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THE OPENING OF TECTONIC FRACTURES AT THE LANGALDA DAM

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INTRODUCTION

Hydropower sites in Iceland are commonly found in a geological setting of very pervious, mostly postglacial lava flows, i.e. less than 10.000 years old, and glacial pillow lava and tuff formations. The latter two are mostly ridges and hills, which are also pervious but less so than the lava flows, especially at the top due to a cover of moraine or moraine like material from the last glaciation. Through this type of geology great rivers are flowing usually partly fed by glacier melting and with a considerable amount of sediment load. These rivers flow high above the ground water and have no connection with it except in deepest canyons where they cut below the ground water table. This indicates that the rivers flow on an impervious bed created by their own sediment load.

This setting was the reason for choosing the Langalda area for a test in which it was intended to measure the initial leakage through the lavas and how it decreases with time due to sealing brought about by the deposited sediment load of the river.

THE SMALL SCALE TEST

The test started in 1966. Then a branch of the river Tungná was diverted on to the highly pervious postglacial lava flows surrounding the river (see fig. 1). In the course of the diversion small shallow ponds were created where permeability could be calculated. The size of these ponds was 0,17 km^2, usually 1-2 m deep and the inflow was 1-2 m^3/s. The result from these small ponds showed an initial leakage of 30-40 $m^3/s/km^2$ of lava which decreased in a few months down to 10 $m^3/s/km^2$ and was then confined to relatively few open swallow holes at the lava margin which stayed open for a long time and had to be closed with a material with filter criterion to start the self sealing mechanism. This was done with good results and in 1968 the leakage was only 2 $m^3/s/km^2$.

Figure 1

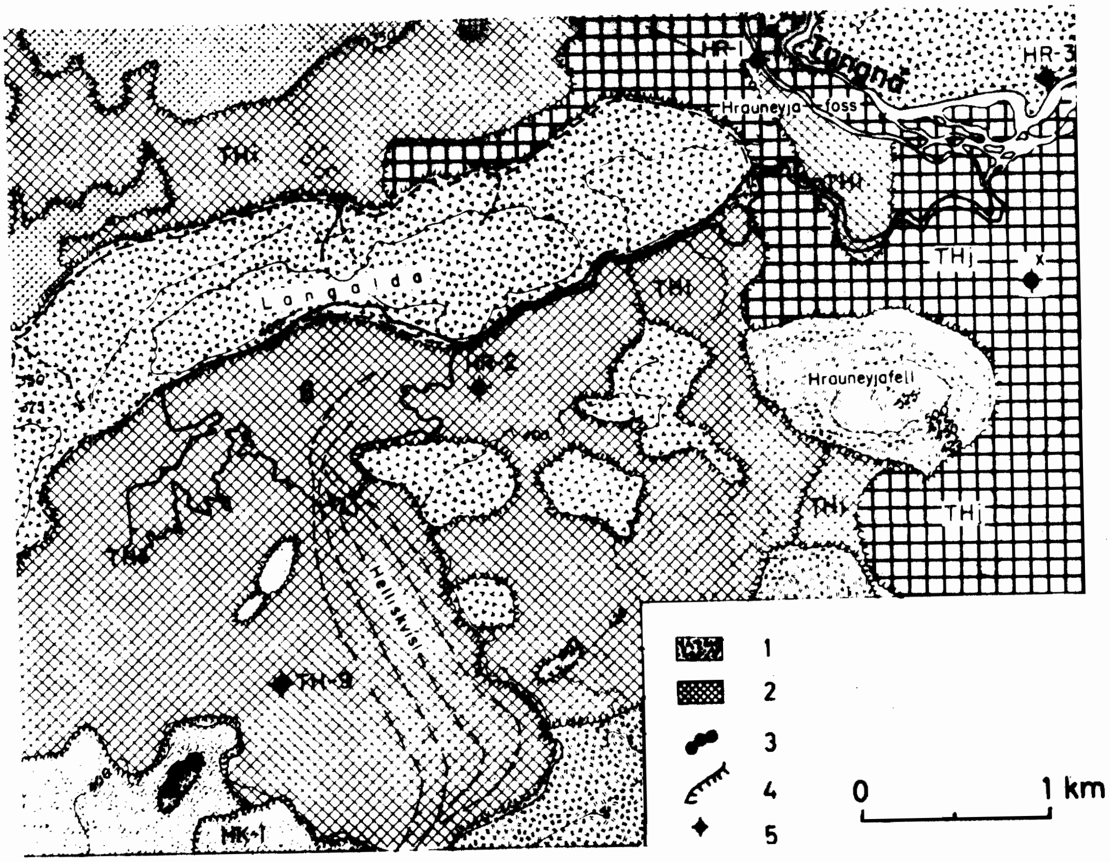


Figure 1

Geological map of the project area

1 Móberg formations, consisting of pillow - lavas, breccias and tuffs, often covered with moraine
2 Postglacial lava flows
3 Craters
4 Lava fronts
5 Bore holes, piezometers
6 Test reservoir

THE LANGALDA DAM

We then wanted to increase the scale of the experiment to a so to say full scale model. In order to do that the Langalda dam was built in 1969. This dam is 10 m high and capable of creating a lake, 8 m deep and 1,5 km^2 in area. In the spring of 1970 the extended experiment was started and from that date the inflow was gradually increased to 6-12 m^3/s in the following two years.

The dam was designed by Thoroddsen and partners in Reykjavík who also assisted in other civil engineering aspects of this project. The material used was sandy moraine covering the area adjecent to the right abutment. No foundation preparation was done, only loose overburden stripped off for the foundation of the impervious core. The impervious core was moraine, better rolled than the rest of the fill material. Both filters and shell material was also moraine but less compacted. Along the lava front at the left abutment an imperious blanket of moraine, about 150 m long, was made. As rip-rap one used very hard moraine or tillite which was loosened by bulldozer with ripper.

The equipment used for the construction of the dam were two bulldozers, one backhoe and two trucks. The trucks were mainly used for transporting material to the far end of the dam and to the impervious blanket. Otherwise the bulldozers were used for the loosening of the material, transporting it to the dam and compacting it.

As a result of this construction method the slope of the dam became much steeper than intented and the crest wider. The intended side slope was 1:1,8 but became almost 1:1 and the crest width intended 4 m became almost 10 m. A map showing the dam is on fig. 2.

As a result of these steep slopes a slip fracture developed in the dam in 1970 when the water depth had been 3-4 m for a while. This fracture was parallel to the long axis of the dam and extended all along the highest part of it. A settlement of 10-20 cm took place in the upstream part of the dam.

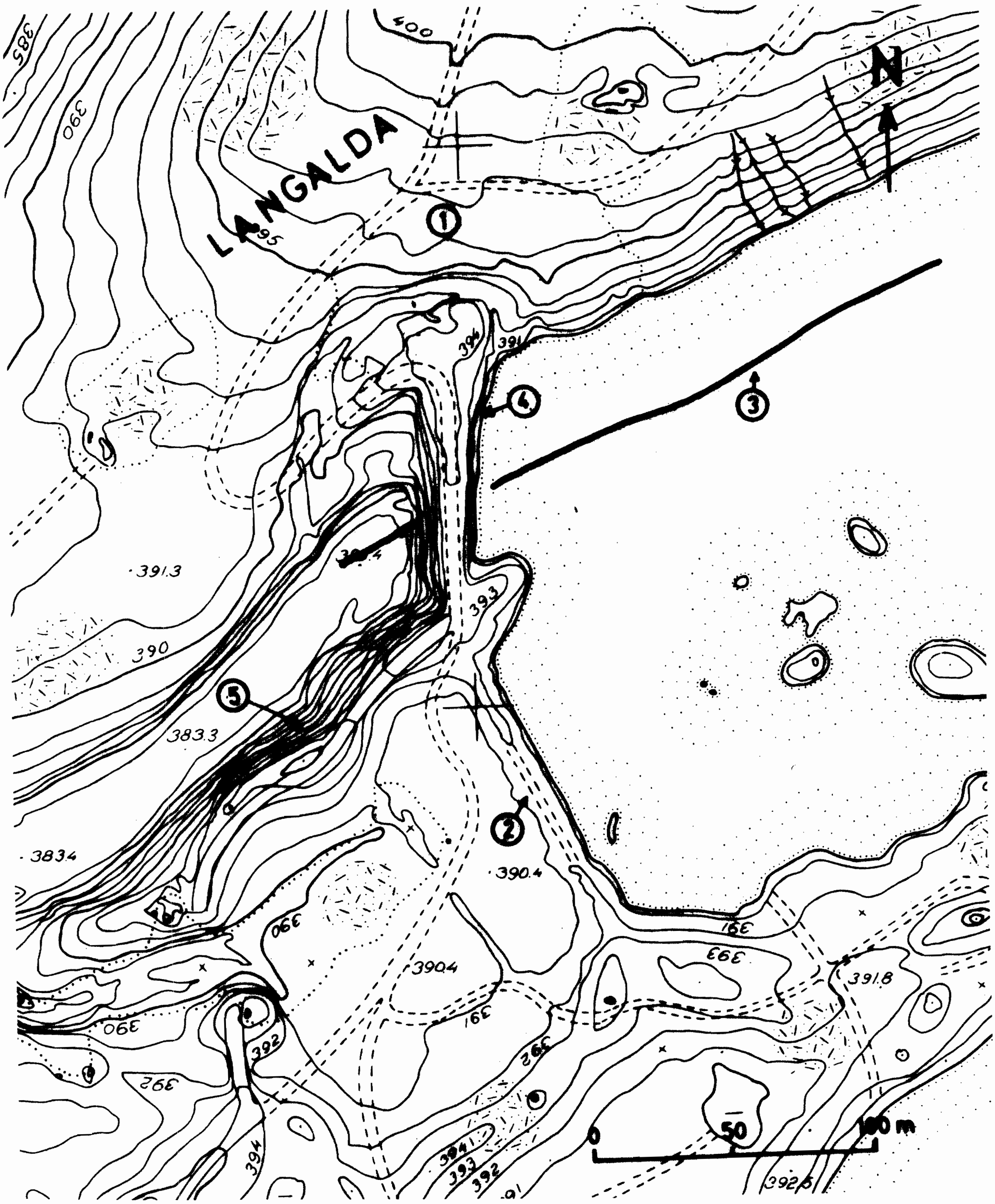


Figure 2

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.

In 1972 6 piezometers were put into the dam. The result of drop in pore pressure is shown in fig. 3. The irregularity in the drop of piezometer readings is probably due to the fracture in the dam. Leakage through the dam seems to be small and of no concern. A short path leakage through the left abutment has occured several times when the lake has reached a new peak in elevation and it has gradually decreased or disappeared when the lake level went slightly down again. No indication of piping has been observed.

RESULT OF THE LARGE SCALE TEST

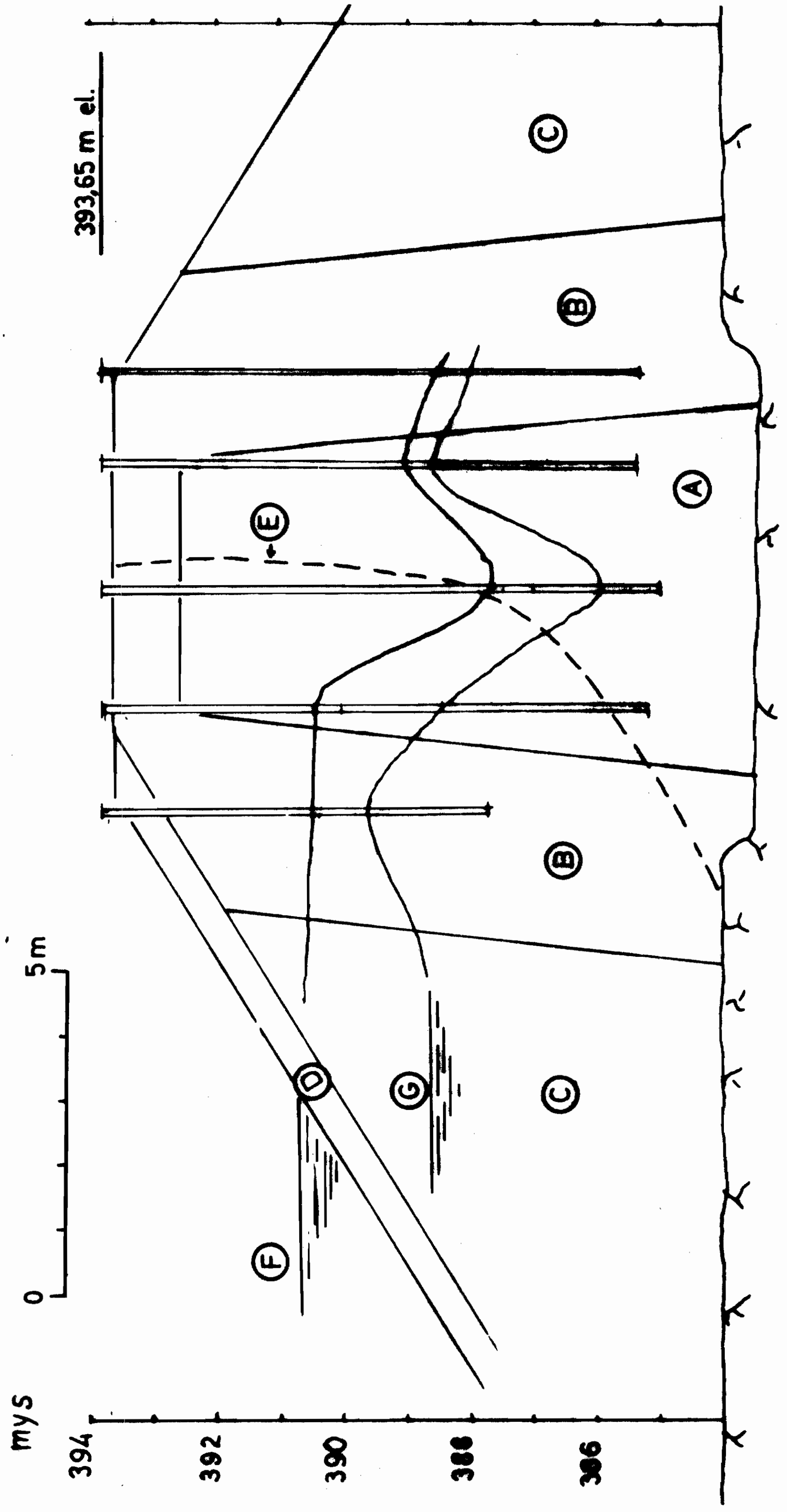
The general result of this very much extended part of the self sealing test was similar to the part previously done. The leakage was in the beginning 20-30 $m^3/s/km^2$ of lava and decreased rapidly down to approximately 1/3 of this. Swallow holes were formed at lava margins and often at small hillocks which are probably pseudocraters. Swallow holes can stay open for several years but it is also possible that wave action brings enough sand into them to close them. The lavas in this area are usually covered with sand, at least in depressions.

In winters the diversion from the Tungná is usually closed. The inflow into the lake is then limited to occasional winter meltwater floods from the postglacial lavas south of the lake. In summer there is no run-off from this area. These winter-floods can be much bigger than the diverted flow. In some of these winter-floods the lake was first filled for a short duration of time.

THE FORMATION OF THE FIRST FRACTURE

During the winter 1970-71 there was constantly some water in the Langalda basin as the diversion gate at Tungná had been damaged. In a great flood on March 8 - 9th the lake reached the highest level it has ever gained. The bulk of this water entered the lake via the old Helliskvísl channel and other usually dry channels in the lava fields south of Langalda. The amount of water entering the lake at this point of time is not known but is estimated to have been not less than 20 m^3/s.

Figure 3



A Impervious core; B Filters;
C Shell material; D Rip - rap;
E Cylindrical slip plane in dam;

F Lake level and piezometer readings, high level; G Lake level and piezometer readings, lake level dropping.

Figure 3

Cross - section of the dam (intended) with piezometers.

On April 17th 1971 voluminous springs were observed issuing out downstream of the Langalda dam. Two days later the writer inspected these springs together with S. Thoroddsen. The following day these springs were still observed while a day later when the writer visited the site again together with S. Thoroddsen the lake had completely emptied. Then I observed for the first time a rift in the rock on the lake bottom just upstream of the dam and concluded that it continued under the dam causing the above mentioned springs. From the above said and weather forecasts it is obvious that the fracture under the dam was formed on April 15th or 16th.

At my first inspection after the emptying of the lake, all the lake bottom was strewn with large ice-floes making it invisible except in two places. On April 23rd a bulldozer started clearing the ice and snow covering the bottom, the purpose being to repair the rift under the dam as soon as possible as further spring floods in the river Helliskvísl were imminent, that could erode a gap in the dam. We managed to find the rift at the dam but just afterwards the Helliskvísl rushed forward like a wall almost immersing the bulldozer. In two hours time the water level rose 4 m. The discharge in this flood has amounted to about 20 m^3/s. This discharge very soon decreased, but a considerable flow, yet gradually decreasing, remained for 18 days.

Langölduveita never reached maximum lake level during this time. During this period the gates at Tungná were repaired to check as far as possible inflow from the river. The subsequent inflow only amounted to a few hundred liters per second. Water flowing underneath the dam eroded it somewhat on the downstream side leaving a small groove in it on that side. Certainly a gap would have been cut into the dam with continued flow. As the Helliskvísl ceased to flow the lake emptied in 2 - 3 days. A day later, i.e. on May 12th, the writer again visited the lake and for the first time could survey the whole lake bottom as the ice had largely disappeared. Now a distinct fracture pattern was discernible extending for 1 km along the lake bottom, the main trend being parallel with Langalda in this reach while each separate fracture had a more northerly direction.

STUDIES OF FRACTURES AND THEIR FORMATION

All these early fractures are situated in móberg (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. The water therefore plays an evident role in making this phenomenon so distinct. When the fractures open up the water washes down into them all loose material from the banks leaving the fractures clear as far down as can be seen, which is between 10 and 20 m. Figures 4 and 5 show the fractures at different places.

Each individual fracture seems to extend for almost 100 m, the width amounting to as mush as 20 cm near the middle. Some of the fractures are evidently old, having old fillings on their inside walls, which when loosing their support have caved in more or less. The remaining fracture fillings often indicate a divergence of 20 cm or so. The broadest fracture is about 70 cm wide of which nearly 50 cm constitute old filling. In the tillite the fracture planes frequently match accurately but a strike-slip or strike-dip movements can also be detected widely amounting to a few cm. The movement either vertical or horizontal seems be at random.

Immediately after the fracture system was discovered the meteorological office in charge of the seismometer network in Iceland was asked to look for earthquakes in this area. No such larger than 2 on Richter scale was observed but that is the lowest level of seismic activity they can detect in this part of the country with their set up of seismometers.

A portable micro earthquake station was therefore set up at Langalda in the beginning of May and also there were 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 good, hard tillite. While the lake was empty no movement could be observed, neither with the seismometer nor the glass plates.

Figure 4

The fracture where it disappears under the upstream toe of the dam.

Figure 5

The fracture at a place were it is rather wide. In the foreground there is an old fracture filling loosened from both walls but not collapsed. A small brook is flowing into the fracture.

THE REPAIR WORK

The repair of the dam was started on the 17th of May by pumping down into the fracture under the dam a mixture of sand and bentonite. At the latest stage a cement bentonite mix was used until the fractur was full. The repair of the dam amounted to 2500 $ in cost.

All the other fractures were filled with local material, mostly sand and moraine, packed with running water that was either pumped or one used the small inflow of water into the reservoir to do this. A suitable filter material was not found nearby and it was therefore too expensive to haul it in. But certainly a fracture should be filled with filter material as swallow holes are if the best results are to be obtained. About 300 m^3 of sand and moraine was used to fill up the fractures.

On the 10th of June the filling of the lake was started again and done slowly. Everything went well until 19th of June when the water depth in the lake was about 4 m a small leakage was observed from the fracture downstream of the dam. The lake was then emptied again and the water disappeared in 3 days. It was then seen, that a part of the fracture system had opened up again. The glass plates did indicate compression which amounted to a millimeter or more.

The next days were used to repair the fissures again and now a plasti sheet was placed above the fissures and filled over with sand. The repairs used 70 m^3 of sand. The filling of the lake was started again on the 25th of June and since then no observation has been possible because the lake bottom near the dam is always covered with water in summer but ice and snow in winter.

BEHAVIOUR OF FRACTURE AFTER REPAIR

Downstream of the dam the behaviour of the fracture has been studied. In 1971 nothing more happenen there but in the spring of 1972 the glass plates broke and the fracture was extended several tens of meters further downstream. No leakage due to this was observed. The widening of the fracture was about 3 mm. New glass plates were concreted across the fracture.

In 1973 some small movement was recorded; about 4-5 mm widening of the fracture in the spring and then contraction in the fall when lake level was falling. Small components of normal faulting and strike slip faults could be discerned. The result of these measurements are shown in fig. 6.

In 1974 the measurements were done by invar rod and measuring clock. The accuracy is very much increased and the movement was also much smaller but showed the same seasonal trend as in the previous year.

LATER FAULTS IN THE RESERVOIR

Several other faults did open in the Langölduveita lake bottom. The biggest one no. 2 on the map figure 7 opened up in September 1972. It extended about 100 m up on dry land and this made observation possible. Sudden increase in leakage recorded in continuous stage records in lake and inflow indicate that the fault was found 1 or 2 days after it was formed. These later faults were formed both in móberg and the postglacial lava. They are probably new in the postglacial lavas as old fracture fillings were not observed there. But in the móberg underneath these are certainly old faults in most cases. The faults no. 3, 4 and 5 were found when lake level was lowered in 1972 to repair swallow holes and to repair fault no. 2. At this time it was obvious that fault no. 1 was practically tight as the lake level did not go much below the lowest point of fracture no. 2 although no inflow was allowed for several days. Figure 8 shows fault no. 2.

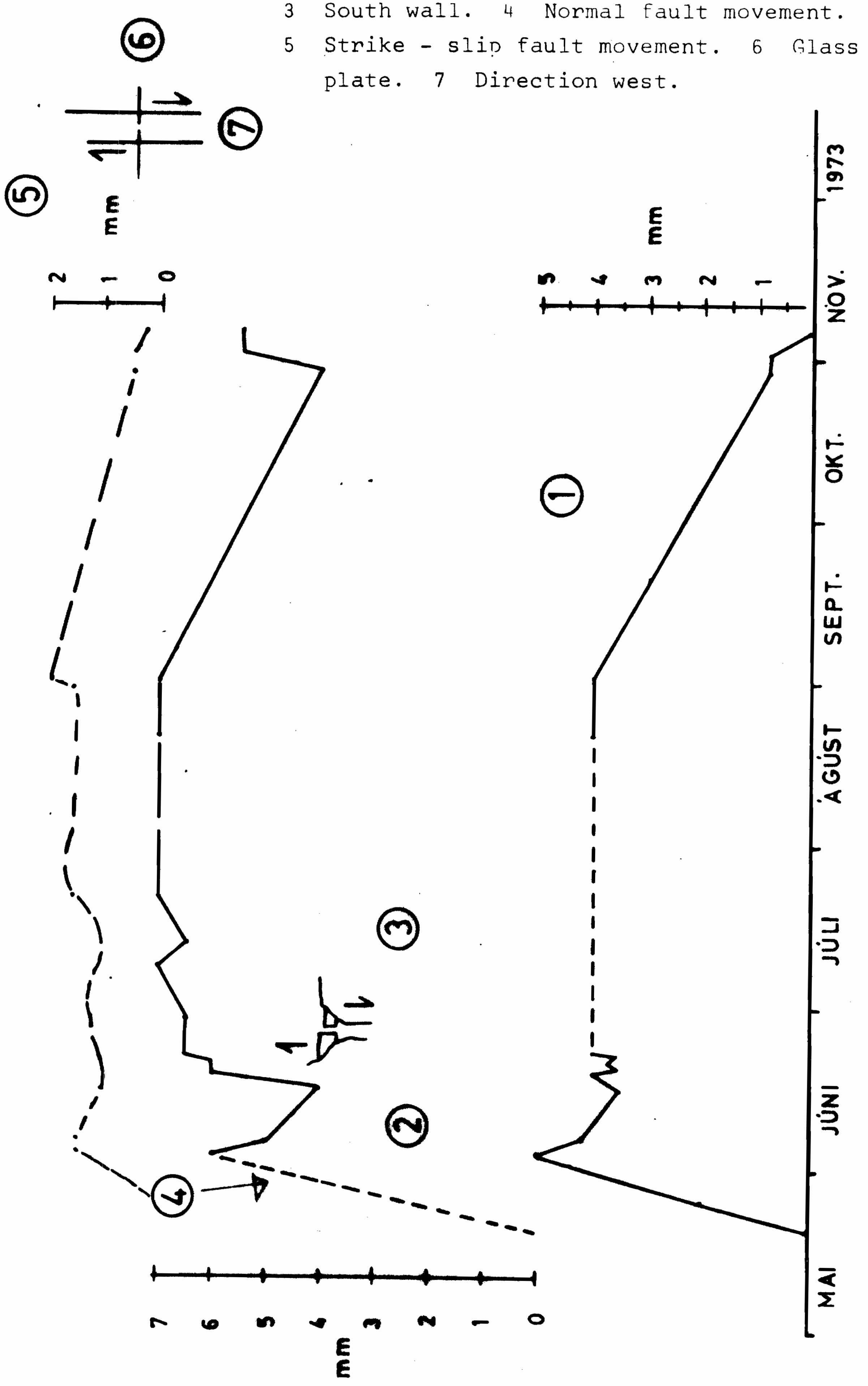
The other faults were repaired in similar manner as the first one, except we tried to use canvas as an artificial filter, to decrease the transport by lorries of filter material into the dry lake bottom, but that is very difficult due to the slippery silt layer. The results indicate that this is sound reasoning, although nylon filter would be stronger and more durable and should be used in actual practice. Absolutely impervious blankets such as plastic sheet can only be used with good results on solid rock, as piping does always occur along the edges of plastic sheets if placed on loose material. Pervious filter is recommended in order to minimize the dependence on the natural sealing process for decreasing the leakage.

Figure 6 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.



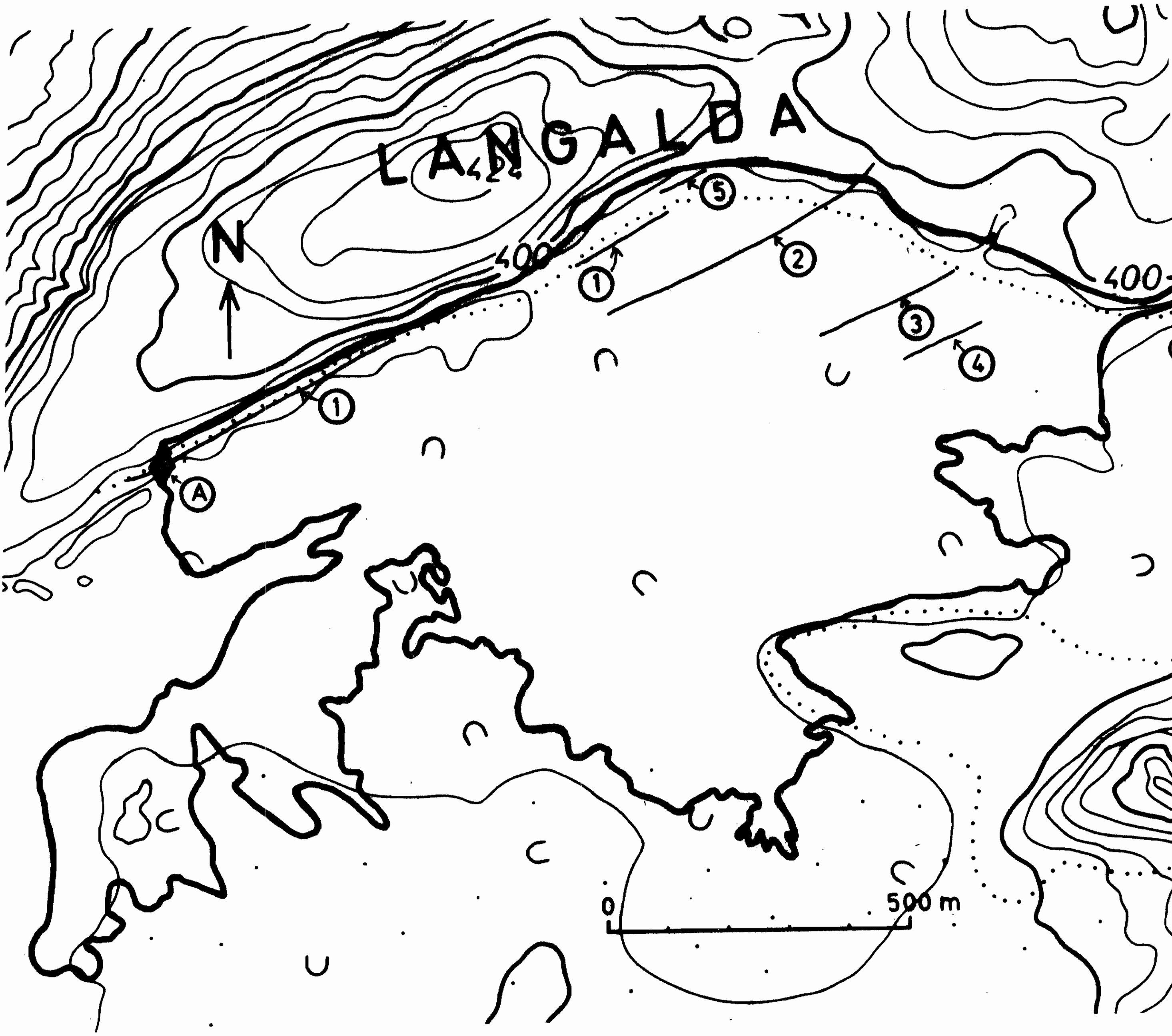
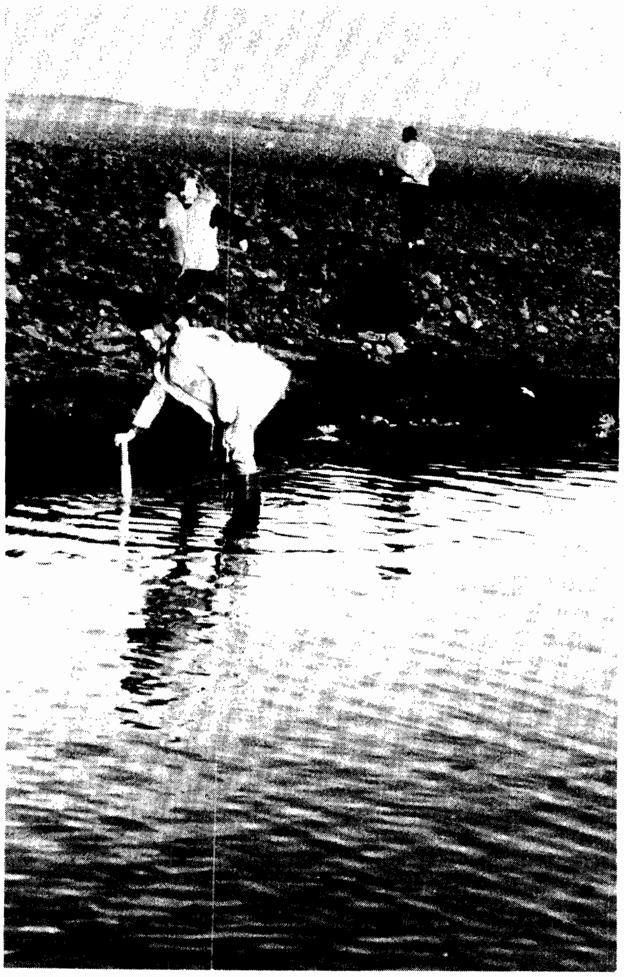


Figure 7

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.

Figure 8



The fracture which opened up in September 1972. Photograph taken where it extends up to dry land.

RESULTS OF INVESTIGATIONS

The micro-earthquake seismometer installed at Langalda, after the initial rifting, has since been in operation every now and then. In 1971 it showed occasionally very small movements and once an earthquake was actually heard by people on location just after the second emptying of the lake, These small quakes were 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 this movement should be classified as creep but not tectonic fracturing. Unfortunately the seismometer was not operating when fracture no. 2 opened up.

The area under consideration here is very close to the main volcanic zone in Iceland or about 20 km NE from the summit of the famous volcano Hekla and in fact the northenmost craters of the Hekla fissure shown on the geological map fig. 1, are only 1-2 km from the lake. About 10 km south east of the lake is one of Iceland´s most productive volcanic zones, where from the Tungná and Thjórsá lavas have originate The latter zone is with extensive normal faulting but without earthquakes recorded by the network of seismometers in the country. Hekla on the other hand is the easternmost part of a narrow east-west trending earthquake zone in southern Iceland stretching from Hekla to the Reykjanes peninsula. The earthquakes there have usually a strike-slip solution. In fig. 9 the earthquake zone is shown and the zone of normal faulting and its relation to Langalda.

It is worth mentioning here the theory of plate tectonics and continental drift. According to that theory the axis of the Mid Atlantic Ridge is the volcanic zone in Iceland and from there the drift is approximately 1 cm/year in each direction. The movement seems to occur without earthquakes in the areas where production of lava is highest in Iceland.

An explanation of our phenomena in the Langalda has to take into account all these geological facts. The reason for the aseismic

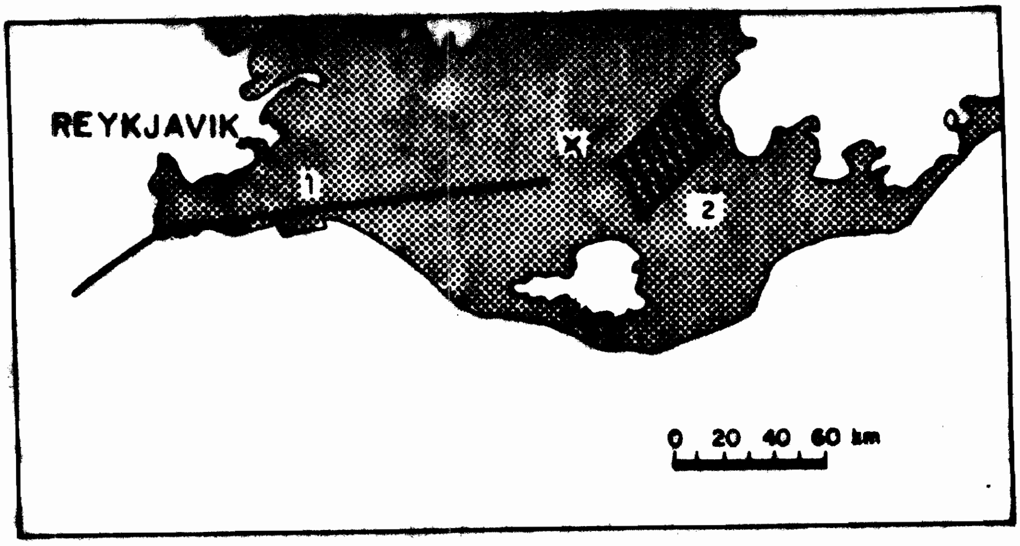


Figure 9

The map shows; 1 The line of seismic acitvity in Southern Iceland, 2 The zone of most productive volcanism and normal faulting. x the Langalda.

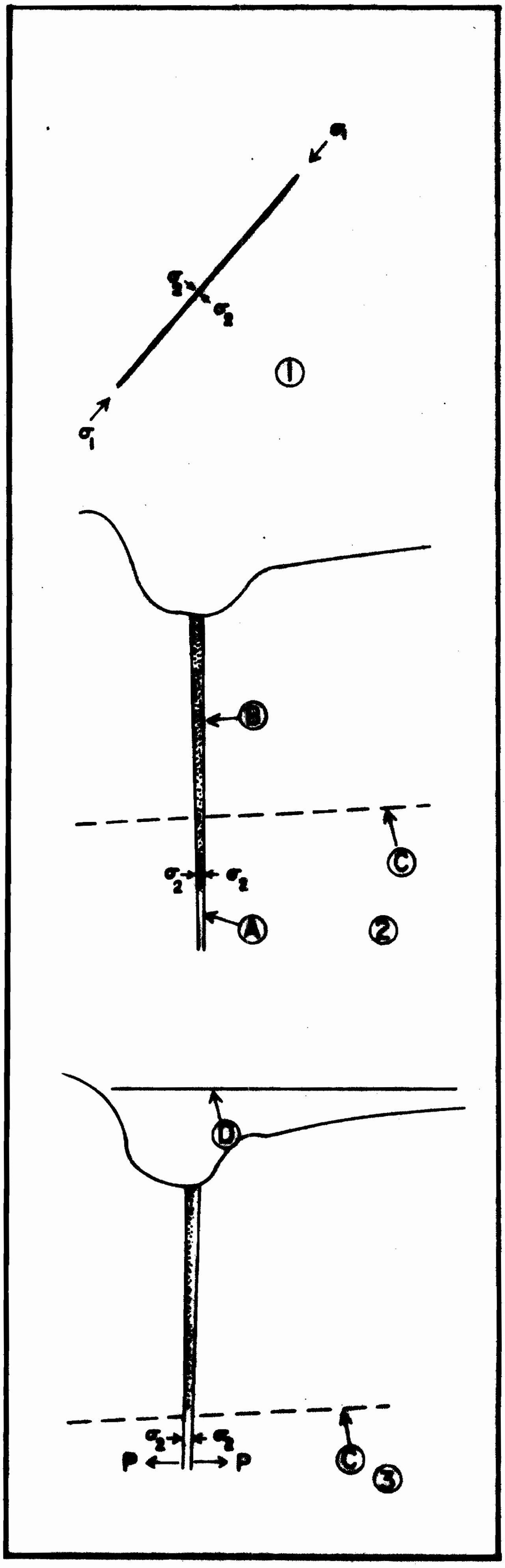
Figure 10

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.

Figure 10


σ_1
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P
P
③

character of this highly active zone is probably the weakness of the earth's crust in this area. Due to that it can not build up horizontal stresses high enough and all movement is more or less continuous and creeping.

However we have a horizontal stressfield. The lower principal stress is perpendicular to the rift axis, probably 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 phenomena like this. This happens at a very shallow depth or the uppermost few hundred meters or even less.

In fig. 10 there is an effort to explain this further. The fault has a lower principal horizontal stress perpendicular to the faultplane but higher principal stress along the faultplane. The fault is an old normal fault. At that time the lower stress was tension. The lower stress is still very small or of the order of magnitude 1-2 kp/cm^2. The geological condition is such that ground water 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 the contact is made with the lake the hydrostatic pressure at the faultplanes exceeds the horizontal stress and the fault opens up.

CONCLUDING REMARKS

It is likely that this can happen in any place where the same or similar geological conditions exist. At a few hydropower sites in Iceland this is the case. This does not necessary stop the construction on any otherwise good power site, as this can only occur during the first years after construction and can easily be repaired and at a low cost. But this 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 this type of geology.

Very few records exist of this phenomena in literature. Still there is one from New Zealand which I know of. This was the Arapuni hydroelectric scheme on the Waikato River discribed by William Furkert 1935. The problem there and the geological conditions seem to be identical to the one I have described here. In New Zealand they fought this problem for 4 years at an enormous cost. I would expect that their final victory was due to a new equilibrium in the ground between hydrostatic pressures and stress fields in the rock which, according to the experience at Langalda and Waikato, takes about 4 years.

Probably these two examples are not the only ones which have occurred but published data are lacking, perhaps due to pride of owners and consulting engineers who have kept quiet about it. There is however no reason for being quiet about this phenomena as it is not at all a death sentence for a project or an engineering firm and by right understanding of the facts we can avoid unnecessary hazards and panic decisions which cost a lot of money.

THE OPENING OF TECTONIC FRACTURES AT THE LANGALDA DAM

SUMMARY

The Langalda test reservoir was built in two stages in 1966 and 1969. The purpose was to test the self sealing capacity of the silty waters of the glacier fed river Tungná. In 1971 a great fracture opened under the main dam, a 10 m high earth dam, and extended about 1 km upstream and a few tens of meters downstream of the dam. In 1972 other fractures were found elsewere in the lake. The cost of repairing these fractures is relatively low. The explanation of this phenomena lies in the geological condition. 1) A very low horizontal stressfield perpendicular to the fracture which is an old normal fault. 2) Ground water level tens of meters below surface. The lake opens up the fault at the weakest point in the fracture fillings. The hydrostatic pressure inside the fracture then becomes higher than the horizontal stress perpendicular to fault planes and therefore opens up the fracture.