservoir water (leakage water) with groundwater from time to time. In this way a general idea of the leakage and leakage paths in the ground could be obtained and a clearer picture of the behaviour of the reservoir water and/or groundwater in the Sigalda area established. The study was centered on the areas in the vicinity of the engineering structures, i.e. the lava area to the west and downstream of the dam, so-called damsite area and the moberg area at the headrace canal site, the so-called headrace canal area.

In the Sigalda area more than one hundred samples were taken in one year, or during October 8 in 1976 to October 2 in 1977, and in most cases more than one sample was taken at each station during the period.

The following components were analyzed: Cl^-, SiO_2, Ca^{++}, Mg^{++}, Na^+, K^+ and $CaCO_3$. The conductivity and the alcalinity of many samples were also measured.

Calculation of the chemical analyses are done in the following manner: First, the values obtained by the chemical analization expressing the content of the above mentioned components in ppm (ppm=mg/l) are converted into mille-Moles, then so-called Mole-ratios are calculated with reference to chlorine, i.e. $[X]/[Cl^-]$. On the values thus obtained the calculations of mixing are used in such a way, that the basic values or Mole-ratios for each component in the reservoir water on one hand and natural or uncontaminated groundwater on the other are used to find the percentage of reservoir water in the groundwater or mixed water at various places and times.

The mixing calculations show rising Mole-ratios or contamination in the damsite area. In the third impounding which began on January 20 in 1977 and lasted for five months this contamination was mainly in water samples which coincide with speedy rising or lowering of the reservoir level. The contamination effect disappeared when the water table had been stable for some time, but that was again observed in the beginning of third impounding.

This variation in the chemical composition of the spring water applies to the entire damsite area. Therefore, far lower percentages of reservoir water were found in the spring water than there actually were. This chemical deviation or contamination is highest in the Silicon-ratios but lowest in Kalium-ratios while other ratios are more variable.

It is not clear if this contamination is to be traced to the grout-curtain through the lava cross-section below the toe of the dam and/or only to the rising groundwater level in the lavas.

The fourth impounding started on August 20. Water samples from that date show that the groundwater did not regain its natural chemical composition during the two months interval between the 3rd and 4th impoundings due to the high water level of the 3rd impounding, and its relatively long duration (5 months).

The mixing calculations show that the share of reservoir water (leakage water) gradually increased at the expense of the natural groundwater in the Sigalda area in the 3rd impounding.

Due to the relatively great number of sampling stations and water samples collected on the damsite area at the end of 3rd impounding (June 1977) and the fairly good results of the chemical analyses an attempt is made to estimate to what degree the water emerging in springs and canals downstream of the dam (on the damsite area) owes it origin to the reservoir and otherwise how this water can be traced to natural ground-water on one hand and reservoir water (leakage water) on the other.

According to discharge figures and mixing calculations it seems clear that all or almost all additional flow on the damsite area can be traced to leakage from the reservoir and not to natural groundwater flow under the reservoir bottom induced by the impounding or about 11 m^3/s.

Water balance calculations point out that all leakage water from reservoir appeares as spring water flow on the damsite area and discharges into Sigalda canyon.

TABLE 1

DAMSITE AREA, PERCENTAGE OF RESERVOIR WATER

									Max. reservoir level 13th June, 490,16 m			
Reservoir level		el in m:	482,8	484,9	484,9	484,8	488,7	488,8	489,5	487,3	477,3	Empty
			Date 77.02.05.	Date 77.03.15.	Date 77.03.27.	Date 77.04.21.	Date 77.06.08.	Date 77.06.09.	Date 77.06.15.	Date 77.06.17.	Date 77.06.25.	Date 77.06.26.
Location number		Sampling station	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %	Reserv. Water %
Drainage canals	S04	MW-1	50		70		95		~80		~60	
	S14	MW-2	30	50			95			~65		~55
	S15	MW-3	~20		~20		75			55	~45	
	S16	MW-4	~0		~20		65			40	~40	
Springs	S06	Spring from contact of moberg-lava (TH_f)				30		65	50			
	S25					20		65	~30			~40
	S32							75	~45			~35
	S31	Spring from contact of lavas TH_f-TH_h.						90	~75			

~ = Irregularity in mixing calculations between individual Mole-ratios of single sample due to contamination.

Table 1 only summarizes the results of the mixing calculations for the damsite area during the 3rd impounding but is representative for the Sigalda area. It is obvious from the table how the percentage of the reservoir water in the natural groundwater in different drainage canals and springs increases with time. The contamination is also clear, especially immediately after the maximum reservoir level is reached. Then the water level is lowered very fast and the reservoir emptied. It is also significant that the reservoir water (leakage water) percentage is highest in the drainage canals nearest to the dam (MW 1-2). This is also the case at about 700 m distance directly west of the southern abutment of the dam, in the first discovered leakage path according to temperature measurement, in spring S 31. It´s waterlevel had reached the elevation of the contact of the lavas TH_f-TH_h.

4.4 Other measurements

S.P. measurements. During the first impounding of the reservoir an attempt was made to locate the leakage spots with natural electric-current method, with the water in the reservoir basin. The method is based on the concept that negative electric potentials appear as a result of water movement downwards through fractures or pores in rocks or loose soil on the reservoir bottom, sometimes amounting from tens to hundreds of millivolts. The potential field was measured by keeping one electrode tight while the other was pulled behind a boat along the suspected leakage spots. The measurements were recorded on an automatic recorder. The results obtained by this method were promising in locating swallow holes. The reservoir has, however, always been emptied for repairing the leakage spots. Because it is easier to locate swallow holes on dry land, little effort has been directed at this method recently.

Measurements of direction and velocity. The direction and actual velocity of groundwater movements in separate wells were determined by observations of the deformation of artificial electric fields due to electrolyte displacement in the water flow. The standard method is saturating a borehole with salt and measuring the displacement of the electrical field. The permeability was then calculated according to the following equation $k = \frac{\alpha . Va}{i}$ where α is effective porocity estimated in this area about 0,3, Va is the average velocity measured by the above mentioned method but i is the gradient. The permeability obtained was about 1 cm/sec but the measured hole is shallow and did not reach bottom layer of the lava flow. It must therefore be regarded as minimal value.

Calculations of permeability, based on temperature changes in boreholes with time using the same equation give similar permeability $\sim$10 cm/sec. Exact timing of temperature changes in boreholes will provide similar basis for calculations of permeability. The values obtained in this way are of the range 10-30 cm/sec in the scoria.

4.5 Permeability

The lithology of the moberg formation and of the lava series suggests a wide range of permeability. The mean coefficients of permeability calculated or measured show a considerable variation. The following table is a rough estimate of the permeability. It is, however, based on field measurements such as pressure tests, temperature measurements and eletrical methods.

TABLE 2

PERMEABILITY

Material	Typical thickness of Aquifer in m	Permeability cm/sec
Moberg	50 - 100	$5 - 10^{-2}$
Columnar jointed basalt	10 - 20	$3 - 10^{-3}$
Scoria	0 - 3	$10^{2}-5x10^{1}$
Lava interbed	1 - 3	$1 - 10^{-3}$
Varved clay	0 - 10	$10^{-5}-10^{-7}$

These figures do not take everything into account. For example, tectonic lineations seem to control the groundwater flow in the moberg series. Furthermore the varved clay which is almost watertight has a horizontal leakage paths due to tephra layers, sandwitched in between the varves.

4.6 Leakage and swallow holes

In order to have exact measurements of the total water loss due to impounding two river discharge gauging stations have been run, one located upstream of the reservoir and the other downstream of Sigalda canyon, further downstream than the above mentioned spring horizons.

Direct measurements show that at elevation 491±1 m a.s.l. the water loss by the dam is about 12 m^3/s.

During and after the impoundings an enormous number of swallow holes have been located at the lava front TH_h. There is no doubt that here is the main leakage path out of the reservoir. The water loss this way is estimated to be about 8 m^3/s at reservoir level 491 m a.s.l. The leakage water raises the water level in the lava field west of the dam and seeps into Sigalda canyon downstream of the dam.

Calculations of mass balance at reservoir level 491±1 m a.s.l. give no indication of water loss out of the Tungnaá catchment area. This means that the major part of the ground- and leakagewater returns into the river at the spring horizons in Sigalda canyon, immediately downstream of the dam, but upstream of the gauging station below Sigalda. Therefore one must assume that there are relatively tight barriers south west of the reservoir, preventing the water to seep through there out of the catchment area. These assumed barriers are possibly moberg ridges buried in the enormous lava flows from recent time. Lack of boreholes or other information of value prevent us to affirm the existence of these barriers or to locate them.

5 THE HYDROGEOLOGICAL MODEL

5.1 Conditions

The following facts observed before, during, and after impoundings of the reservoir at Sigalda, must be included in any hydrological model of this area.

1. Groundwater table and measurements of groundwater temperature give a direct indication of two distinct groundwater flows, which drain into Tungnaá in Sigalda canyon.

2. Direct and indirect measurements show that the horizontal permeability of the bottom zone of the lava flows is hardly less than 30-70 cm/sec.

3. Groundwater table at a distance of 2,5 km from the reservoir rises almost simultaneously with the reservoir level during impounding. There also occurs significant increase in backwater at the beginning of the impounding.

4. Two boreholes stand side by side downstream of the dam. One of them passes through one interbed, but the other is shallower. During impounding the groundwater level is much higher in the deeper one.

5. A borehole located downstream of the dam penetrating into moberg has higher water level than any of the shallower holes in its surroundings.

6. New springs developed quite rapidly after emptying of the reservoir, from lake level 490 m a.s.l. These springs had an outflow of 1 m^3/s. The outflow did not decrease during the two months of reservoir emptying.

7. A large number of swallow holes was located at the lava front TH_h efter emptying of the reservoir.

8. The outflow of the former spring horizon in the Sigalda canyon increased to a significant degree during the impounding. New springs formed there.

5.2 Model

Measurements of the initial groundwater table and groundwater temperature give a direct indication of two distinct groundwater flows. One coming from east and the other from south. They drain into the reservoir basin and Sigalda canyon.

The initial groundwater level is shown on two schematic geological sections drawn along the reservoir bottom, Exh. 9. Even though the figures are drawn schematically here, they are based on borehole and geophysical data and are thus quite reliable. It can be seen on both of these figures how the eastern groundwater flow drains partly into the lake basin and partly underneath the impermeable lake sediments deposited in the ancient lake Króksvatn. Then the water leaves the moberg and is conducted along the highly permeable bottom layers of the lava flows.

After impounding of the reservoir, Exh. 10, the springs at the contact zone between the moberg and the lake basin are prevented from draining out because of the impounded water. This causes an immediate increase of the backwater pressure which increases almost simultaneously with the groundwater level west of the reservoir and downstream of the dam. In addition there is direct leakage through the lava front TH_h and also through the river bottom where the river has eroded the sediment from above the lava TH_f and through the highly pervious tephra layer H_4 as can clearly be seen on the Exhs. 9 and 10.

The increasing backwater pressure in the eastern groundwater flow and the direct leakage forces the groundwater flow coming from southeast to bend more westwards, where it drains into the Sigalda canyon.

The sudden drawdown of the reservoir caused the formation of new springs on its bottom as the high backwater pressure had no time to stabilize. Under conditions, such as where very scoriaceous lava front lies underneath rather thin sediments, the uplift force of the backwater was therefore higher than the weight of the sediment. This caused an uplift of the lake sediments and the formation of new springs. Once being formed the springs are likly to persist.

Unless repaired, as was done in this case, these springs are likely to persist and with increasing head of water to change into swallow holes.

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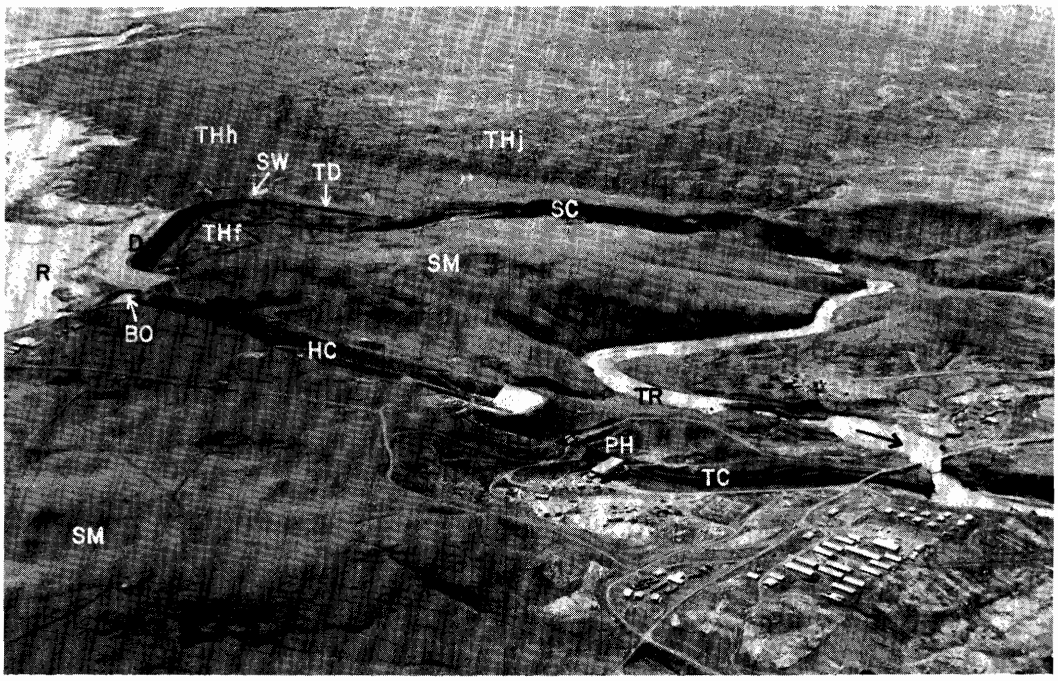
EXHIBIT CAPTIONS

Exh. 1	Aerial photograph showing the main geological and engineering features of the Sigalda Project area. View to south.
Exh. 2	Map of Iceland showing the volcanic zones and the location of Sigalda.
Exh. 3	Geological sections of the headrace canal.
Exh. 4	Geological map og the Sigalda area.
Exh. 5 and 6	Groundwater potential contour map of the Sigalda area and its vicinity before impounding, zero reading (exh. 5) and after impounding at lake (reservoir) level 492 m a.s.l. (exh. 6).
Exh. 7	Rise in groundwater level and general changes in flow pattern after impounding to lake level 492 m a.s.l.
Exh. 8	Temperature measurements in boreholes and springs showing two different groundwater flows, the so-called "cool" and "warm" flows and their flow directions.
Exh. 9 and 10	Schematic geological sections (location, see exh. 4), explaining the groundwater conditions before and after impounding.



SIGALDA PROJECT SITE

R = Reservoir

D = Dam

TD = Training dike

SW = Spillway

BO = Bottom outlet

HC = Headrace canal

PH = Power house

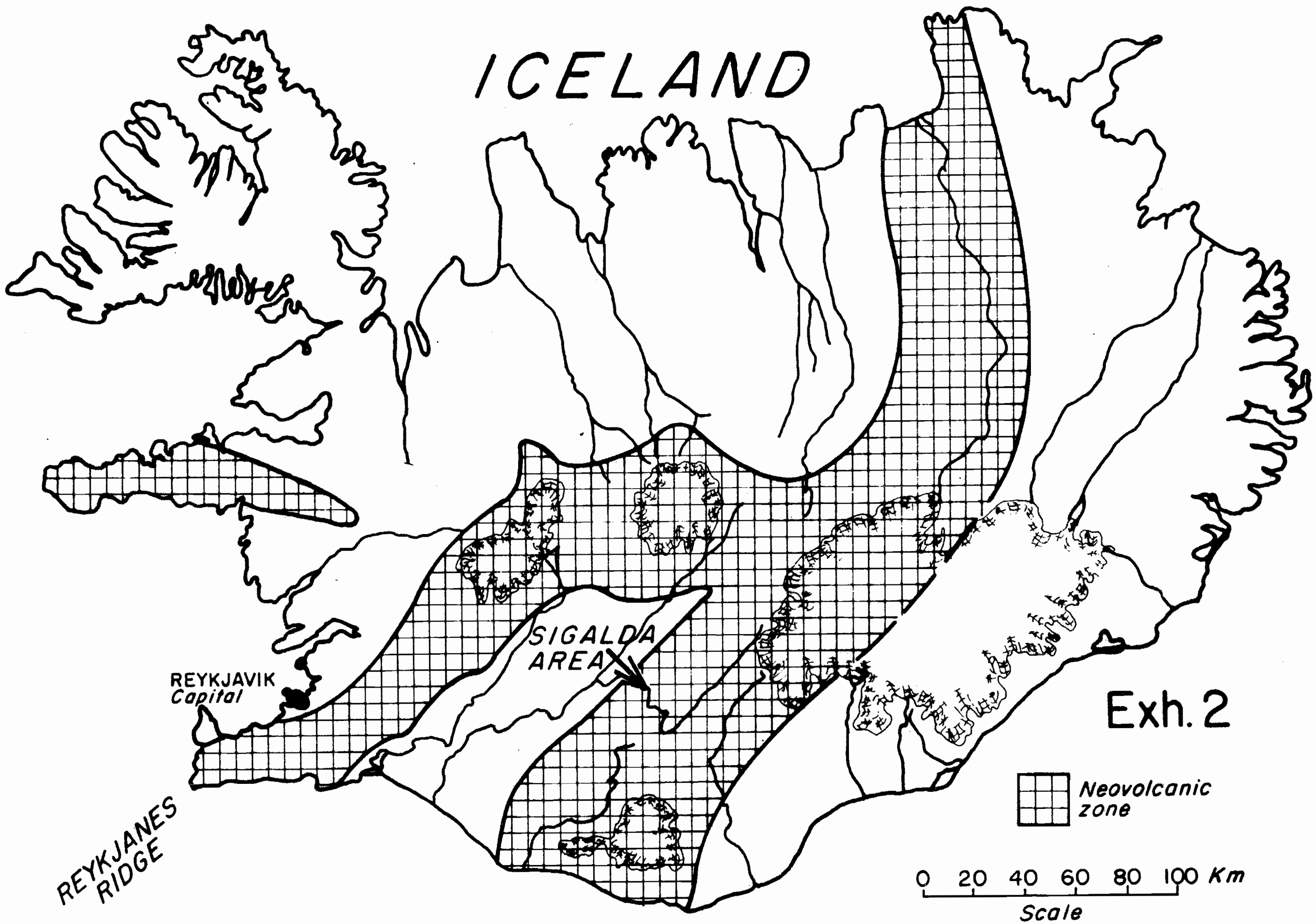
TC = Trailrace canal

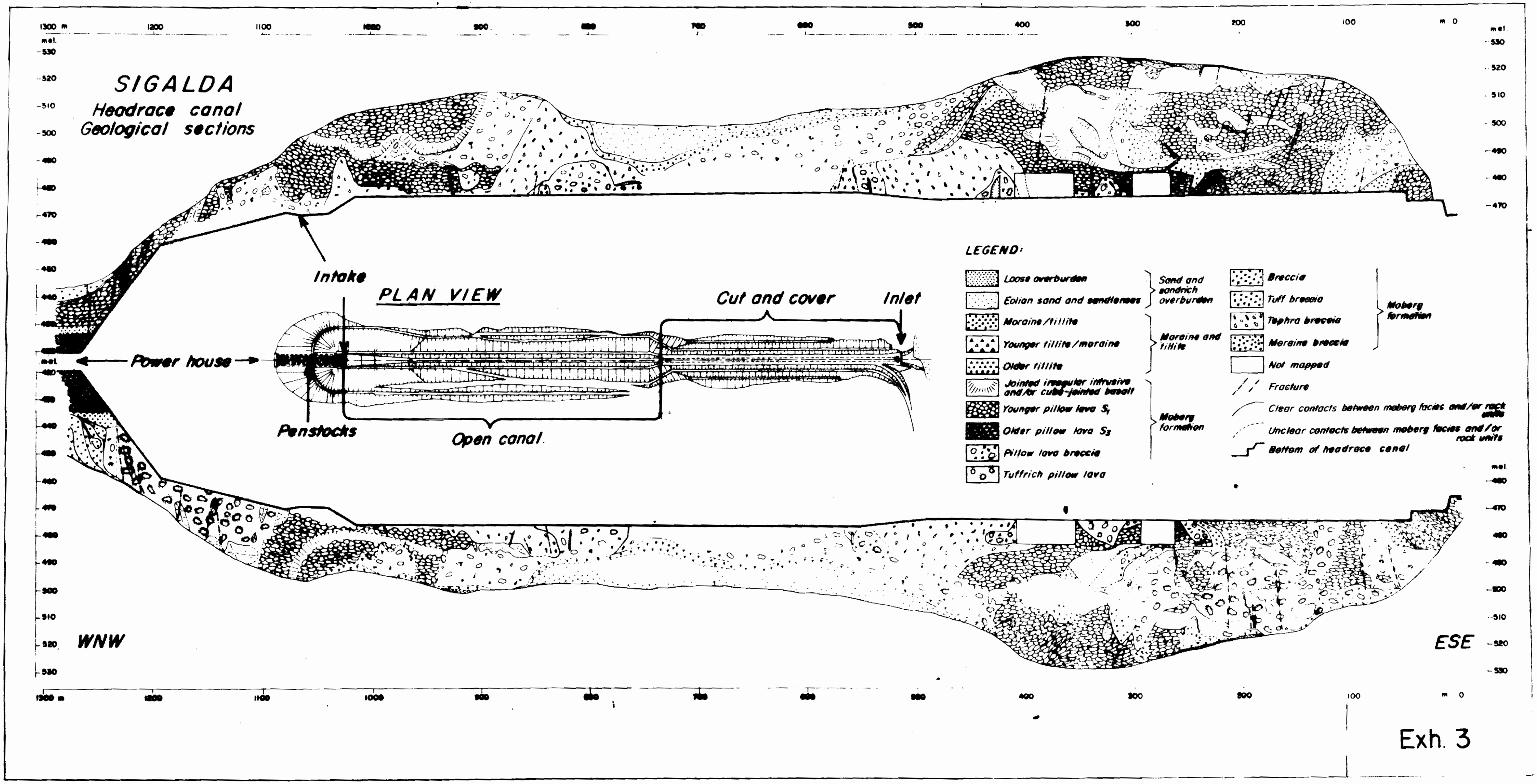
TR = Tungnaá river

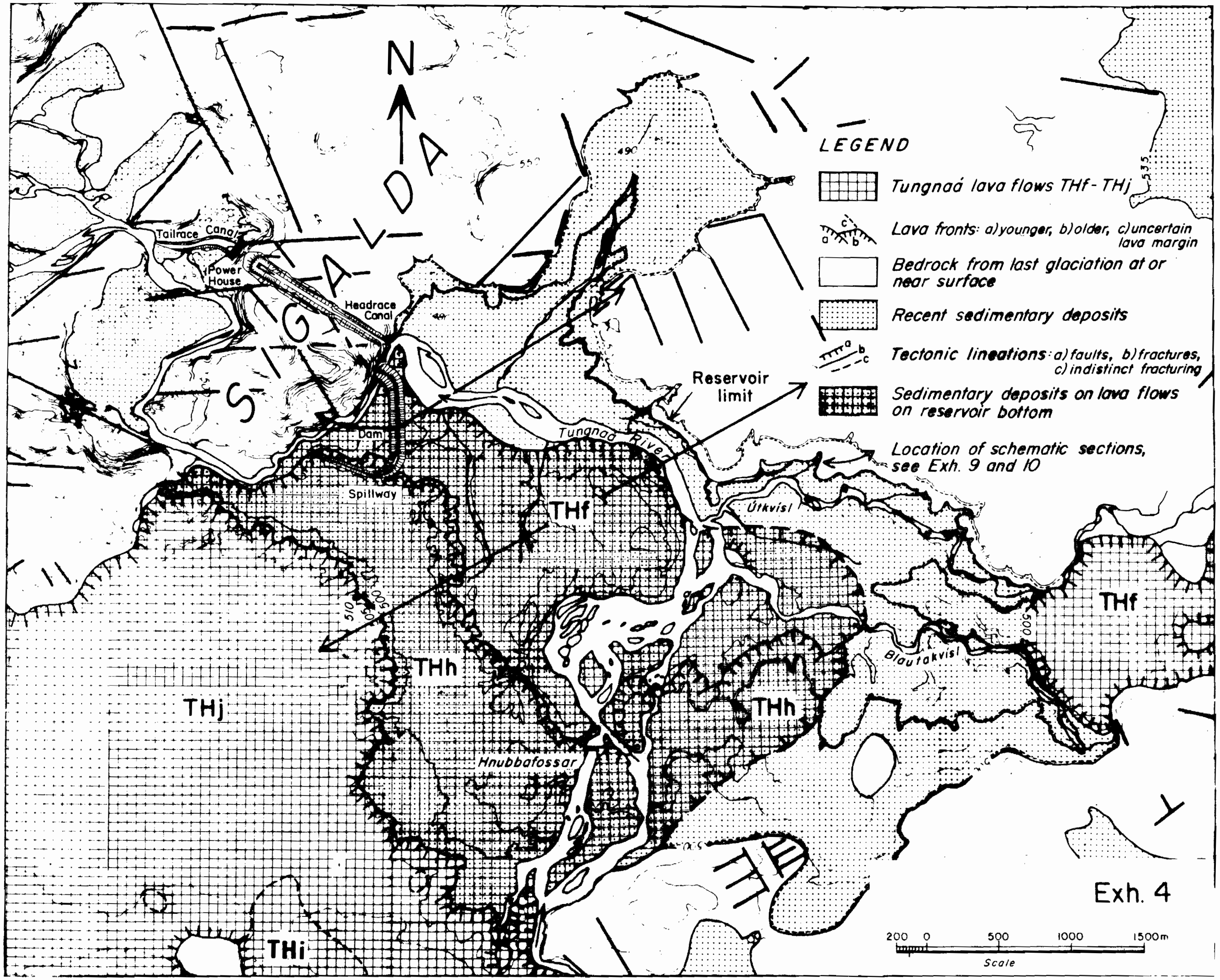
SC = Sigalda canyon

SM = Sigalda moberg

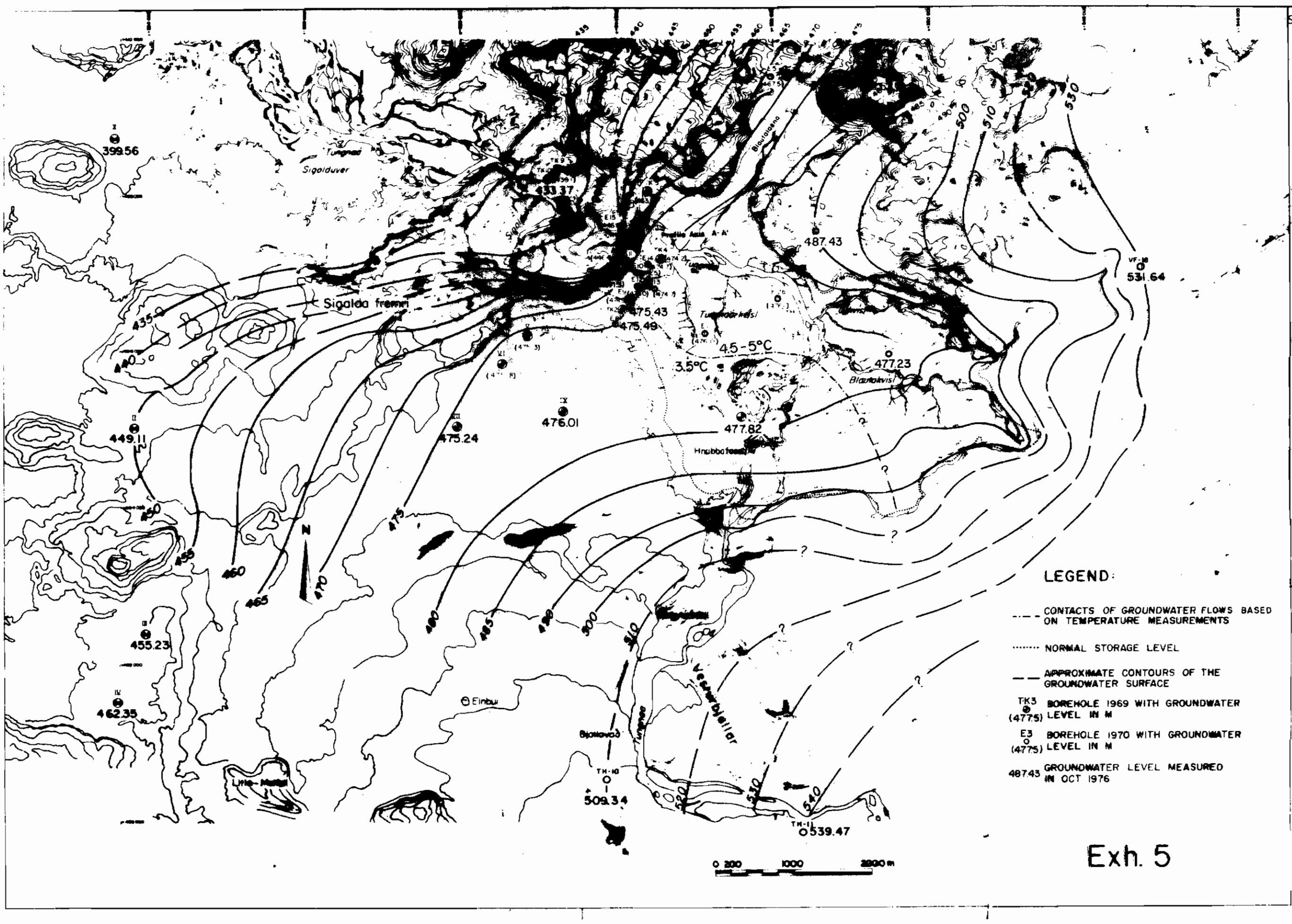
THf, THh, THj = Tungnaá lava flows


ICELAND
SIGALDA AREA
REYKJAVIK
Capital
REYKJANES RIDGE
Exh. 2
Neovolcanic zone
0 20 40 60 80 100 Km
Scale

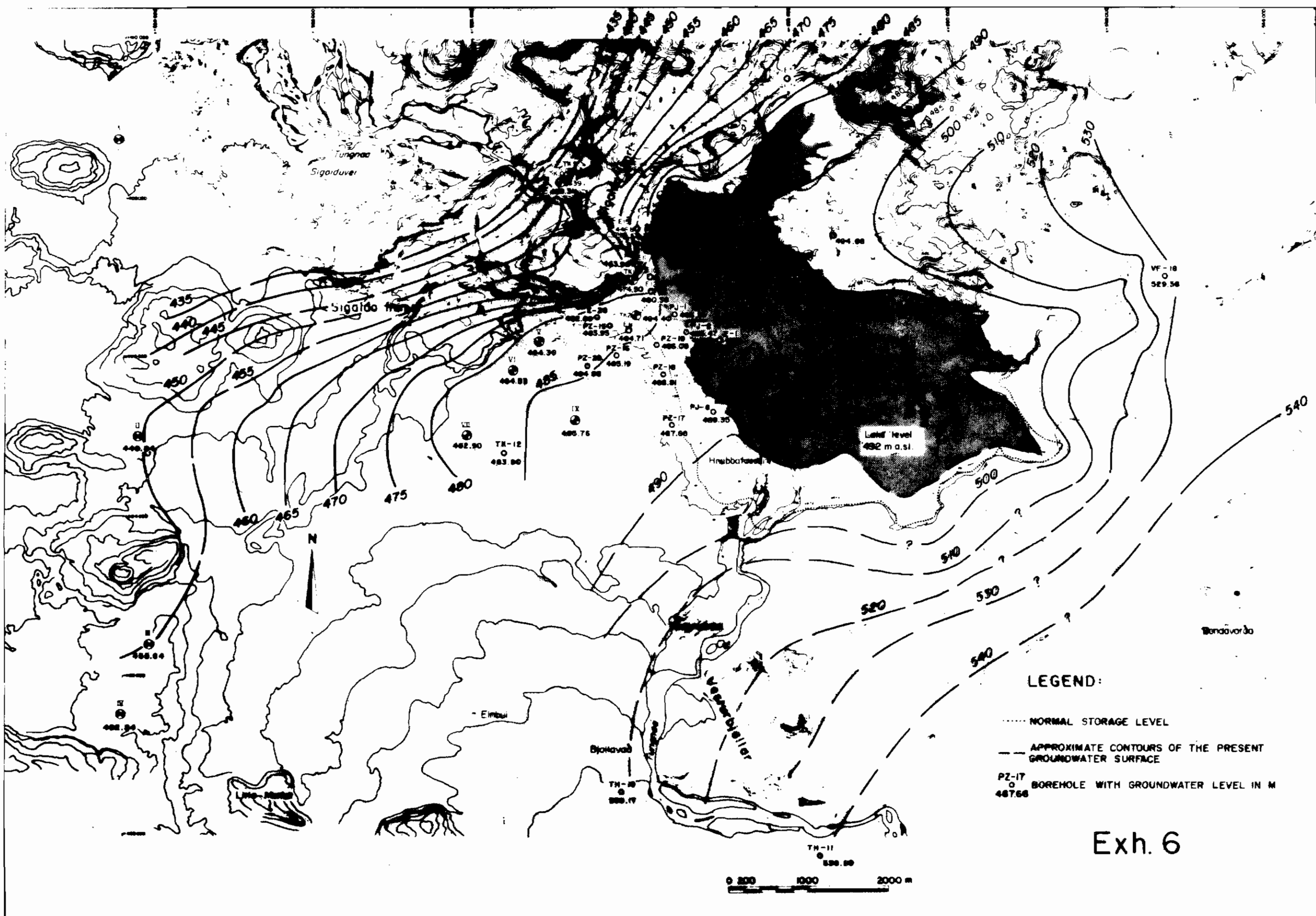

SIGALDA
Headrace canal
Geological sections
WNW
ESE
Intake
PLAN VIEW
Cut and cover
Inlet
Power house
Penstocks
Open canal.
LEGEND:
Loose overburden
Eolian sand and sandlenses
Sand and sandrich overburden
Moraine/tillite
Younger tillite/moraine
Older tillite
Moraine and tillite
Jointed irregular intrusive and/or cube-jointed basalt
Younger pillow lava S_1
Older pillow lava S_3
Pillow lava breccia
Tuffrich pillow lava
Moberg formation
Breccia
Tuff breccia
Tephra breccia
Moraine breccia
Moberg formation
Not mapped
Fracture
Clear contacts between moberg facies and/or rock units
Unclear contacts between moberg facies and/or rock units
Bottom of headrace canal
Exh. 3


N
SIGALDA
Tailrace Canal
Power House
Headrace Canal
Dam
Spillway
Reservoir limit
Tungnaá River
Útkvisl
Blautakvisl
Hnubbafossar
THf
THh
THj
THi
490
550
535
500
510
LEGEND
Tungnaá lava flows THf - THj
Lava fronts: a) younger, b) older, c) uncertain lava margin
Bedrock from last glaciation at or near surface
Recent sedimentary deposits
Tectonic lineations: a) faults, b) fractures, c) indistinct fracturing
Sedimentary deposits on lava flows on reservoir bottom
Location of schematic sections, see Exh. 9 and 10
200 0 500 1000 1500m
Scale

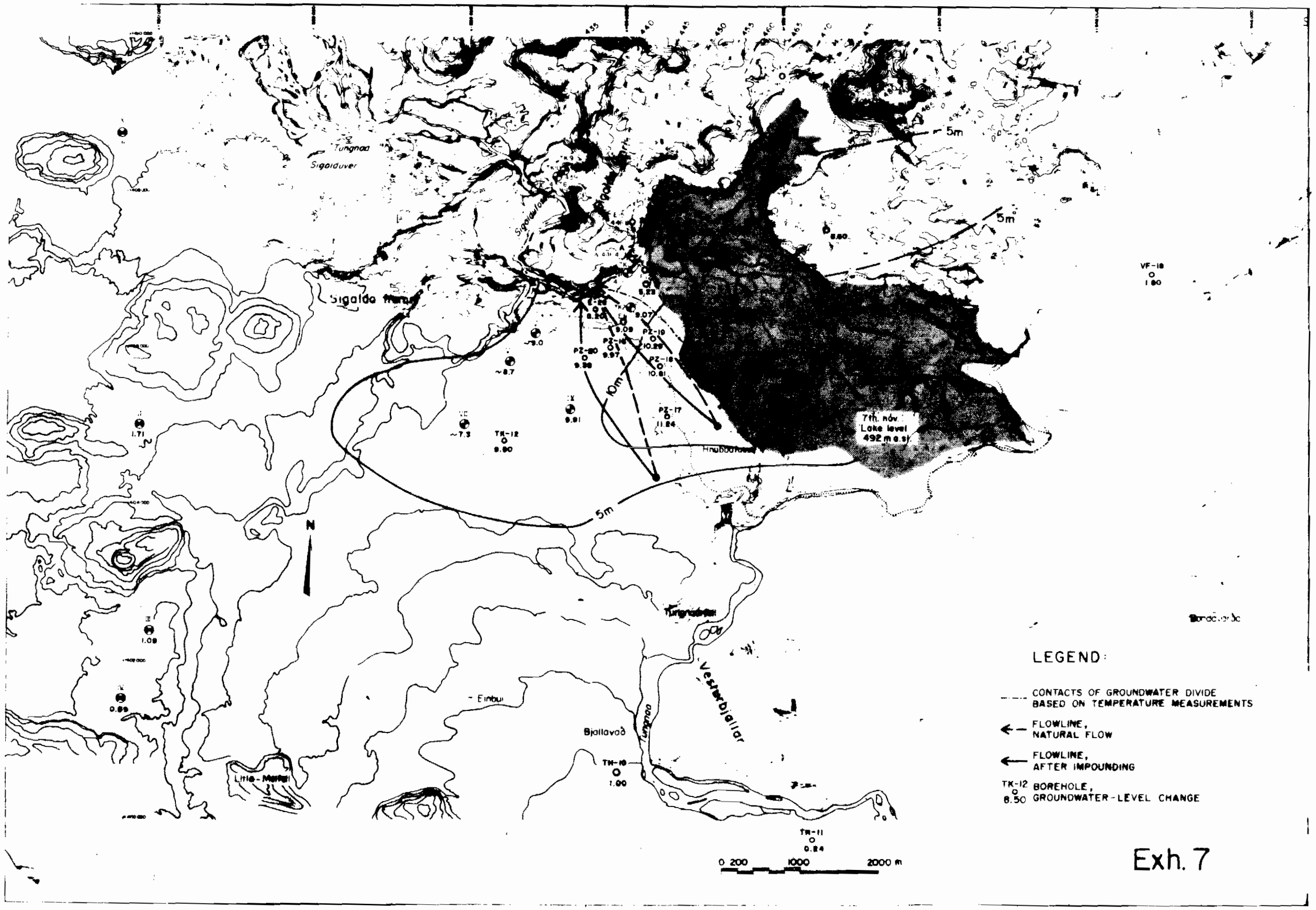
Exh. 4


LEGEND:
CONTACTS OF GROUNDWATER FLOWS BASED ON TEMPERATURE MEASUREMENTS
NORMAL STORAGE LEVEL
APPROXIMATE CONTOURS OF THE GROUNDWATER SURFACE
TK3 (477.5) BOREHOLE 1969 WITH GROUNDWATER LEVEL IN M
E3 (477.5) BOREHOLE 1970 WITH GROUNDWATER LEVEL IN M
487.43 GROUNDWATER LEVEL MEASURED IN OCT 1976
Sigalda fremri
Tungnaá
Sigalduver
Blautakvísl
Hrauneyjafoss
Einbúi
Bjallavað
Vatnaöldur
4.5-5°C
3.5°C
399.56
449.11
455.23
462.35
475.24
476.01
477.82
477.23
487.43
531.64
509.34
539.47
0 200 1000 2000 m

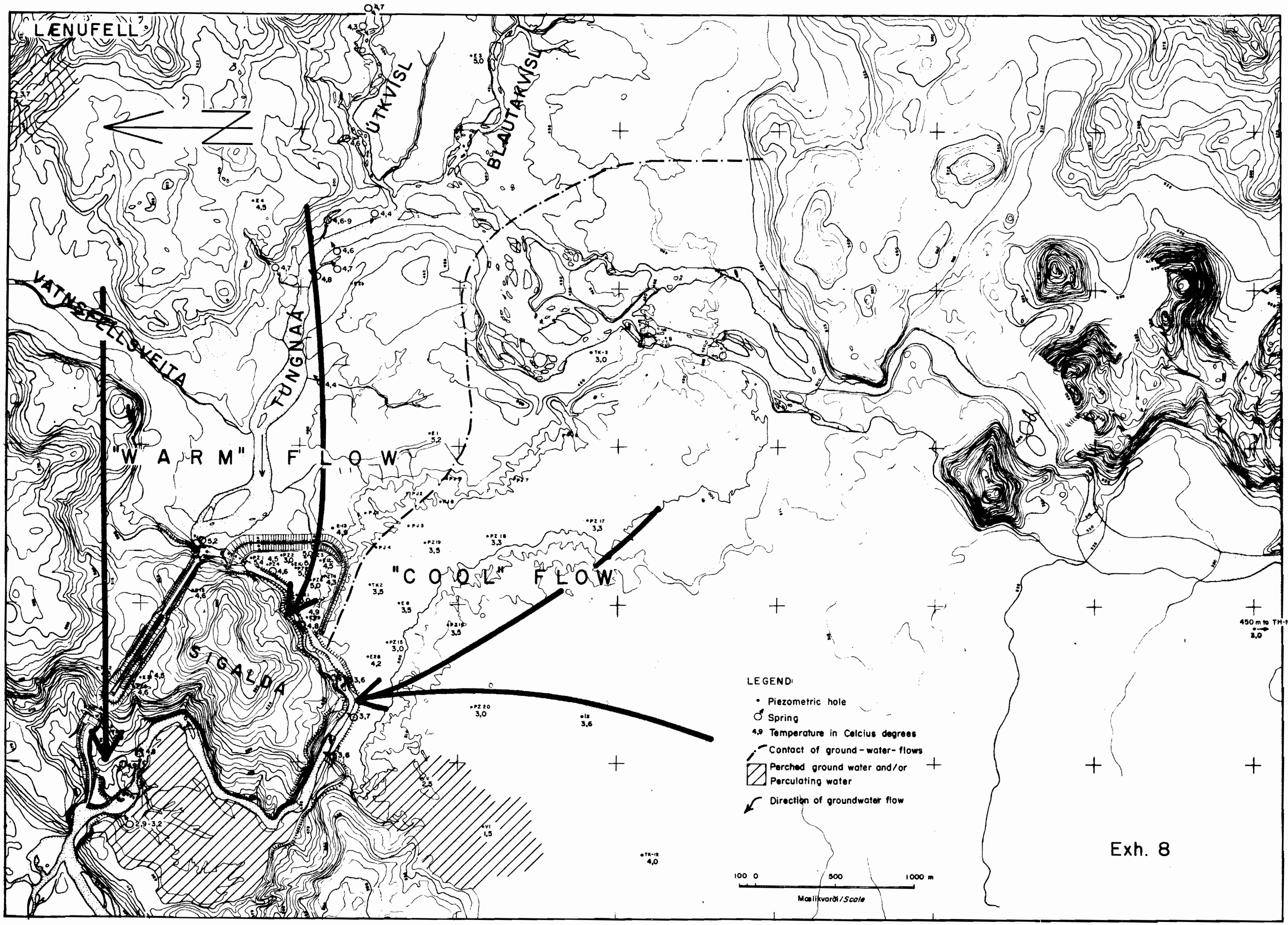
Exh. 5


LEGEND:
NORMAL STORAGE LEVEL
APPROXIMATE CONTOURS OF THE PRESENT GROUNDWATER SURFACE
PZ-17 487.66 BOREHOLE WITH GROUNDWATER LEVEL IN M
Lake level 492 m a.s.l.
Sigalda fremri
Tungnaá
Sigalduver
Hrauneyjafoss
Einbúi
Bjallavað
Vatnaöldur
0 200 1000 2000 m

Exh. 6

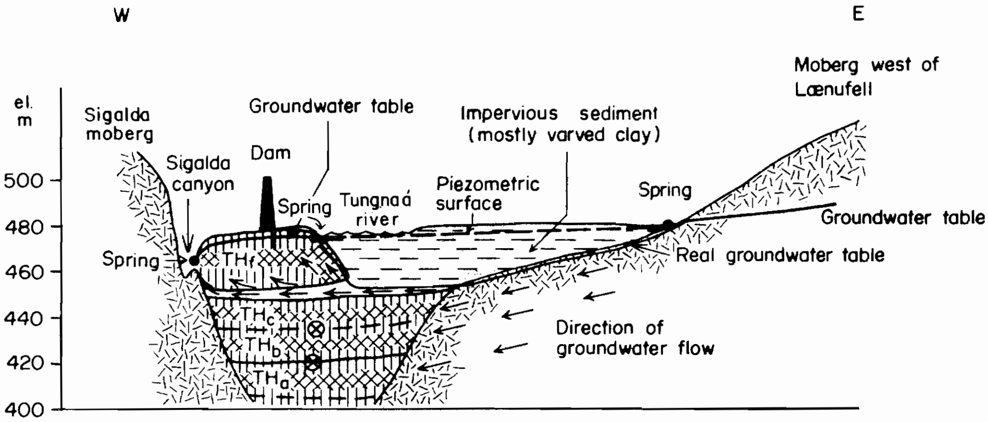

LEGEND:
CONTACTS OF GROUNDWATER DIVIDE BASED ON TEMPERATURE MEASUREMENTS
FLOWLINE, NATURAL FLOW
FLOWLINE, AFTER IMPOUNDING
TK-12 8.50 BOREHOLE, GROUNDWATER-LEVEL CHANGE
7th. nov. Lake level 492 m a.s.l.
Sigalda
Sigölduver
Vesturbjallar
Bjallavað
Einbúi
Litla-Melfell
5m
10m
N
TK-12 8.50
TK-11 0.24
TK-10 1.00
VF-18 1.80
PZ-17 11.24
PZ-18 10.81
PZ-19 10.29
PZ-20 9.38
0 200 1000 2000 m

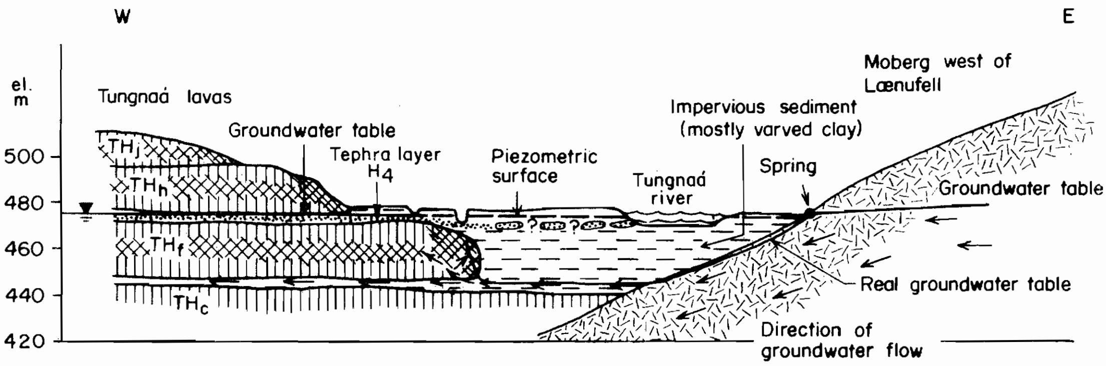
Exh. 7


LÆNUFELL
VATNSFELLSVEITA
TUNGNAÁ
ÚTKVÍSL
BLAUTAKVÍSL
"WARM" FLOW
"COOL" FLOW
SIGALDA
450 m to TH-10
LEGEND:
Piezometric hole
Spring
4,9 Temperature in Celcius degrees
Contact of ground-water-flows
Perched ground water and/or Perculating water
Direction of groundwater flow
100 0 500 1000 m
Mælikvarði/Scale
Exh. 8

BEFORE IMPOUNDING

Exh. 9



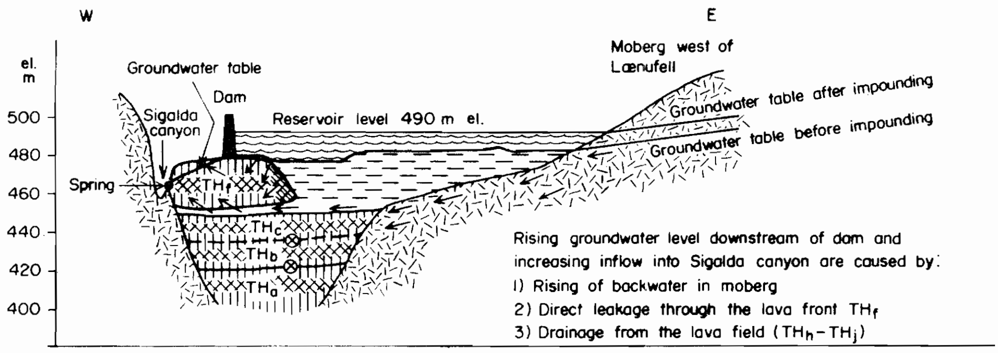


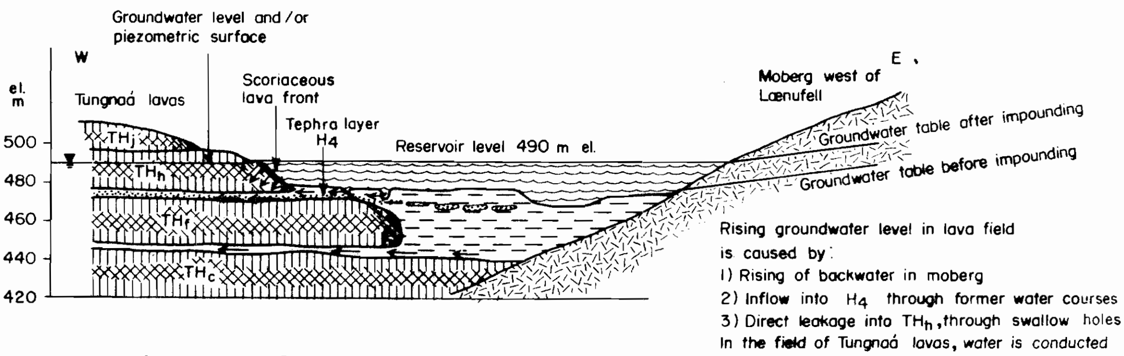
⊗ In the lava field water is conducted along scoriaceous lava zones

Location of sections, see Exh. 4

AFTER IMPOUNDING

Exh. 10





Location of sections, see Exh. 4

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NATIONAL ENERGY AUTHORITY
DEPARTMENT OF WATER POWER

DAMAGE TO EARTH DAMS AND OTHER MAN-MADE STRUCTURES CAUSED BY RIFTING ACTIVITY IN NORTH ICELAND 1975-1977

ODDUR SIGURÐSSON
BIRGIR JÓNSSON

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DAMAGE TO EARTH DAMS AND OTHER MAN-MADE STRUCTURES CAUSED BY RIFTING ACTIVITY IN NORTH ICELAND 1975-1977

O. Sigurðsson and B. Jónsson
National Energy Authority, Dept. of Water Power, Reykjavík, ICELAND.

Abstract.

The plate boundary between the American and European crustal plates runs through Iceland as a zone of active volcanism, seismicity and graben structures. During an extensive rifting episode occurring at the plate boundary in North-Iceland 1975-1977, reopening of faults and fissures as well as subsidence of segments between the faults, took place with accompanying earthquakes. This caused great damage to some man-made structures, such as earth dams, roads, bridges, drill-holes, transmission lines, buildings and a small harbour. The constructions worst hit were located across the faults and fissures where displacement had taken place, or near the epicentre of the largest earthquake.

Rifting of earthern embankments and floors of diatomite reservoirs caused the emptying of two of them. In one, the embankment on one side failed and in the other the water-diatomite mixture drained through fissures that formed on the bottom. The third reservoir is slightly damaged due to fissuring but still holding its contents. Buildings, unless specially designed, were badly damaged by fissures.

Some reopened faults and fissures, cutting across roads, had escarpments of up to 90 cm high and in some places the old fissure filling fell down leaving a gaping fissure in the road. Rifting and subsidence continued for some time after each earthquake spell, so the roads had to be repaired repeatedly, especially where the overburden consisted of loose and saturated sand.

One small harbour and several bridges were damaged by a 6.3 magnitude earthquake 6 km offshore near the village Kópasker North Iceland.

Steam drillholes for the new Krafla hydrothermal power plant, located on a hillside, were slightly displaced at a shallow depth, possibly by creep or landslip caused by the earthquakes. The 3 MW Bjarnarflag geothermal power plant was temporarily put out of action because of excessive steam. In Sept. 1977 one of the Bjarnarflag drillholes, 1100 m deep, erupted some fresh magma material in the form of volcanic bombs and scoria.

Earthen embankments have been constructed in order to divert possible lavaflows away from the Reykjahlíd village at Lake Mývatn.

DAMAGE TO EARTH DAMS AND OTHER MAN-MADE STRUCTURES CAUSED BY RIFTING ACTIVITY IN NORTH ICELAND 1975-1977.

1. Introduction

Iceland is situated on the Mid-Atlantic Ridge with two transform fault zones flanking the island along the south and north coasts. These two zones are connected by active rift belts running through the country in two parallel belts 50-100 km wide in the south, running SW-NE, and one belt in the north with a N-S direction (Sæmundsson 1974). Another less active volcanic belt is in Western Iceland running WNW-ESE. The rift belts mark the boundary between the American and the European crustal plates. Two major active central volcanoes lie outside the active belts. Within the transform fault zones, earthquakes greater tahn magnitude six are liable to occur but elsewhere within the active volcanic belts earthquakes greater than magnitude five do rarely take place (Fig. 1)

The rift belts in Iceland have the average spreading rate of 1-2 cm/year. Major rifting episodes take place about every hundred years, mainly confined to fissure (and fault) swarms each in connection with a central volcano (Fig. 2). The rifting in each episode is one or two meters, fitting nicely to the spreading rate. As the rifting episodes in Iceland are so scarce very little data on this phenomenon is avaliable. The only episode sufficiently documented is the one still proceeding within the Krafla fissure swarm in the northern volcanic belt in Iceland since Dec. 1975 (Björnsson et al. 1977.

On Dec. 20 1975 a small volcanic erupton took place within the Krafla caldera in North Iceland, along with a severe earthquake swarm which spread rapidly along the fissure zone towards north some 50-60 km causing considerable rifting and subsidence there of an area 5x20 km. The earthquake swarm culminated in a 6.3 M earthquake of distinct transform fault character off-shore in the Axarfjördur Bay, some 10 km from the village Kópasker within the so called Tjörnes Fracture Zone, causing a system of ruptures in the sea floor and on shore. Since then there have been six events with a very similar pattern of earthquake swarms and rifting within the fissure zone, both to the north and the south of the Krafla caldera, none of them occuring farther than 20 km away from the area within the caldera that inflates between events and subsides during events suggesting the presence of a magma chamber within the Krafla caldera (Einarsson 1978). Besides the initial event, two other events have caused extensive damage in the south of the caldera. The three events that have caused some damage will be dealt with in this paper.

2. Rifting events

On Dec. 20 1975 pressure within the magma chamber in the Krafla caldera reached a breaking point and some of the magma reached the surface in a small eruption. Epicentres of subsequent earthquakes, constant tremors on the seismographs, magnetic and gravity surveys and precision levelling suggest that most of the magma flowed at some depth north along the fissure swarm (Björnsson et al. 1978). Two hours after the magma flow started, fissures and faults were reactivated 40 km to the north of the Krafla caldera, i.e. in the Axarfjördur region. The total E-W spreading of the area amounted to approximately 2 m and the subsidence was of a similar magnitude. Roads running across the rifting zone were severely damaged especially where they lie over unconsolidated and saturated sand and gravel. Small widening of fissures allowed the saturated sand to "flow" into the fissures which swallowed more and more of the road material due to vibration from the traffic.

On April 27 and Sept. 8 1977 there were two almost identical rifting events to the south of the Krafla caldera. This was caused by pressure relief within the magma chamber and a flush of magma south along the fissure system. One of several 1 km deep drillholes erupted fresh pumice during the latter event.

In the first event on April 27, the rifting across the graben that was formed amounted to 2 meters. Many of the reactivated (and perhaps some new) fissures cut across the basement of a diatomite factory and its reservoirs, cuasing extensive damage. On Sept. 8 almost exactly the same fissures were active but this time the total rifting was only 1 meter.

3. Damage to man-made structures

a) Kópasker village and surroundings.

On Jan. 13 1976 a 6.3 M earthquake occurred with epicentre in the the Axarfjördur Bay 10 km from the small village of Kópasker (pop. 140). The earthquake was caused by a right handed movèment on the transform fault zone running WNW from Axarfjördur Bay. The village is outside the rifting zone but considerable movement on other faults took place due to the severity of the shocks resulting in damage to houses adjacent to the faultlines. The small pier at Kópasker is made up of concrete box caissions which moved about 1-2 feet apart and tilted in the earthquake (Fig. 3)

The roads south of Kópasker were slightly damaged in the earthquake. The frozen surface of the soil, 20-25 cm thick, broke up severely. At some of the cracks the frozen surface blocks had been pushed together forming small ridges 30-50 cm high, other cracks had opened a few cm. Three small and old concrete bridges south of the Kópasker village were damaged in the earthquake.

In the area south of Kópasker and south of Axarfjördur Bay a number of farmhouses were damaged in the earthquake (Sigurdsson 1976).

b) Roads

South of the Axarfjördur Bay the first rifting event in Dec. 1975 caused a shallow graben, 6 km wide to be formed. The measured rifting amounted to 1-2 m across the graben during this event and escarpments formed in the main road were 0.5 m high. North of the main road the escarpments were up to 2 m high (Fig. 5). They were most prominent at the eastern edge of the graben. The road across the rifting zone lies on unconsolidated, saturated sand and gravel a few m thick, which lies on top of postglacial lava flow. The depth to the ground water table is only about 2 m. The postglacial lava and the older lavas are badly fissured where the rifting zones run through. Widening of a few cm on some of these fissures caused the old fracture fillings to fall down and, enhanced by the traffic vibration, some of the loose, saturated sand "flowed" down into the fissures, causing trenches, a few meters across, to be formed across the dirt roads in places. These trenches had abrupt edges due to the frozen surface layer of the road and were open down to groundwater at 2 meters depth (Fig. 6).

c) Earth dams.

During 1965-1967 a diatomite plant with three earth dam reservoirs was constructed on top of a 250 years old lava flow within the Krafla fissure swarm in a locality called Bjarnarflag situated 2 km east of the Reykjahlíd village at Lake Myvatn and 4 km south of the Krafla power plant. No fissures could be seen in this lava flow, but both north and south of it fissures and faultlines could be seen that seemed to extend under the lava. The diatomite is pumped as liquid mud from the bottom of nearby Lake Myvatn and settles in the three reservoirs near the plant. The reservoirs are homogeneous earth dam types, made of sandy gravel and sealed with polythene cover on the inside. During the rifting event in April 1977 fissures opened up in the postglacial lava under the reservoirs. One of them was emptied through a gaping fissure on the bottom of the reservoir (Fig. 7) and another one was emptied due to a breach in the earth dam (Fig. 8). The third reservoir has held its contents in spite of some fissuring in the dams.

d) Buildings

The diatomite plant itself has not been damaged although the whole site is riddled with open fissures but the separate office block is severely broken up. The reinforced foundations of the factory obviously resist tensional forces better than the lavafield does, so the fissures side-step around the most important units of the factory. This suggests that if foundations are properly reinforced or designed to accommodate rifting by letting the superstructure slide on top of the foundation, there should be little danger of damage to buildings due to rifting.

The power house of the new 60 MW Krafla geothermal power plant, 8 km north of Bjarnarflag, is designed to be able to slide on its foundations if rifting occurred there. Furthermore the postglacial lava flow on which the powerhouse stands was thoroughly grouted to increase the tensile strength of the lava mass, which was very low beforehand due to columnar fracturing. It is hoped that these measures will divert cracks around the power house, but so far the main rifting zone is 1 km west of the power house.

Near the diatomite plant, there is a small factory that produces light building stone out of lapilli and scoria from nearby. The factory house was somewhat damaged due to ground movements and due to the excessive steam and heat omitted out of the ground. The house was completely hidden in steam for weeks.

The Reykjahlíd village is just west of the rifting zone, but there was some movement on one fissure that is very conspicuous south of the village. This fissure caused damage to two houses in the village.

In order to secure the Reykjahlíd village from a possible lavaflow coming up in the Bjarnarflag area, a dyke has been constructed east of the village that will divert any lavaflow towards south. Such an earthen barrier was constructed during the Heimaey eruption in 1973. The barrier diverted the lavaflow from the Vestmannaeyjar town for two months, or until the lava nearest to the crater had piled up high enough to flow over the barrier.

e) Drillholes.

Two geothermal fields lie in the area affected, the Krafla field, which lies about 1 km east of the fissure swarm where it runs through the Leirhnjúkur eruption centre, and the Bjarnarflag-Námafjall field which lies within and just east of the fissure swarm proper 8 km south of Leirhnjúkur and 2 km east of the Reykjahlíd village at Lake Mývatn. The drillholes at Bjarnarflag were greatly affected during periods of magma movements along the fissure swarm to the south, which resulted in higher temperature and increased steam output, both much greater than the holes were designed for. During the rifting events in April and Sept. 1977 the field was most affected and the 3 MW Bjarnarflag geothermal power plant was put out of action for some time because of excessive steam. During the event in Sept. 1977 one of the drillholes, 1100 m deep, erupted some fresh magma material in the form of volcanic bombs and scoria. This material broke through 8 mm thick steel in the well head.

In the Krafla field the steam production for the new Krafla power plant has been interupted due to excessive silicic and calcarious deposits in the holes, partly clogging them. This deposition has possibly been enhanced by the increased activity in the area. Some of the holes, situated on the hillside east of the power house have been displaced slightly during the disturbances, at a depth of 60-120 meters, possibly due to a slight movement on old slip planes.

f) Other man-made structures.

Understandably most constructions that stretch across reactivated fissures, sometimes completely across the 1 km wide rifting zone, were damaged during the rifting. Among these are electric transmission lines and telephone lines in the Axarfjõrdur region and at Bjarnarflag (Fig. 4). These lines were strained until they ruptured in the most active places. Barbed wire fences were torn asunder in most places where they crossed rifting fissures. In the Mývatn area water mains between the Reykjahlíd village and the factories in Bjarnarflag, both for cold and natural hot water were torn apart in many places during the rifting events in April and Sept. 1977.

4. Conclusions.

Very little regional planning has been done in Iceland regarding geological hazards. However, an Icelandic commission on earthquakes proposed, twenty years ago, to divide the country into four zones of different earthquake risk, and the transform fault zones in the north and south were pointed out as the most intense areas.

When considering danger from rifting and earthquakes, planning on a local scale is more important than regional planning. A very accurate large scale geological/tectonic map should be at hand when planners are locating even single structures in earthquake prone areas, whether a house, factory, bridge etc. in order to minimize the possibility of faults and fissures running through the foundations of the structure. In areas of rifting, the earthquake shocks are not very large, but the rifting itself, if occurring underneath a structure, is very damaging unless the design makes allowances for such movements. If it is unavoidable to locate structures within an active rifting zone then the foundations must be designed correctly, i.e. the tensile strength of the foundation of the structure must be increased until it exceeds the tensile strength of the surrounding natural ground. This should cause fissures to sidestep around the structure. Further safety is introduced by allowing the superstructure to be able to slide on top of the foundations in the case of rifting taking place through there.

In the transform fault zones larger earthquakes take place with much greater effects, especially right at the fault breaks (Einarsson et al. 1977, p. 199-200). Therefore the faultlines should be detected beforehand so they could be avoided as possible locations for man-made structures. Locating faultlines is also very important for areas outside the transform fault zone itself, but near enough for the larger earthquakes to cause some disturbance on faultlines. From an engineering point of view it is therefore necessary to have access to accurate tectonic maps to be able to predict where surface breaks are likely to occur during earthquakes.

5. Note on rifting episode, Jan. 1978.

A new rifting episode occurred in January 1978 resembling the one from dec. 1975. Most of the activity was in the Axarfjördur Bay area. Electric transmission lines and telephone lines where strained and torn apart in places and two meters of new wire had to be added due to the rifting. Roads were damaged much in the same way as in 1975 and in the same places. A few houses were badly cracked due to fissuring under the foundation.

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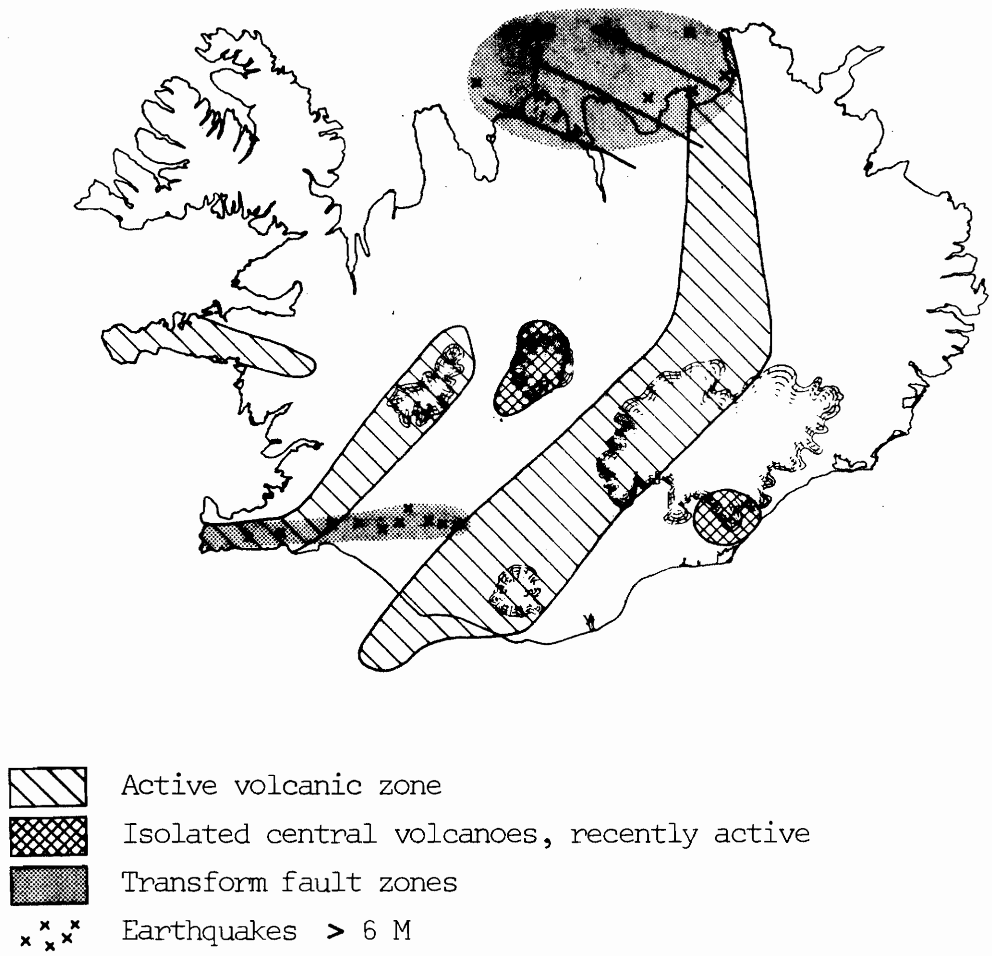

<u>Fig. 1:</u> Map of Iceland showing the active volcanic zone and the two transform fault zones.

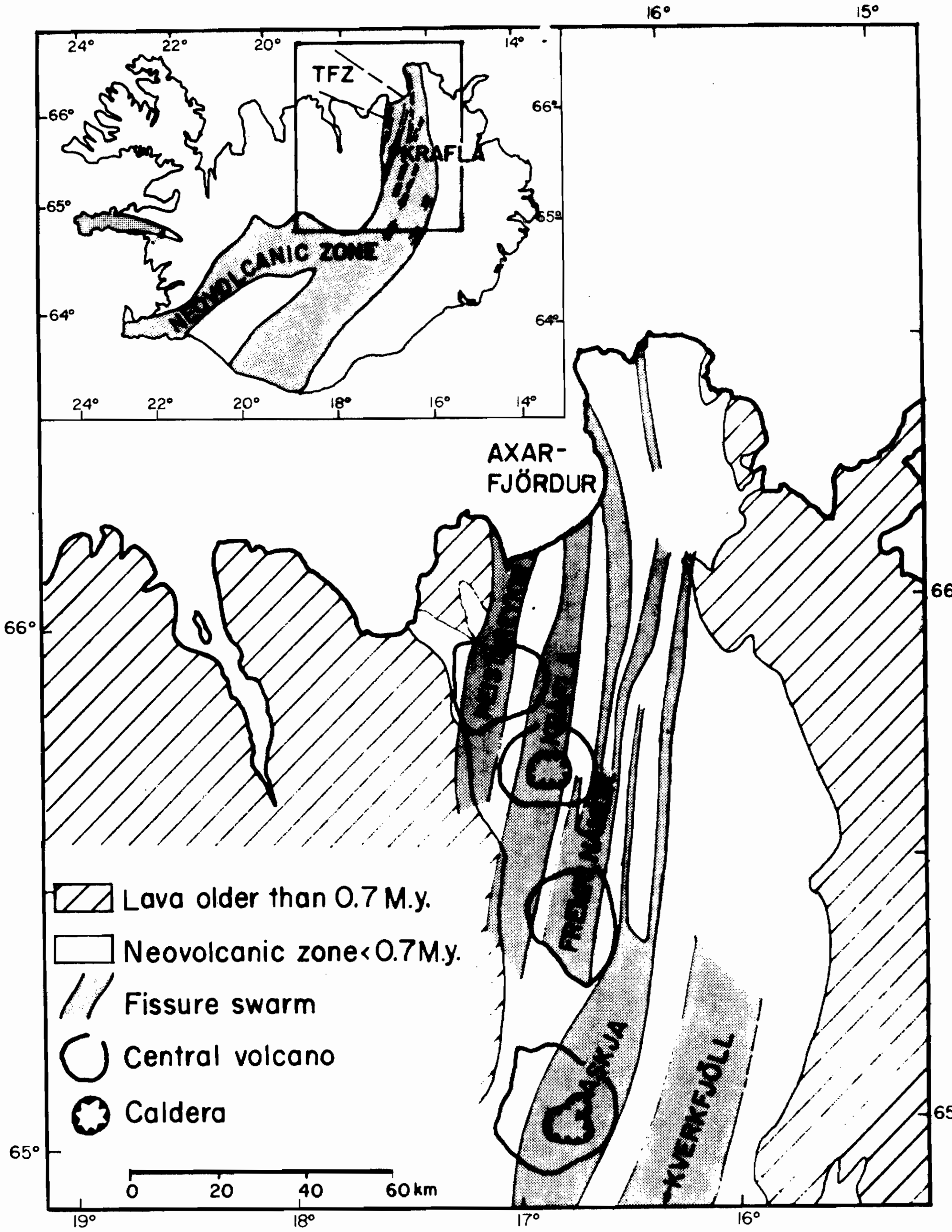

Fig. 2: The rifting zone in North Iceland. Central volcanoes and associated fissure swarms are named after the high temperature geothermal fields in the central volcanoes. Mapped by K. Saemundsson. (From Björnsson et. al. 1978).

Fig. 3: The concrete box caissions in the Kópasker pier moved about 0.5 m apart and tilted in the 6.3 M Kópasker earthquake of Jan. 13 1976.

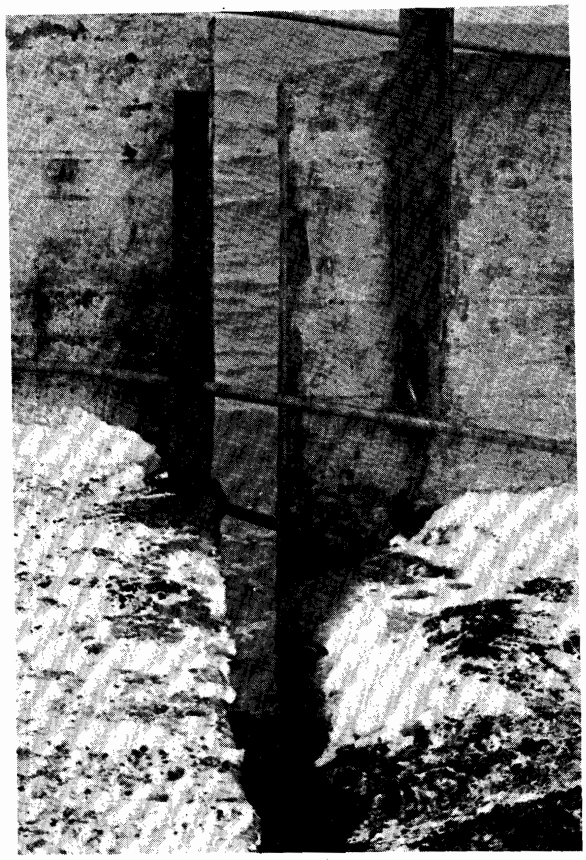

Fig. 4: Electric transmission lines across the rifting zone in Bjarnarflag, south of Krafla. The wires are strained almost to breaking point. The photograph shows a man lengthening the wires in the evening of April 29, during rifting.

Fig. 5: On the outwash plain south of Axarfjörður bay, escarpments over 2 m high were formed during the rifting and subsidence in the Winter of 1975-76. On the photograph a rough car track has been displaced. Length of shovel is 1 m.

Fig. 6: One of the trenches formed in the Axarfjörður main road. The hardened snow forms a bridge across the trench. See text for explanations.

Fig. 7: One of the empty diatomite reservoirs at Bjarnarflag. This one was emptied through the fissure seen on the bottom of the reservoir.

Fig. 8: Another diatomite reservoir was emptied through this breach in the earth dam caused by a fissure that can be seen in the background running through the reservoir bottom. The polythene sheet can be seen on both sides of the breach.