ORKUSTOFNUN
NATIONAL ENERGY AUTHORITY

THORODDSEN AND PARTNERS

ÞÓRISVATN
GEOLOGICAL REPORT

Volume I

by

Haukur Tómasson geologist NEA
Elsa G. Vilmundardóttir " "
Birgir Jónsson " "

Prepared for

LANDSVIRKJUN
THE NATIONAL POWER COMPANY

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CHAPTER 1

ÞÓRISVATN

1.1 Introduction.

Lake Þórisvatn is located in the southern central part of the Icelandic high plateau at 571 m elevation. The area dealt with in this report is 27 km long and 15 km wide. The center of it is the 70 km^2 Lake Þórisvatn. The lake is approximately 50 km by road from the nearest habitation, which now is the Búrfell Power Plant. Corresponding distance to Reykjavík is 180 km. See Exhibit 1.01.

Þórisvatn has for a long time been under consideration as a major storage reservoir for power plants on the main stem of Þjórsá and its tributary Tungná. Geological investigation, reconnaissance and subsurface exploration has been going on occasionally for more than a decade. This work has mostly been performed by Raforkumálastjóri (the State Electricity Authority) and its successor Orkustofnun (the National Energy Authority, NEA). During the last two years Landsvirkjun (the National Power Company) has been ordering and paying for the majority of the investigations although still performed by NEA personnel and tools and partly paid by it. Consulting civil engineers on the Þórisvatn projects have been Verkfræðistofa Sigurðar Thoroddsen sf (Thoroddsen and Partners) except in 1962 it was Harza Engineering Company International.

The present investigation has been carried out in cooperation with and under the supervision of Thoroddsen and Partners. On behalf of Landsvirkjun, Harza Engineering Company International has been informed of the progress of the work and several meetings have been held with the engineers and geologists of this firm, where the geology of the site and the investigation have been discussed.

In Þórisvatn a storage development from 200 Gl up to 2500 Gl has been under consideration, mainly by lowering the level of the lake but also possibly by some raising of it. The maximum drawdown cosidered is 40 m and the maximum rise of the lake level 10 m.

As a project site the Þórisvatn area can be divided into two categories, i.e. sites for outlet works and damsites. The outlet works under consideration are mainly at the southern shore usually called the Vatnsfell area, but also at the northwestern coast at Rjúpnadalur 15 km by track from Vatnsfell. The damsites are north of the lake 25-30 km by track from Vatnsfell. Also north of the lake is the site for diversion of the Kaldakvísl river into the lake. According to this there are three areas where the investigation has been especially concentrated. These are a) Vatnsfell area b) Rjúpnadalur c) Þórisós - Kaldakvísl damsites and diversion.

All around the lake geological reconnaissance has been undertaken, but subsurface exploration only at these three places. Reports dealing with the geology of the lake have been written by G. Kjartansson, the last one in 1959 in "Report to the State Electricity Authority on the geology at some sites for potential hydro-power developments in the Þjórsá and Hvítá river systems, Southern Iceland." In a report from the Harza Engineering Company on the Búrfell project from 1963 there is a chapter on the Þórisvatn geology together with results on subsurface exploration at an outlet structure proposed by them.

Subsurface exploration, drilling and geophysical work has been as follows:

1) In 1956, 6 core holes were drilled at the Þórisós damsite; total depth 134 m.

2) In 1959 electrical resistivity measurements in the Vatnsfell area west of Vatnsfell. The purpose was to map ground water surface.

3) In 1962 core drilling at the Þórisós-Kaldakvísl damsite; 6 holes 65 m total depth.

4) The same year borro sounding was done west of Vatnsfell; 36 holes, 230 m total length and 1 core drillhole 12 m deep.

5) In 1967 borro sounding in the Vatnsfell area east of Vatnsfell; 33 holes, total length 351 m.

6) In 1968 seismic sounding east and west of Vatnsfell.

7) In 1969, drilling was carried out as follows:
   a) At Þórisós 7 core drillholes, total length 151 m and 91 borro soundings 137 m long.
   b) At Rjúpnadalur 3 core drillholes 63 m long and 50 borro soundings on land, total length 201 m and 14 borro soundings on the lake, total length 76 m.
   c) At Vatnsfell 24 drillholes in rock, 1402 m total length, 25 borro soundings on the lake, total length 334 m. Borro soundings on land, 139 holes, total length 1100 m, and sampling of the bottom material of the lake, 15 holes, 22 m total length.
   d) 21 piezometers along the south and east shore of the lake, mainly in the Vatnsfell area, total length 491 m.

8) Seismic sounding in 1969 was carried out at Rjúpnadalur and at Vatnsfell, and in the lake at both places.

The total Þórisvatn drilling up to date is as follows at all three sites.

Rock and core drilling	46 holes	1827 m	total length
Borro sounding	374 holes	2353 m	total length
Piezometer driving	21 holes	491 m	total length.

Besides this subsurface exploration, the investigation in 1969 also included bulldozer trenches and ripping tests in all three areas. All drillholes but one were tested for permeability. Ground water and leakage studies have been undertaken by regular measurements in piezometers and drillholes and by measuring lake levels both in the three permanent lakes in the area and numerous temporary lakes which existed during and first after the spring thaw. Finally a diversion, Fitjavatnsveita, was made from Þórisvatn into a depression immediately west of Vatnsfell in order to measure the permeability of this depression.

Sampling and investigation of construction materials was undertaken in 1958. In 1969 it was done again and a test embankment made at Þórisós. The results of this investigation will not be included in this report, which is prepared for Landsvirkjun (The National Power Company, Iceland), and will include all other results so far available on the geology of the three project areas at Þórisvatn.

1.2 Geography.

Þórisvatn is situated on the very rim of a high plateau which generally is about and above 600 m elevation. Into the high plateau the valley of Kaldakvísl is cut, just west of the lake in a north-easterly direction. The valley is 200-300 m deep south-west of the lake, but north of it the valley becomes only the course of the river. Towards south the land dips away from the lake to the river Tungná, which flows in a north-westerly direction into the Kaldakvísl valley, where the two rivers meet. Between them, in the valley of Kaldakvísl, is Þóristungur at elevation 300-400 m. To the north and east of the lake the land is generally higher than the lake.

The lake is 109 m deep and is surrounded by ridges and low hills which commonly rise 100-150 m above the high plateau. Along both the east and west coasts such ridges exist and another one, Útigönguhöfði, goes into the lake and divides it into two halves in its northern part, i.e. Austurbotn and the main lake. The ridges run from north-east to south-west which is the trend of most landscape forms here. The south coast is bordered in the eastern part by rather high hills, Vatnsfell and the hills east of it. But west of Vatnsfell the border of the lake is rather low with two passes only 10-15 m above lake level. The Rjúpnadalur pass on the west coast is also only 15 m high.

North of the lake and west of Útigönguhöfði there is a continuation of the high plateau towards north with little relief. In this area is the outlet of the lake along the northern end of the ridge bordering the west coast. The outlet, Þórisós, flows into Kaldakvísl.

Surface drainage into Þórisvatn is only in the easternmost Austurbotn where numerous springs flow into the lake itself and into a pond just east of the lake. The only river flowing into the lake is between this pond and the lake. Springs are also known to exist in the northern end of the lake west of Útigönguhöfði, but issue there below lake level.

West and south of the lake, along Tungná and in the valley of Kaldakvísl, especially in Þóristungur, numerous springs issue. These springs must have the same drainage area as the lake and are partly fed by leakage from it. The drainage area of the outlet river, Þórisós, has been estimated 330 km^2, but due to the fact that all drainage is underground the real size of it and the meaning of the term drainage area is in this case very uncertain.

Vegetation in the area is very sparse and east and north of the lake, there is absolutely no vegetation. Rock exposures are good along the lake, but east of it the rock is very often covered with tephra and west of it with moraine.

1.3 Stratigraphy

The Þórisvatn area is built up by volcanic products during the last two glacials, an interglacial in between, and postglacial time. On the geological map, Exhibit 1.02, the bedrock formations are shown. These formations are arranged according to age and products from many different eruptions are in most cases brought together. Petrographic uniformity is not used as a basis for this subdivision, but some of the formations are chemically rather uniform as far as the present investigation has shown. Outside the three project areas the investigation is of reconnaissance type but not detailed geologic mapping. Within the younger formations eruptive phases are used as a basis for subdivision more than anything else. The formations are subdivided into subglacial volcanism on one hand, and subaerial volcanism, mostly lava flows, on the other. The subglacial volcanism can be subdivided into near surface volcanism which partly is subaerial and produces tuffs and breccias, usually called móberg and volcanism under a thick glacier cover which does not melt through the ice and forms pillow lavas. Intermediate forms and products are also common. The products of the subglacial volcanism are the so called móberg formations. The age relationship between the móberg formations is often found on geomorphological basis. The older formations have more gentle forms and are more eroded and evened out by glaciers. The younger ones have much more rugged forms, steep narrow ridges or remnants of crater forms.

In chronological order the formations are as listed below.

1 Sauðafell Formation SFM
2 Ósöldur Formation ÓSM
3 Launöldur Formation LÖM
4 Harðhausar Andesite HHA
5 Kaldakvísl Grey Basalt KKG
6 Grasatangi Formation GTM
7 Trippagil Móberg Formation TGM
8 Útigönguhöfði Formation ÚHM
9 Þóristindur Pillow-lava Formation ÞTM
10 Vatnsfell Móberg Formation VFM
11 Tungná Lavas TH

The Sauðafell formation (SFM) is a móberg formation from the second last glaciation. It is only in contact with the project at the lower damsite at Kaldakvísl-Þórisós where it consists mostly of móberg breccia.

The Ósöldur formation (ÓSM) forms the rim of Þórisvatn from Þórisós to Rjúpnadalur. It consists of móberg, both tuff, breccia and pillow lava. The uppermost parts of it are mostly tuff and so is also the case at Rjúpnadalur. Near Þórisós it is mostly breccia or even pillow lava. The contact between Ósöldur formation and Sauðafell formation is indistinct and the age relationship too. As yet petrographical examination has not been done. The Ósöldur formation is formed in several eruptions.

The Launöldur formation makes up the rim of Þórisvatn from Rjúpnadalur to Snoðnafit. Along the lake this formation is rather uniform as it is built up of pillow lavas of feldsparporphyritic basalt. Further away it has not been examined. From the drilling in Rjúpnadalur it is rather obvious that it is younger than the Ósöldur móberg and very likely older than the Harðhausar andesite. The contact with the next younger móberg formation is as yet only a qualified guess.

The three formations now metnioned have all been formed by subglacial volcanism during the last but one glaciation. The eruption centers have been within the present distribution of these formations; most likely in fissures situated where the hills are highest now. The following two formations are lava flows from craters outside the project areas. These formations flowed along valleys on each side of the ridges that these móberg formations had created.

On the eastern side of these ridges there are andesitic or even more acid lava flows. These are termed the Harðhausar andesite formation, HHA. It is found along Þórisvatn at Ósöldur and north of Þórisós and along Kaldakvísl. It rests on Sauðafell móberg at Kaldakvísl and on Ósöldur móberg at Þórisvatn. The rock is very fine grained and with a strong laminar flow banding. There must be at least 3 or 4 flows within the project areas. Dip and strike is very difficult to find out and in any case the dip is very small. The flow at Harðhausar is the thickest one, at least 20-30 m thick and is probably the most acid of them all. It is possible that andesitic lavas have flowed through passes between móberg ridges at Kaldakvísl or Rjúpnadalur to the western side of the ridges. Still, it has not been observed by the present authors.

On the western side of the móberg ridges, lavas made of coarse olivine basalt (grey basalt) have flowed down the present valley of Kaldakvísl. These have been many thin flows, each of them only a few meters thick. A good outcrop for showing the age relationship between the Ósöldur móberg and the Kaldakvísl grey basalt has not been found and neither is there any known section with both andesite and grey basalt. But from the young appearance of it and on a morphological basis the conclusion drawn is that the dolerite is younger than the móberg east of it. It is probably from craters lying in a northerly direction and flows into the valley of Kaldakvísl near the confluence of Kaldakvísl and Þórisós.

The Grasatangi formation (GTM) consists of móberg, pillow lava and tuffs from many different eruptions. Within the Grasatangi formation is the Sigalda móberg at Tungná. This formation is south of Þórisvatn and is from the last glaciation; probably from the first half of it. The contact with the Launöldur formation is indistinct but towards east it is clearly overlain by the Vatnsfell formation. The Grasatangi formation forms the rim of Þórisvatn along half of the south coast. The formation is in many places strongly evened by glacial erosion like the Launöldur formation.

The Trippagil móberg formation is at Kaldakvísl and is underlain by the Kaldakvísl grey basalt. It is mostly móberg and on a morphological basis it is concluded that it must be from the latter half of the last glaciation.

The Útigönguhöfði formation consists mostly of pillow lava which forms the majority of Útigönguhöfði northeast of the lake. It looks rather young but is definitely older than the Vatnsfell formation which rests on it.

The Þóristindur pillow lava formation and the Vatnsfell móberg formation are both formed very late during the last glaciation. The difference between them is that the Þóristindur formation is mostly pillow lava but Vatnsfell is a móberg formation, mostly breccias and tuffs. The Þóristindur pillow lava formation is formed in rather quiet eruptions under a thick ice cover; the eruptive products heaped up above the vents and formed in that way the narrow ridges so characteristic of this formation. It has not been much affected by glacial erosion which strongly indicates its youth. The ridges are strictly parallel to the postglacial volcanoes in the vicinity and the postglacial graben tectonics in the formation, and especially to the east of it. The Þóristundur pillow lava formation forms the rim of Þórsvatn at the eastern part of Austurbotn where the lake is fed by numerous springs. The formation is in contact with the project site at Blautukvíslarbotnar and eventually in some parts of the project site on tunnel and canal routes east of Vatnsfell.

The Vatnsfell móberg formation forms the rim of Þórisvatn along most of the eastern and half the southern coast and it also forms the western coast of Austurbotn. It is mostly formed in phreatic eruptions, causing the formation to be mostly móberg tuffs and breccias. Eruptions have been taking place in this formation until the margin of the retreating glacier was only 5-10 km away. The volcanic activity extended into postglacial time within the area of this formation and the Þóristindur pillow lava formation. The topography of the Vatnsfell móberg formation is extremely irregular. Although the north-easterly trend of the formation as a unit is obvious the smaller topographical forms are irregular in their orientations. These forms are both hills and depressions. The reason for this irregular topography is that it is formed by eruptions along elliptically shaped fractures of a caldera subsidence in the south-east corner of Þórisvatn. Most of the depressions are actually craters where from there are frequently radially oriented small faults. Bordering the outermost rim of the caldera, in a semicircle from south to east, there are hills with soft surface forms. These are mainly built up of pillow lava and badly consolidated tuffaceous sand. Genetically they can be compared with lava flows in having been issued in a molten state from the nearby craters. The craters are also filled with almost unconsolidated sandy material. The Vatnsfell formation is mostly rather fine grained basalt with few feldspar phenocrysts and practically no olivine. The latest eruption in the formation was, however, very much different mineralogically as the magna was extremely rich in olivine and feldspar phenocrysts. This eruption built up the mountain Brandur, which is made of thin-bedded tuff with pisolites, that is to a considerable extent made of crystals of these two types of minerals. Brandur is situated on the Brandur graben, which has been active in postglacial time, and all its volcanic products are of the feldspar-olivine porphyritic type, the same as the Tungná Lavas TH. The same kind of material forms sandy deposits in the valley of Kaldakvísl where it forms considerable terraces. Both upstream and downstream from these deposits the land surface is obviously water eroded, a sort of scabland, which indicates that the terraces were deposited by a great flood. The flood was by all evidence a glacier burst formed by the meltwater formed during the Brandur eruption. At that time the margin of the glacier has been near the Þórisós-Kaldakvísl confluence and at the Ósöldur and Launöldur hills.

In postglacial time, which in our case is 8-9000 years, the volcanism has been going on in the immediate vicinity of Þórisvatn. In this volcanism, which mainly has come through fissures 5-10 km to the east of the lake, enormous quantities of lava have been produced in at least 10 big eruptions during 6.000 years of the postglacial time. Enormous quantities of tephra have also been produced in some of the eruptions which party have been carried over the lake and the formations east of it. The common name for the lavaflows is Tungná lava flows (TH) and among them is one that flowed all the way to the sea and forms the coast between the eastuaries of the rivers Þjórsá and Ölfusá, the two largest rivers in Iceland.

All the Tungná lavas are feldspar porphyritic and also contain some olivine occurring as big phenocrysts. It resembles in that way the eruption products from Brandur.

Two or three Tungná lava flows have flowed into Þórisvatn at the northeastern coast and each time raised the lake level. At least one of the lavas flowed down into the valley of Kaldakvísl. The youngest of the flows is just younger than the ash layer H_4 on which it rests or about 4.000 years old. It is on the damsite at Þórisós. At the northern coast of the lake there are numerous springs issuing from the flow and also into the Þórisós river.

1.4 Superficial Deposits

Loose materials or overburden are of various origin; glacial, alluvial, lacustrine, eolian and directly volcanic, i.e. tephra. At many places these deposits form thick beds, up to several tens of meters thick. On the map in Exhibit 1.03 are shown the types of loose materials covering the bedrock and generally reaching several meters in thickness.

The moraine is covering the old móberg formation west of the lake. It is especially continuous at Launöldur and in the lower slopes of Ósöldur og Sauðafell. The moraine is usually quite loose down to 1.5 m depth and there often mixed with sand and ash. Below this it is usually too hard for digging but can easily be ripped by a bulldozer at least a few meters further down. The lower part of the moraine can be hard like rock. At Grasatangi formation, moraine cover is widely found, but seems to be thin and is totally lacking at many places. In the Vatnsfell and Þóristindur formations typical moraine is not found, but the surface of the formation is often reworked by the glacier to form a hard and dense crust. On pillow lava this crust can have the color of tillite but on tuffaceous material it has the same color as the tuff. This crust we term pseudomóberg.

As already stated in the stratigraphy chapter there are deposits in the valley of Kaldakvísl with identical petrographic composition as the tuff in Brandur. These deposits are interpreted as glacier burst deposits. On the map, Exh. 1.03 the probable route or routes of the flood under the ice cover are shown but the probable ice margin at this time has been along the hills west of Þórisvatn. These deposits are mostly sand and are deposited in terraces which resemble very much shore line terraces of a lake. The depositional area has also been a sort of a lake at elevation approximately 525 m at the upper end, but the treshold downstream is 510-515 m in the present form. Upstream from the deposits, large blocks of rock are scattered over bare rock and there are also channels eroded into the bedrock which in this case is the Kaldakvísl grey basalt. Such land is termed scabland in Western U.S.A. At the downstream end there is also bare rock and dry channels along the Trippagil móberg. The size of this flood is estimated 10-20.000 m^3/sec at the maximum discharge.

All depressions in the area have a thick cover of sandy material. This sand is partly postglacial windborne volcanic ash but in the Vatnsfell móberg formation this is also formed subglacially. The subglacial sand is sometimes rather hard and can in some cases reach many tens of meters in thickness. The top layer is always postglacial and has also considerable thickness although not much compared with the former.

At the lake we have considerable quantities of beach deposits, which consist mostly of sand with gravel mixtures in the zone of strongest wave action. Movement of this beach sand is very rapid. It has also formed many types of bars and tombolos. In the lake there must be enormous quantities of sediments. From grain size distribution and topography of the bottom, there is an indication of two submerged shorelines at approximately 6 and 12 m depth. In this reach, from 15 m to the present lake level, the bottom has at one time or another been under wave action. This causes the lake deposits to consist of sandy or gravelly material down to 15 m depth. The gravel content depends on the coast material. The sand is mostly volcanic ash or derived from the material which makes up the bedrock at the coast. At 15 m depth, substantial mixing with diatomaceous earth starts, which at 30 m depth is a considerable part of the material, but the rest is ash. For grain size of the bottom material see Exhibit 2.03.

At some places along Kaldakvísl some alluvial deposits formed under the present conditions are found. This is material with higly varying grain size and usually ranging from sand to gravel and cobbles. The mineralogical composition is also mixed, although basalt is predominant but andesite and rhyolite are also common.

The source of most of the volcanic ejecta in the area, which makes up thick layers in depressions and in the lake, is the volcanic fissure belt just east of Þórisvatn at Vatnaöldur and Heljargjá. From there ash and pumice has been airborne during the eruptions into the area and then redeposited due to wind and water action in the depressions. As can be expected the majority of the ash and pumice is found at or near the craters in the active fissure belt where it forms thick deposits. Because of this most of the flat land and lava flows are totally covered with this material. Also after the eruptions materials are brought long distances by the wind and create the base material for the windblown sand everywhere present in the area. Although rather coarse at the craters the grain size of this material is often down to that of dune sand or even smaller at the river Tungná and west of Þórisvatn.

1.5 Tectonics

The regional tectonics in the Þórisvatn area are shown on the geological map, Exh. 1.02. Most common are systems of normal faults with NE-SW direction. These faults are often graben walls and are most prominent in the volcanic belt east of Þórisvatn, where crater rows are usually connected with the grabens. The ridges formed in subglacial eruptions have the same direction and are piled up above fissures in the same way as the postglacial crater rows are in the grabens. One small graben is within the project area at Vatnsfell, the so called Brandur graben which extends from south of Fellsendavötn in northwesterly direction towards Brandur. The width of the graben is 200-400 m and the dislocation varies from approximately 2 to 15 m. In the Brandur graben tiny eruptions have taken place in postglacial time. The biggest flow from these eruptions is shown on the maps in Exh. 1.01 and 3.01 between Fellsendavötn. The dislocation in the main postglacial graben systems the Heljargjá and Veiðivötn systems, is commonly 5-20 m. The graben tectonics have probably been active all through the postglacial time but there seems to have been a maximum of this activity 5.000-2.000 years before the present.

In the older formations west of Þórisvatn, faults are also observed although much less frequent than east of the lake. There are also some graben tectonics with the same direction as east of the lake or slightly more northerly. In that area there is also a more easterly system. That system is observed at Búrfell to be primarily strike-slip faults and it becomes more prominent in still older formations. The total dislocation of the faults in this area, at least in postglacial time, is not more than a couple of meters. The age of the movement as we observe it is probably mostly finiglacial and early postglacial. At least the lava flow at Þórisós is not cut by any of these faults although it is 4.000 years old.

The most peculiar structures in the area are in the Vatnsfell móberg formation and on a smaller scale at Grasatangi. In both these places elliptically shaped subsidence seems to be present. At Vatnsfell there are concentric fractures, most of them acting as feeders for magna. But the southeastern corner of the lake is formed by subsidence. Also at Vatnsfell there are fractures radially arranged out from the supposed craters. Dislocation at these fractures is always small but in the case of the concentric fractures the dislocation is not known,as they are more or less masked by the craters, but total dislocation from the outermost fracture to the lake may well be 100 m or more. The Vatnsfell caldera is about 3,5 km wide and 7 km long. The direction of the long axis is a little more easterly than that of the Brandur Graben.

The Grasatangi caldera is much smaller and volcanic activity has not been associated with it during late glacial time. It is approximately 1.2 km wide and 2.4 km long.

Such calderas as described here have not been observed in Iceland in connection with basic volcanism only but are common for acid and mixed acid and basic volcanism. On the other hand there may have been some acid volcanism in the Þórisvatn area earlier, although we have not yet found any trace of this. These acid products could be either in the lake or buried under the deposits filling the caldera, which ususlly are basaltic. This may be comparable to the Grímsvötn area in Vatnajökull which is a subsidence area only with basic volcanism at the present.

1.6 Geologic History and Geomorphology

The geologic history of the Þórisvatn area is marked by a continual drift of the active volcanic belt towards east. This drift of the volcanic belt is by many authors interpreted as continental drift; the volcanic belt then is stationary but the land drifts away from it to both sides. But in the center a new land is formed.

It is apparent, that the volcanic belt was most active west of Þórisvatn during the last but one glaciation which probably is the same as the Illionoian in the United States or Riss in the Alps. This glaciation took place about 300.000 years ago according to some authors. The rock is definitely younger than 700.000 years as it belongs to the Brunhes magnetic epoch, i.e. the present one, that has lasted that long. The subglacial volcanism had a strong tendency to build northeast-southwest trending ridges or mountains with valleys in between. This was the situation after the Illinoian glaciation, during the Sangamon or the Riss-Würm interglacial. Along the present valley of Kaldakvísl a much smaller river was flowing as the Sauðafell-Ósöldur-Launöldur was a water divide and most of the present drainage to Kaldakvísl was towards the valley east of this water divide where Þórisvatn is now. In that valley the major river in this area may have been flowing. As in post-glacial time the valleys were partly filled by lava flows. The flows came from a northerly or northeasterly direction. The acid and intermediate flows in the easternmost valley may have been from a rhyolitic massif in the Hágöngur area, 35 km towards the northeast, but more likely they originated much closer to Þórisvatn and even within the present basin of Þórisvatn. The coarse olivine basalt (grey basalt) on the western side is from some still unknown source.

As previously stated, it is quite possible that during this inter-glacial some volcanic activity was going on in the Þórisvatn basin but during the last glaciation it is obvious that the main volcanism took place there. The last glaciation started some 70.000 years ago and lasted until 9-10.000 years ago in this area. Many warmer interstadials are within the last Wisconsin or Würm glaciation. But whether the Þórisvatn area became icefree during these interstadials is not known but no deposits are known which are likely to be from these interstadials. The volcanism during the Wisconsin glaciation has been especially active south of Þórisvatn. Because of this, the valley, previously existing there, became closed towards the south and the lake basin was formed which subsequently was occupied by the lake in postglacial time. The forming of the lake basin has been in two steps. First the western part of the rim was formed by the Grasatangi formation. This took place during the first half of the last glaciation. Late during the last glacial the Vatnsfell móberg formation was formed, associated with or following a caldera subsidence in the southeast corner of the lake basin. This built up the southern rim of the basin, so it became higher than a col into the valley of Kaldakvísl, where the outlet of the lake is now. Late during the last glacial the most active volcanic belt has been just east of the lake and along the eastern coast. The last eruption there took place a few hundred years before deglaciation of the lake basin. The deglaciation took place 9-10.000 years ago and the glacier seems to have retreated in an easterly direction, or towards the present Vatnajökull. South of Þórisvatn the glacier may have retreated to the present Torfajökull area. When the above mentioned eruption in Brandur took place the glacier margin was in the valley of Kaldakvísl near the confluence of Þórisós-Kaldakvísl and from there it followed the hills along the western coast of Þórisvatn. The eruption has probably taken place beneath some 300 m thick ice and melted through the ice and mostly been a phreatic eruption. The eruption caused an enormous glacier burst which sculptured the valley of Kaldakvísl to a considerable extent, both through erosion and deposits which mostly are eruption materials.

The Brandur graben has also been active during postglacial time as on the continuation of it towards northeast and southwest there are postglacial craters and lava flows. Two or three flows from this graben north of the lake have flowed into the outlet and raised the elevation of the lake. The rise of the lake level has been in two stages: First from 12 m lower up to 6 m lower than the present lake level. Then, after a considerable time, it was raised by 6 m, up to the present level. The youngest flow which dammed up Þórisós is approximately 4.000 years old.

The postglacial time has otherwise been marked by enormous eruptions only a short distance east of the lake where the big lava flows, the Tungná lavas, were issued in the least 10 eruptions. In this volcanism, big ash eruptions have also taken place and graben tectonics too. During the geologic history of the Þórisvatn area which extends over a period of 300-400.000 years or so, the volcanic belt has moved 15-20 km, i.e. if this reflects continental drift, the movement of the crust has been of the order of 5 cm per year towards northwest.

CHAPTER 2

GROUND WATER AND LEAKAGE

2.1 Model of Ground Water Flow and Water Balance

Geologic engineering in connection with Þórisvatn as a storage reservoir for power plants in the rivers Þjórsá and Tungná is mainly concerned with ground water and leakage. Exhibit 2.01 shows the main characteristics of ground water flow around the lake. As we are here mostly dealing with very permeable formations, the móberg formations from the last glacial and postglacial lava flows, they consequently form very good aquifers. We are therefore dealing with large ground water streams, one of which flows along Þórisvatn, i.e. in the móberg areas east of it feeding the lake with an unknown quantity of water while also feeding springs in Blautukvíslarbotnar, the Sigalda reach of Tungná and in Þóristungur. Springs in these areas are known to be 8 kl/sec upstream from Sigalda, 10 kl/sec at Sigalda and downstream from it and 8 kl/sec in Þóristungur. Thus this aquifer and the ones in the lavafields south of Tungná issue altogether 26 kl/sec. But it is not known whether this is all the water carried by this aquifer. Quite possibly, a considerable quantity is carried further and more than half of the 10 kl/sec at Sigalda may stem from the lava fields there. Anyway, we are dealing wtih an aquifer carrying water of the order of 20 kl/sec in this area.

The other aquifer is in the lava fields north of Þórisvatn. It feeds the lake while also yielding about 10 kl/sec of ground water into Þóriós and Kaldakvísl.

Lake Þórisvatn is fed from three sources: a) inflow of ground water; b) precipitation on the lake; c) snowmelt from the surrounding hills. Water is released from the lake in three ways: a) surface runoff through Þórisós, b) leakage into ground water and c) small amount by evaporation. The balance between these factors and the quantity of water in the aquifers is of utmost importance for the design of the lake reservoir. Unfortunately most of these factors are not known with any degree of accuracy. However, an analysis of this will be attempted.

Inflow of ground water occurs at the northeastern coast as shown in Exh. 2.01. The quantity is not known and is in fact very difficult or impossible to survey. The only discharge measurement done was in the river at Austurbotn which has a discharge of 2.35 kl/sec. Certainly this only accounts for a part of the inflow; it must be several times greater. A fair estimate would be 10 kl/sec.

Precipitation on the lake probably amounts to 2-4 kl/sec as the estimated precipitation is between 1000-2000 mm a year. Total inflow can therefore be estimated 15 kl/sec. The inflow caused by snow melt on frozen ground during spring thaws and occasional winter thaws can amount to 1-2 kl/sec.

The only outlet of the lake is Þórisós with a summer discharge of 5-6 kl/sec, while in winter the outlet is often blocked by ice and snow. The rest of the incoming water, which may be as much as 10 kl/sec, is lost by leakage.

What has been stated here about ground water flow, inflow to the lake and leakage is primarily considered as a model, but as most values are estimated and can not be measured, the actual values may be considerably off. But still the model is the same, even if we have an error of factor 2 in most of these estimates. An error bigger than that is not probable and an error so big is not even possible in some of the estimates.

At Orkustofnun an investigation is under way to get a better qualitative and even quantitative picture of this model. This investigation will not be treated in this report and a good estimate is not to be expected until after the first draw-down cycle of the lake.

2.2 Leakage from the Lake.

Exhibit 2.01 shows the three areas, where most of the leakage from the lake is supposed to take place. Some minor leakage may also occur along the western coast and in the Vatnsfell area to the south.

The relative importance of the three leakage areas is not known but most important for the design of the reservoir, is the leakage at area No 3 as compared to the other two. Leakage area No 3 is at a lava front and the water goes into a lava aquifer, which has a very high permeability. The k value is of the order of 10^{0}-10^{1} cm/sec. A factor to decrease leakage is low ground water gradient or of the order of 0.2 per cent. With the low gradient and the above mentioned k values and a 20.000 m^2 cross-sectional area of the lava aquifer, which is a reasonable figure, the leakage here would be between 0.4-4 m^3/sec.

This leakage and the water flowing in the lava aquifer north of Þórisvatn can easily be diverted into the lake by an impervious cut-off through the lava at the Þórisós damsite. This would secure an inflow into the lake of at least 10 m^3/sec from this aquifer.

It is possible that a dam at Þórisós, although absolutely necessary in the long run, will be put aside in the initial storage development. In the latter case the magnitude of the inflow into Þórisvatn will remain unknown. However it is easy to predict what qualitative effect a drawdown of the lake would have on the leakage and inflow to the lake from the lava aquifer. The leakage would decrease with drawdown and the inflow increase. With no sublava water divide between the water entering the lake and that flowing in the aquifer downstream from the lake, all water will enter the lake at a level equal to the sublava threshold. The most probable level of the threshold is at 558 m elevation. With sublava water divide, leakage would be diminished to zero at the threshold elevation of the lake level, but inflow from the aquifer would in most cases increase but the quantity would depend on the shape of the sublava landscape north of the lake.

An estimate of increased available discharge from this source into Þórisvatn due to drawdown would be conservative if a linear relationship is assumed from zero at the present lake level to 10 m^3/sec (in case of no sublava water divide) at threshold elevation. In reality this is not a linear relationship but rather a parabolic or a hyperbolic one with the fastest increase at the beginning of the drawdown.

In the above speculation, we have only been dealing with a steady flow of ground water. Bank storage, which certainly is considerable, will not be dealt with here.

Elsewhere on the shores of the lake the leakage has been studied through piezometers and drillholes. Table 2.1 shows location and depth of the piezometers, and Table 2.3 shows elevation of the ground water table in drillholes and piezometers. From the results of these studies we base the division of the lake shores into the two additional leakage areas. The rest of the lake shores is considered as not leaking. At many places there are sandy beaches at the lake and the sand often fills depressions behind the beach. At those places piezometers have been put down to observe whether the ground water in the sand, saturated by lake water, is dipping away from the lake or not. When the ground water in the sand is dipping away, the rock behind the sand must be as permeable or even more permeable than the sand. If it is not dipping away the permeability of the rock is less than that of the sand. In Exhibit 2.02 the result of this investigation is shown. The distance from lake shore to piezometer or drillhole is plotted against the elevation of the ground water table. It is obvious that all the sandy bays at the southern and eastern coast are leaking while along the western coast and the rocky coast in the Vatnsfell area, this is not so.

For an investigation of the sand on the beaches, samples were taken at some places and grain size curves were made. A hole was also drilled through the sediments at the beach and furthermore they have been studied through sampling in the lake at various depths. The result of this sampling and that from drillhole VF-11 on the beach are shown in Exhibit 2.03, where the amount of material with grain size smaller than 0.06 mm and with grain size smaller than 0.2 mm is shown. These two grain size values indicate the permeability of the sediments. There is a good agreement between the drillhole and the bottom of the lake. In the drillhole the material is much coarser as should be expected as there is only about 30 m distance between the hole and a precipitous rock wall.

In the Vatnsfell area there are numerous depressions without surface drainage and most of them do not have any permanent lakes either. All the depressions are also without surface or ground water inflow. These depressions have been used for leakage studies which can be of much value as the depressions are in the same geological formations as the southern and eastern coasts of Þórisvatn. In all these depressions, lakes were formed during the spring thaw, but they ususally disappeared a few weeks after all snow had melted. In two cases lakes existed all the summer and one of them is not known to have ever dried out. This one is Stóra Fellsendavatn, which proved to be 13 m deep.

Lake levels were surveyed in these depressions after the spring thaw, usually once a day. In the permanent lakes the surveying was done once a week after the lake level fluctuations had become stabilized and were very slow. The water marks, where the lake levels were surveyed, are designated VH-3 to VH-10. In the same depressions there are also piezometers designated P-3 to P-10. Table 2.2 shows elevation of water levels in permanent and temporary lakes.

In most cases the water was leaking at a steady rate unaffected by water depth. On the other hand, the leakage rate is dependent on the depth to piezometer ground water as can be seen in Exh. 2.04. The piezometer level is a perched ground water level in these depressions. It comes out on the graph in Exh. 2.04, that the rate of leakage is also dependent on the difference in piezometer level and bedrock ground water level. The observed permeability is in the range of 0.5-2.0 $m^3/sec/km^2$. See also Exh. 2.05.

In the two permanent lakes and in VH-4 the condition is different as here we are dealing with saturated soil or at least much more saturated soil than in the other case. Ground water gradient away from the lakes is also observable and grain size curves of bottom materials are also partly available. The actual leakage can be estimated fairly accurately as both precipitation and lowering of the lakes is observed. The measured precipitation may be somewhat off, as most of the rain falls in strong wind which may cause the measured precipitation to be lower than the actual one. No attempt has been made to estimate the effect of the wind. The available grain size curves are not from the bottom of the lakes as they were in late summer but from the area which was under water at Stóra Fellsendavatn in the spring thaw. On the other hand the gradient is measured in late summer. But still an attempt is made to calculate a proportionality factor C for the permeability dependance on grain size of the material. This calculation is based on Slighter's experiments on ground water flow in soils. The shape factor in Slighter's formula is replaced by the ground water gradient. The formula as used here is

$$q = C \cdot d^2 \cdot i$$

where q is the leakage in $kl/sec/km^2$; C the constant, d the mean diameter of soil grains in mm, taken as d-50 on the grain size curve and i is the ground water gradient. Of this we have q and d observed and i estimated for the condition immediately after the spring thaw, but q and i observed and d estimated for the condition in late summer, both in Stóra Fellsendavatn and in Litla Fellsendavatn. C is therefore fairly well established with an estimated maximum error of factor 2 up or down. As we have grain size of bottom material of the lake and also at one place, VF-11, a section through the sediments of the lake, we can attempt a calculation of the leakage through the sediments. The results of this calculation, which is based on a hydraulic gradient of 2 per cent for both hole and bottom material, is shown in Exhibit 2.06. It is obvious that most of the leakage is at the beach itself and down to one or two meters depth. From 2 m depth to approximately 15 m it is about 50 $l/sec/km^2$, but below 15 m the leakage is less than 10 $l/sec/km^2$ and even down to 1 $l/sec/km^2$. We can therefore conclude that below 15 m depth the reservoir is tight, between 15 m and 2 m the total leakage is between 50-200 l/sec but the rest of the leakage occurs in the very narrow zone of intense wave action. A calculated figure would result in 750-3000 l/sec of which half takes place west of Vatnsfell in leakage area 2 and the other half occurs in leakage area 1.

Along the western coast of Þórisvatn the bedrock is usually rather tight and also covered with moraine (Exh. 1.03). In the lake the moraine is now covered with sediments and is probably tighter than the sediments. However at some places the moraine has been washed away and the waves have even cut into the bedrock. South of Rjúpnadalur the bedrock is pillow lava which can have a fairly high permeability. At the promontories in this area, some leakage may be present directly into bedrock. North of Rjúpnadalur the bedrock is andesite and tuff which seems to be practically impervious. In this area leakage is for all practical purposes absent.

At Grasatangi the waves have cut into pillow lava and breccia, which is most likely highly permeable. In this area considerable leakage should be expected through the rock.

In the Vatnsfell area the bedrock is tighter than the sediments. There we can estimate leakage from a known ground water gradient and permeability as observed in drillholes. The total leakage according to that is 100 l/sec in this area.

At many of the promontories east of Flekavík the wave action has cut into rock. This rock is highly varying, but at some places it is pillow breccia which seems to be highly permeable. This pillow breccia must have considerable leakage and contribute to the leakage in leakage area 1. By a lowering of few meters, the rock will not be in contact with water any more. Therefore the rock leakage will not change the general picture that more than 90% of the leakage from areas 1 and 2 is restricted to the uppermost 2 or 3 meters.

The effect of raising the lake level has been studied by diverting water from the lake into a depression west of Vatnsfell. This diversion is named Fitjavatnsveita. The above mentioned studies in depressions in the Vatnsfell area do also give some valuable information in this respect. In Exhibits 2.07 and 2.08 a map of Fitjavatnsveita and the result of the experiments done last summer are shown. Table 2.4 shows the elevation of water levels and estimated inflow in Fitjavatnsveita. The depression there was occupied by a temporary lake during the spring thaw and the lowering of this lake is also shown. There is a big scatter of the points mainly due to uncertainity on the inflow figure as measurements were done only once a day, but very rapid changes in inflow could occur due to changes at the beach. It was very difficult to keep the inlet open because of drifting sand along the shore. After ice cover was formed on the lake in late November there has been no trouble at the inlet.

The permeability of the depression varies from 1.5 $m^3/sec/km^2$ to more than 10 $m^3/sec/km^2$. The low permeability is at the lowest pressure and may be partly explained by this but it probably is also because saturation is so low, that the movement of water is only capillary at that stage. By increased saturation the permeability should increase until all the sand under the depression is saturated and groundwater gradient is formed. The gradient gradually decreases until an equilibrium is reached. Fitjavatns-veita indicates that this process takes quite a long time. It had not formed an equilibrium after more than 2 months of continuous flow this winter. The leakage is still much more than 50 percent of the maximum leakage. A continuation of the experiment will probably furnish the necessary data in this respect during the present or the following winter, but the results hitherto obtained indicate that it takes several months and even years to reach a new equilibrium. In the depression VH-6 a calculated leakage according to grain size of the material and 100% hydraulic gradient will give 5 times the observed leakage during spring thaw.

The effects of raising the lake level will be a very large increase in the leakage. By one meter's rise very little new land will be submerged. The extremely leaky area will increase somewhat, but the gradient in some cases will become much steeper. This will cause a substantial increase in leakage. More than one meter's rise of the lake level will cause a substantial areal increase, which causes a much greater leakage. This leakage should be expected to be so great that the lake level will hardly rise more than 3 meters with only the discharge of Þórisós and the ground water from the lava aquifer north of the lake contributing to the inflow. On the other hand it can certainly be raised 10 m with the Kaldakvísl diversion, which will also yield fine grained sediments that will tend to decrease leakage. In small lakes this does occur very fast, but in a large lake like Þórisvatn it probably takes a much longer time. Still, this is an important factor in the probable future rise of the lake level.

2.3 Storage and Ground Vater Reservoirs

The results from Fitjavatnsveita (Exhibit 2.07) indicate the speed of the ground water flow. There is a time lag between the inflow into Fitjavatnsveita and the maximum rise of ground water in drillhole 0-1, about 1 km away. This time lag indicates that the pressure wave in the ground water travels about 1 km a month. This indicates how long it takes for the leakage water to reach the springs south and west of Þórisvatn. It will take months for the peak of the ground water to reach the nearest springs in Þóristungur from the Grasatangi-Snoðnafit area. For the water leaking out east of Vatnsfell it may take a year and even more for the peak of the leakage to enter the springs. The ground water wave is very much flattened out and therefore a peak flow due to leakage will be much lower than the peak leakage and have a several times longer duration. Leakage water will therefore be stored in the ground for years.

The leakage from Þórisvatn is mostly flowing into Þóristungur and to the Sigalda reach of Tungná. This leakage water will not be useful for the future at the Sigalda power plant and much of it not even at the Hrauneyjafoss future power plant, which together will utilize 150-175 m head. However, a part of the leakage water from leakage area 1 can be reached for utilization in both power plants if a canal in Fellsendalægð is built deep enough to intersect the ground water stream underneath. Then at least a part of the ground water would be diverted into Tungná upstream from Sigalda. This would be especially important if the lake level was raised with a substantial increase in leakage.

At the SW-end of Austurbotn there is a barrier which makes it a closed basin below 550-560 m elevation. Should the proposed storage be built with a 30-40 m drawdown this basin would contain a considerable storage. In order to find out what makes up this barrier one borro sounding was done at the very tip of Brandseyri and two piezometers were also put down on Brandseyri to give an indication of the depth to bedrock in this reach (Exh. 2.01, 2.13 and 2.14). The borro sounding indicates that the sand in this reach is very thick, at least 40 m, and we could therefore suppose that this barrier is a sand bar, possibly formed at the former lowest lake level, 12 m lower than the present one. Most likely will this sand bar be cut through by erosion of a stream flowing from Austurbotn through the bar when the drawdown occurs. The basin will therefore become a part of the resevoir without excavation.

The mean level of Lake Þórisvatn when used as a storage reservoir, will certainly be lower than the present level. This will cause increased inflow and with a lowering of 2-3 m practically all leakage will cease making some additional discharge available for Sigalda and Hrauneyjafoss.

TABLE 2.1

LOCATION AND DEPTH OF PIEZOMETERS

Hole No.	Co-ordinates X	Co-ordinates Y	Surface Elevation	Depth m	Bottom Elevation	Height of pipe above ground
P-1	544.988	412.133	573.1	16.5	555.8	0.8
P-2	544.908	412.002	573.6	22.3	550.6	0.7
P-3	544.332	411.418	554.9	24.4	529.9	0.6
P-4	544.056	410.112	550.5	21.9	527.9	0.7
P-5	545.122	408.867	540.7	10.6	529.2	0.9
P-6	545.609	411.105	575.8	29.0	546.2	0.6
P-7	546.267	411.051	592.3	41.5	550.2	0.6
P-8	547.278	409.795	532.7	31.1	500.9	0.7
P-9	546.854	407.202	534.1	19.0	514.5	0.6
P-10	547.555	412.212	573.8	16.3	556.8	0.7
P-11	547.094	413.002	573.9	7.9	565.2	0.8
P-12	546.413	412.162	596.9	55.0	541.3	0.6
P-13	536.480	415.650	581.6	6.3	574.9	0.4
P-14	532.970	418.510	587.5	36.5	550.4	0.6
P-15	542.970	411.730	569.4	17.1	551.7	0.6
P-16	540.440	415.080	572.5	30.0	542.5	0.7
P-17	540.490	414.580	572.4	13.5	557.8	1.1
P-18	548.490	414.978	573.4	21.6	550.7	1.1
P-19	546.671	417.574	573.2	14.4	(558.8)	
P-20	550.419	410.790	516.0	29.2	585.9	0.9
P-21	543.210	412.650	572.7	26.5	545.2	1.0

TABLE 2.2

ELEVATION OF WATER LEVEL IN PERMANENT AND TEMPORARY LAKES

Date of measurement.	NAME OF LAKE								
	Þóriavatn	VH-3	VH-4	VH-5	VH-6	VH-7	VH-8	VH-9	VH-10
29/5 '69	571.13	551.73	550.88	539.87	575.95	591.63	531.18	532.00	
30/5 -		551.63	550.82	539.81	575.80	591.44	531.14	531.99	
31/5 -	571.11	551.54	550.77	539.76	575.68	591.29	531.12	531.97	
1/6 -		551.45	550.73	539.71	575.51	591.11	531.08	531.96	
2/6 -		551.36	550.68	539.67	575.37	590.93	531.04	531.96	
3/6 -		551.28	580.63	539.63	575.20	590.73	531.02	531.96	
4/6 -	571.06	551.20	550.58	539.58	575.07	dry			
5/6 -		551.12	550.54	539.57	574.91				
6/6 -		551.05	550.49	539.54	574.76				567.09
7/6 -		550.96	550.44	539.51	574.57		530.90	531.86	566.80
8/6 -		550.87	550.40	539.48	dry				566.57
9/6 -		550.79	550.35	539.47			530.85	531.89	566.27
10/6 -		550.70	550.30	539.44			530.85	531.90	566.00
11/6 -		550.62	550.26	539.43			530.85	534.90	565.69
12/6 -		550.53	550.22	539.41			530.77	531.83	565.51
13/6 -	571.06		550.18	539.38			530.75	531.84	565.25
18/6 -		dry	549.93	dry			530.64	531.82	dry
19/6 -			549.88				530.62	531.81	
20/6 -			549.84				530.60	531.81	
21/6 -			549.78				530.59	531.80	
22/6 -			549.72						
23/6 -	570.99		549.67				530.54	531.78	
24/6 -			549.67				530.53	531.80	
30/6 -			549.36				530.62	531.69	
1/7 -	571.00						530.59	531.77	
7/7 -			548.97				530.56	531.74	
8/7 -			548.93				530.56	531.73	
14/7 -	570.98		548.55				530.49		
15/7 -	570.98		548.53				530.47	531.70	
16/7 -			548.48				530.46	531.70	
18/7 -			548.34				530.45	531.70	
19/7 -			dry				530.45	531.71	
20/7 -							530.45	531.70	
21/7 -							530.48	531.65	
22/7 -							530.40	531.60	
24/7 -							530.40	531.60	
25/7 -							530.38	531.57	
26/7 -							530.42	531.64	
29/7 -	570.94						530.38	531.64	
30/7 -							530.37	531.64	
6/8 -							530.36		
7/8 -								531.63	
11/8 -							530.33	531.64	
14/8 -							530.33	531.67	
20/8 -								531.61	
21/8 -							530.30	531.64	
25/8 -							530.28	531.65	
28/8 -							530.27	531.67	
2/9 -							530.23	531.57	
4/9 -	570.91						530.25	531.63	
21/9 -							530.21	531.50	
23/9 -	570.88						530.21	531.50	
25/9 -	570.90						530.09		
30/9 -	570.91								
2/10 -	570.92						530.19	531.49	
4/10 -	570.95						530.12	531.53	
6/10 -	570.93						530.08	531.56	
8/10 -	570.89						530.06	531.56	
10/10 -	570.88						530.06	531.56	
14/10 -	570.90						530.07	531.57	
16/10 -	570.91						530.07	531.58	
18/10 -	570.92						530.08	531.60	
20/10 -	570.91						530.05	531.58	
22/10 -	570.91						530.06	531.58	
24/10 -	570.91						530.00	531.56	

T A B L E 2.3

ELEVATION OF GROUNDWATER TABLE IN DRILLHOLES AND PIEZOMETERS

Date of measurement	Hole No.								
	VF-1	VF-2	VF-3	VF-4	VF-5	VF-6	VF-7	VF-9	VF-10
12/6'69				535.85					
13/6 -							524.80		
20/6 -						529.10			
23/6 -				535.84		529.50	524.97		
26/6 -				535.70		529.19	524.82		
1/7 -				535.64		529.19	524.78		
4/7 -				535.61		529.16	524.46		
5/7		542.38							
6/7 -		542.36		535.58		529.14	524.70		
7/7 -									528.90
9/7 -		542.34		535.55	1) 570.89	529.11	524.71		528.90
- -					2) 537.31				
15/7 -		542.28		535.49	1) 570.90	529.07			528.82
- -					2) 536.04				
21/7 -	1) 560.34	542.20		535.34	1) 570.90	529.00	524.57		
	2) 543.49				2) 535.12				
26/7 -	1) 563.72	542.11		535.22		528.91	524.54		
	2) 542.60								
30/7 -					1) 570.83				
					2) 534.12				
31/7 -	1) 563.72			535.93		529.11	524.50		
	2) 542.45								
8/8 -	1) 563.58	541.87		535.15			524.32		
	2) 542.97								
11/8 -						528.60			
14/8 -	1) 563.58	541.68		535.06		528.58	524.20		
	2) 542.81								
18/8 -					1) 570.83				
					2) 533.51				
21/8 -	1) 563.64					528.58	524.22		
	2) 542.60								
23/8 -								527.55	
28/8 -	1) 563.62				1) 570.89	528.28	524.18	527.51	
	2) 542.62				2) 533.43				
4/9 -	1) 563.62					528.48			
	2) 542.39								
5/9							524.13	527.50	
19/9 -	542.80					528.52	524.21	527.56	
23/9 -	1) 563.78				1) 570.96				
	2) 542.80				2) 533.45				
25/9	1) 563.74	541.72		535.15		528.30	524.24	527.56	
	2) 542.39								
2/10 -	1) 563.76	541.96	541.00	535.09	1) 571.37	528.54	524.24	527.58	528.30
	2) 542.79				2) 533.47				
9/10 -	1) 563.83	541.60	541.01	535.36		528.52	524.25	527.58	528.23
	2) 542.76								

TABLE 2.3 cont'd.

ELEVATION OF GROUNDWATER TABLE IN DRILLHOLES AND PIEZOMETERS

Date of measure-ment	Hole No.								
	VF-1	VF-2	VF-3	VF-4	VF-5	VF-6	VF-7	VF-9	VF-10
16/10'69	1) 563.91 2) 542.76	541.69	541.05	535.22	1) 571.08 2) 533.38	528.59	524.30	527.62	528.32
-									
23/10 -	1) 563.97 2) 542.89	541.93	541.21		1) 571.18 2) 533.55	527.70	524.42	528.21	528.45
30/10 -				535.30			524.48	527.80	
5/11 -	1) 563.91 2) 542.92	542.06				528.77			
6/11 -			541.35	535.35			524.52	527.83	528.50
14/11 -		542.05	541.38	535.36		528.78	524.52		528.58
15/11 -								527.86	
16/11 -	1) 563.88 2) 542.88				1) 571.06 2) 533.70				
20/11 -	1) 563.80 2) 542.85	542.06	541.41	535.38	1) 571.07 2) 533.61		524.53	527.87	
21/11									528.50
4/12	1) 563.63 2) 542.78	542.01	541.31	535.32	1) 571.03 2) 533.58		524.46		
5/12								527.79	528.48
13/12 -	1) 563.61 2) 542.75	541.94	541.30	535.26			524.41	527.73	528.50
16/12	1) 563.61 2) 542.67	541.90	541.27	535.20					528.38

T A B L E 2.3 c o n t'd.

ELEVATION OF GROUNDWATER TABLE IN DRILLHOLES AND PIEZOMETERS

Date of measure-ment	Hole No.								
	VF-11	VF-12	VF-13	VF-14	VF-16	VF-17	VF-18	VF-19	VF-20
30/7'69	1) 570.92								
	2) 569.42								
	3) 551.88								
15/8 -	1) 570.78								
	2) 569.42								
	3) 548.53								
27/8 -			533.80	533.50					
28/8 -	1) 570.77								
	2) 569.47								
	3) 551.86								
4/9 -			530.03	532.82					
19/9 -			529.99	533.00	527.40	525.65		528.02	
23/9 -	570.91								
	569.60								
	551.80								
25/9 -		528.40	530.03	533.00	527.54	525.62		528.00	
2/10 -	1) 570.91	527.45	530.20	533.00	527.60	525.51	526.00	528.00	
	2) 569.62								
	3) 551.87								
9/10 -		527.43	530.18	533.00	527.60	525.64	525.93	528.00	
16/10 -	1) 570.93	527.54	530.16	532.98	527.71	525.94	525.97	528.08	
	2) 569.62								
	3) 551.70								
23/10 -		527.67	530.85	533.66	527.76	525.80	526.06	528.21	
30/10 -					527.80	525.86	526.11	528.26	
5/11 -			530.39	533.12					
6/11 -					527.82	525.87	526.13	528.29	
14/11 -			530.40	533.17		525.88	526.13		
15/11 -		527.77			527.87			528.32	
16/11 -	2) 569.63								
	3) 551.93								
20/11 -						525.89	526.15		
21/11 -		527.75	530.38	533.13					
4/12 -			530.38	533.14		525.81	526.08		
5/12 -		527.65							
13/12		527.65	530.28	533.07		525.77	526.00		
16/12			530.28						

TABLE 2.3 cont'd.

ELEVATION OF GROUNDWATER TABLE IN DRILLHOLES AND PIEZOMETERS

Date of measurement	Hole No.								
	VF-21	VF-22	VF-23		0-1	0-2	0-3		
9/10'69	1) 530.05 2) 525.90				531.58				
16/10 -	1) 530.03 2) 525.92				532.43				
23/10 -	1) 530.02 2) 526.08	528.07	529.73		532.42				
30/10 -	1) 529.95								
4/11 -					531.88				
5/11 -			528.65						
6/11 -	1) 530.02 2) 526.02	527.84							
13/11 -	1) 529.96 2) 526.06				531.68				
14/11 -			528.66						
15/11 -		527.86							
19/11 -	1) 529.93 2) 526.03				531.49	542.41			
20/11 -						542.33			
21/11 -					531.42	541.50			
25/11 -					531.26	dry			
26/11 -					531.25	"			
27/11 -					531.19	"			
28/11 -					531.18	"			
3/12 -					531.03	541.33			
4/12 -	1) 529.83 2) 525.91								
5/12 -					530.97	541.41			
8/12 -					530.83	541.34			
10/12 -					530.82	541.30			
13/12 -	1) 529.75 2) 525.80				530.78	541.20			
15/12 -					530.80	541.26			
16/12 -					530.77	541.30			
19/12 -					530.84	dry			

T A B L E 2.3 c o n t'd.

ELEVATION OF GROUNDWATER TABLE IN DRILLHOLES AND PIEZOMETERS

Date of measurement	Hole No.									
	P-1	P-2	P-3	P-4	P-5	P-6	P-7	P-8	P-9	P-11
26/6'69			546.21	546.78						
1/7 -			546.17	547.42						
4/7 -			546.10	547.42			567.70			
6/7 -			546.03	547.31	537.85					
9/7 -			546.02	547.26	537.92		567.68		528.22	
15/7-			545.91	547.12	537.92		567.67		528.72	
21/7 -	568.79	562.97	545.85	546.87	533.90		567.54	525.63	528.71	
23/7 -										570.15
26/7 -	568.78	563.00	545.76	546.77			567.60	525.68	528.72	570.09
31/7 -	568.73	563.01	545.69	546.63	533.72	550.61	567.61	525.67	528.73	570.12
8/8 -	568.65	562.91	545.37	546.15	533.48		567.40	525.40	528.62	569.93
11/8 -						550.06				
14/8 -	568.64	562.90	545.32	546.03	533.35		567.36	525.40	528.20	570.01
21/8 -	568.68	562.94	545.16	545.75	533.36	550.49	567.36	525.36	528.18	570.03
28/8 -	568.62	562.96	545.18	545.51	533.29	550.59	567.33	525.31	528.65	569.98
4/9 -	568.50	562.90				550.57				
5/9 -			545.13	545.23	533.11		567.30	525.36	528.40	569.92
19/9 -	568.62	563.05	545.19	544.87	533.36	550.66	567.42	525.29	528.48	570.10
25/9 -	568.61	563.04	545.13	544.82	533.35	550.65	567.47	525.26	528.50	570.36
2/10 -	568.60	563.12	545.52	544.48	533.25	550.61	567.43	525.20	528.51	570.12
9/10 -	568.67	563.17	545.30	544.32	533.24	550.70	567.52	525.24	528.58	570.21
16/10 -	568.65	563.15	545.16	544.17	533.23	550.68	567.42	525.22	528.52	570.13
23/10 -	568.58	563.17	545.12	544.07	533.32	550.71	567.48	525.29	528.65	570.03
30/10 -					533.38			525.32	528.77	
4/11 -										569.86
5/11 -	568.58	563.18				550.69	567.47			
6/11 -			545.35	542.63	533.37			525.40	528.81	
13/11 -								525.43		569.82
14/11 -			545.33	543.80	533.44	550.68	567.55		528.77	
16/11 -	568.37	563.07								
19/11 -										569.73
20/11 -	568.20	563.01	545.32	543.77	533.45			525.48	528.42	
21/11 -						550.68	567.56			569.73
25/11 -										569.65
26/11 -										569.80
27/11 -										569.93
28/11 -										569.99
3/12 -										570.12
4/12 -	567.95	562.85	545.22	543.63	533.43		567.55	525.51	528.64	
5/12 -										570.09
8/12 -										570.09
10/12 -										570.11
13/12 -	567.89	562.73	545.15		533.35	550.61	567.49	525.40	528.55	570.14
15/12 -										570.15
16/12 -	567.97	562.72				550.59				570.14
										570.25

TABLE 2.3 cont'd.

ELEVATION OF GROUNDWATER TABLE IN DRILLHOLES AND PIEZOMETERS

Date of measurement	Hole No.									
	P-12	P-13	P-14	P-15	P-16	P-17	P-18	P-19	P-20	P-21
21/8'69	557.20									
28/8 -	557.04									
5/9 -	556.84									
19/9 -	556.75									
25/9 -	556.63									
2/10 -	556.52									
9/10 -	556.45									
16/10 -	556.37									
23/10 -	556.36						566.05	570.91	504.35	
24/10 -		578.19	582.66	559.59	570.35	570.06				567.55
30/10 -				559.54	570.41	570.27				
4/11 -							566.03	570.89	504.39	568,66
5/11 -	556.22									
6/11 -		578.20	582.64	559.57	570.38	570.20				
13/11 -							565.93	570.86	504.36	
14/11 -	556.19									
19/11 -		578.20	582.71	559.40	570.62	570.08	565.89	570.86		
20/11 -	556.15								504.35	566.67
4/12 -	556.15						565.70	570.82	504.31	
10/12 -							565.60	570.84	504.24	569.78
13/12	556.08									
16/12										569.78

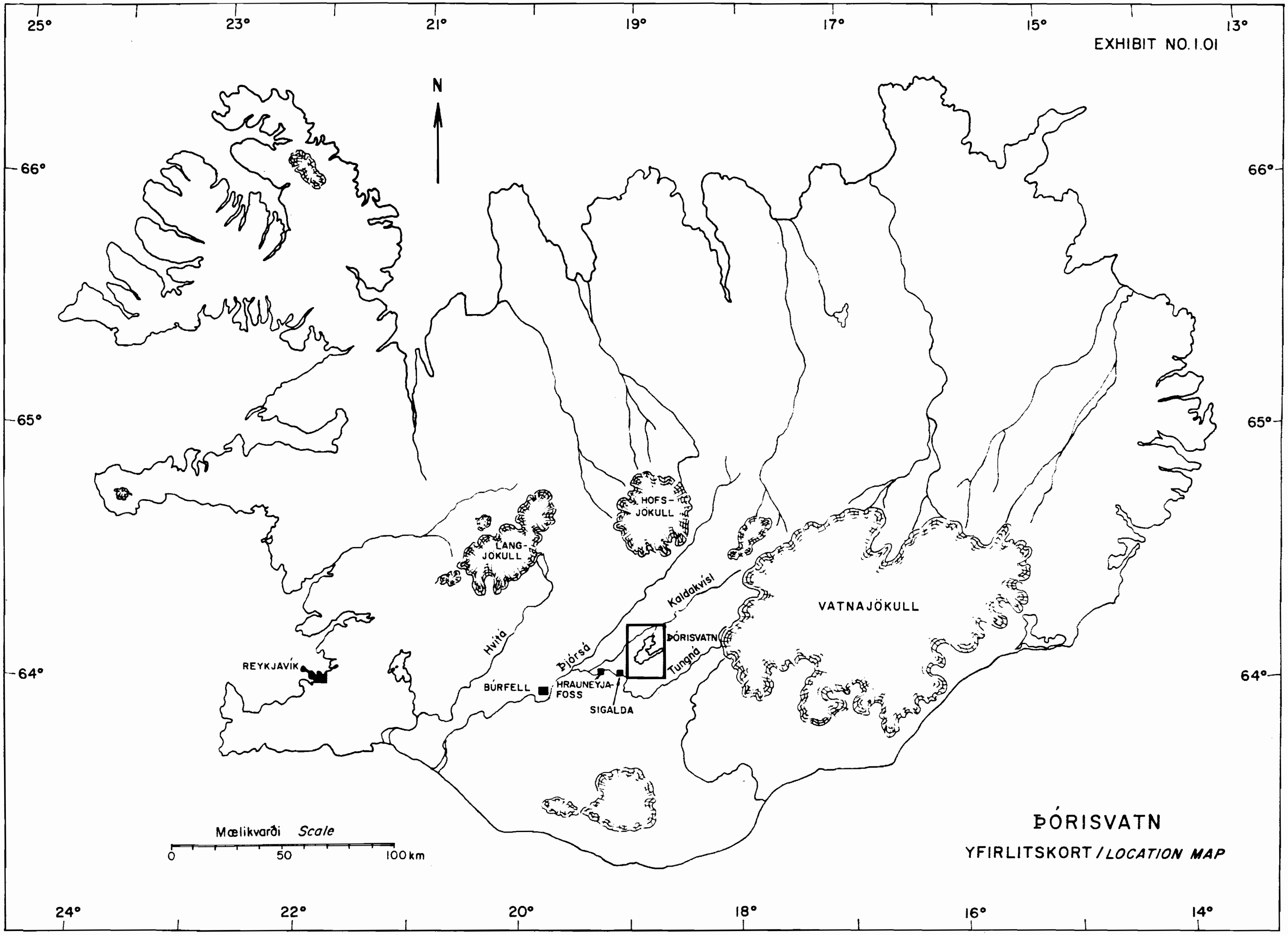
T A B L E 2.4

FITJAVATN DIVERSION

ELEVATION OF WATERLEVELS AND ESTIMATED INFLOW

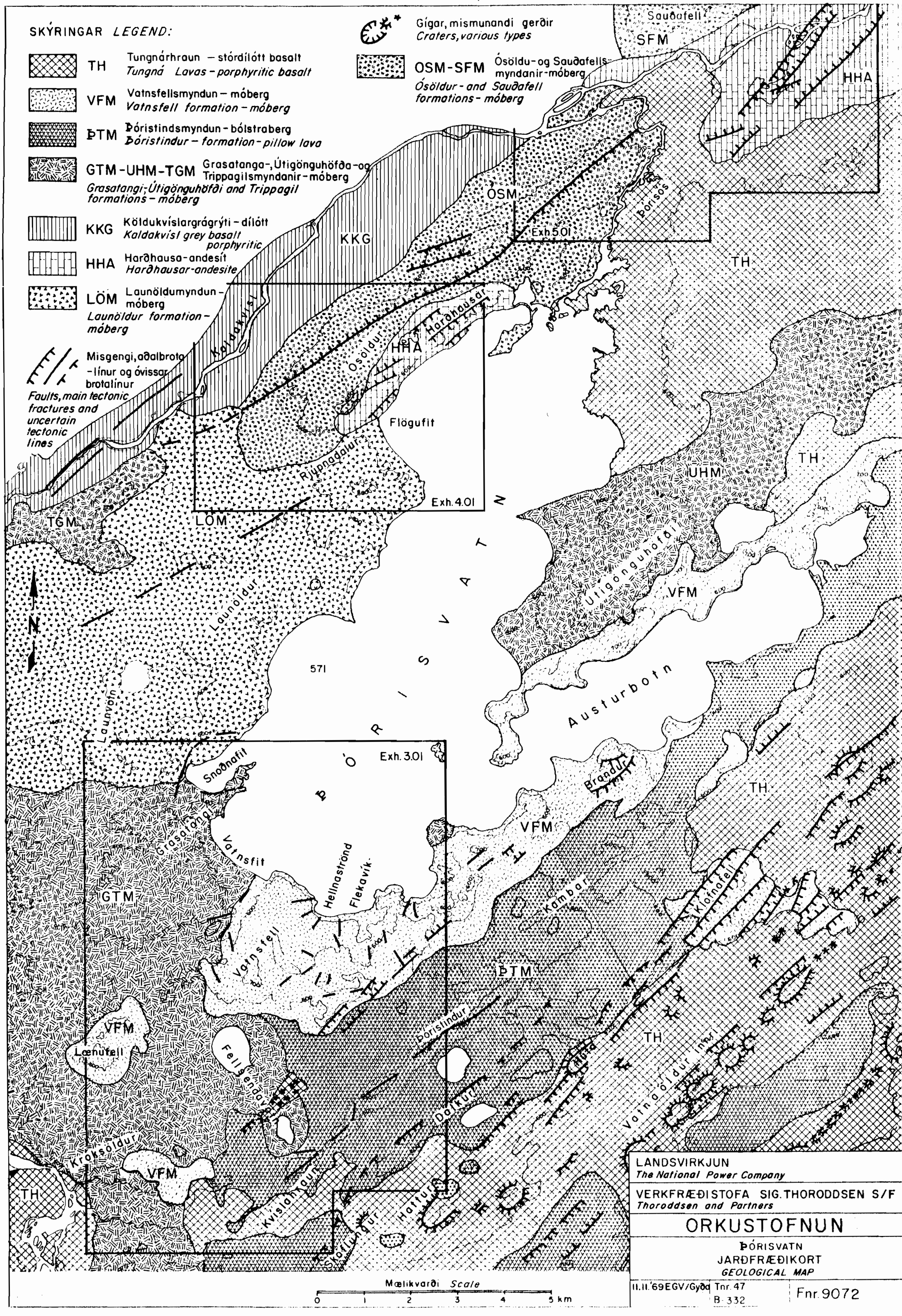
Date of measurement	Measuring station						Estimated inflow in Kl between measurem.
	0-1	0-2	P-10	P-11	Spillway	Fitjavatn	
20/9 '69	530.95		dry	570.18	572.14	568.05	157.000
21/9 '69	531.01		"	570.25	572.14	569.51	135.000
22/9 '69	531.03		"	570.27	572.13	569.99	133.000
23/9 '69	531.09		"	570.27	572.05	570.20	121.000
24/9 '69	531.09		"	570.27	572.04	570.36	86.000
25/9 '69	531.10		"	570.36	572.06	570.51	122.000
26/9 '69	531.13		"	570.36	572.22	570.01	18.900
30/9 '69	531.16		"	570.14	dry	568.09	56.000
1/10'69	531.16		"	570.12	"	567.64	
2/10'69	531.19		"	570.12	"	567.67	9.700
3/10'69	531.16		"	570.11	"	567.55	
4/10'69	531.16		"	570.08	"	567.32	
5/10'69	531.12		"	570.12	572.06	568.74	30.500
6/10'69	531.23		"	570.24	572.07	569.00	75.000
7/10'69	531.27		"	570.24	571.74	568.73	41.000
8/10'69	531.33		"	570.25	571.73	568.29	3.800
9/10'69	531.58		"	570.21	dry	568.10	8.900
10/10'69	531.74		"	570.16	"	567.72	0
13/10'69	531.70		"	570.12	"	566.93	0
14/10'69	532.24		"	570.12	"	566.84	0
15/10'69	532.30		"	570.12	"	566.80	0
16/10'69	532.43		"	570.13	"	566.54	0
17/10'69	532.27		"	570.07	"	566.38	0
18/10'69	532.45		"	570.07	"	566.22	0
19/10'69	532,23		"	570.05	"	566.07	0
20/10'69	532.50		"	570.04	"		0
21/10'69	532.46		"	570.04	"		0
22/10'69	532.38		"	570.04	"	565.58	0
23/10'69			"		572.15		
24/10'69	532.36		"	570.10	dry	566.57	
28/10'69	532.15		"	569.90	"		0
29/10'69	532.09		"	569.94	"		0
30/10'69	532.06		"		"		0
2/11'69			"	569.92			
4/11'69	531.88		"	569.86			
13/11'69	531.68		"	569.82			
14/11'69			"				
19/11'69	531.49	542.41	"	569.73			
21/11'69	531.42	541.50	"	569.73			
25/11'69	531.26	dry	"	569.65			
26/11'69	531.25	"	"	569.80			
27/11'69	531.19	"	"	569.93			
28/11'69	531.18	"	"	569.99			
3/12'69	531.03	"	"	570.12	572.13		
5/12'69	530.97	541.41	"	570.09	572.14		
8/12'69	530.83	541.34	"	570.09	572.15		
10/12'69	530.82	541.30	"	570.11	572.17		
13/12'69			556.80	570.14	572.18		
15/12'69	530.80	541.26	556.77	570.15	572.11		
16/12'69	530.77	541.30	556.80	570.14	572.15		
19/12'69	530.84	dry	556.80	570.25	572.08		

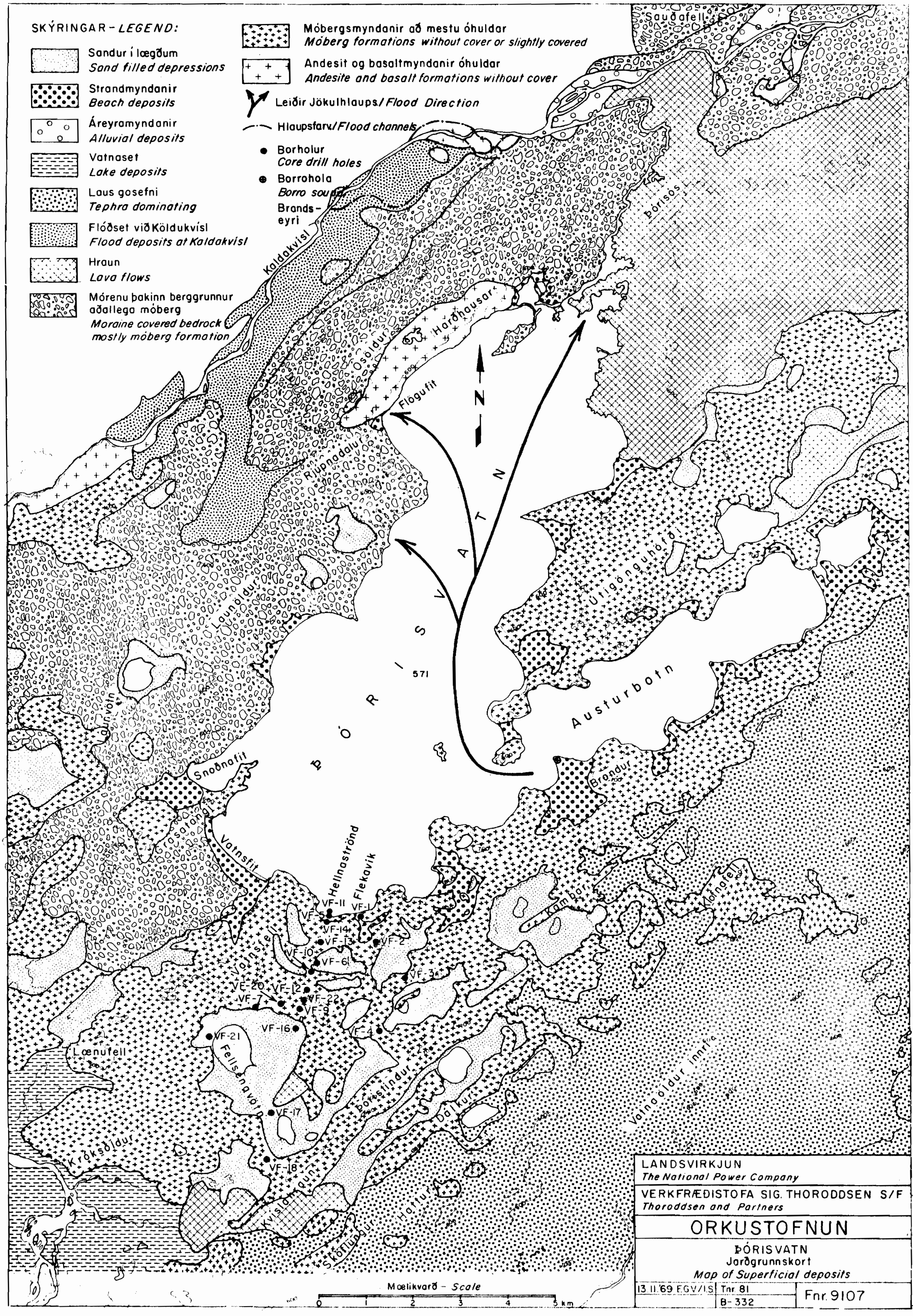
EXHIBIT NO. 1.01



ÞÓRISVATN

YFIRLITSKORT / *LOCATION MAP*


SKÝRINGAR LEGEND:
TH Tungnárhraun – stórdílótt basalt
Tungná Lavas - porphyritic basalt
VFM Vatnsfellsmyndun – móberg
Vatnsfell formation – móberg
ÞTM Þóristindsmyndun - bólstraberg
Þóristindur – formation - pillow lava
GTM-UHM-TGM Grasatanga-, Útigönguhöfða-og Trippagilsmyndanir - móberg
Grasatangi; Útigönguhöfði and Trippagil formations – móberg
KKG Köldukvíslargrágrýti - dílótt
Kaldakvísl grey basalt porphyritic
HHA Harðhausa-andesít
Harðhausar-andesite
LÖM Launöldumyndun - móberg
Launöldur formation – móberg
Misgengi, aðalbrota -línur og óvissar brotalínur
Faults, main tectonic fractures and uncertain tectonic lines
Gígar, mismunandi gerðir
Craters, various types
OSM-SFM Ósöldu- og Sauðafells myndanir - móberg
Ósöldur - and Sauðafell formations - móberg
Sauðafell
SFM
HHA
OSM
Þórisós
Exh.5.01
TH
KKG
Kaldakvísl
Harðhausar
Ósöldur
HHA
Flögufit
Rjúpnadalur
Exh.4.01
TGM
LÖM
UHM
TH
N
Útigönguhöfði
VFM
Launöldur
ÞÓRISVATN
571
Austurbotn
Launvötn
Exh.3.01
Snoðnafit
Grasatangi
Brandur
TH
VFM
Vatnsfit
GTM
Hellnaströnd
Flekavík
Kambar
Klofnafell
Vatnsfell
ÞTM
VFM
Lænufell
Fellsendavatn
Þóristindur
TH
Dalkur
Vatnaöldur innri
Króksöldur
VFM
TH
Kvíslahraun
Hafture
Skáldur
LANDSVIRKJUN
The National Power Company
VERKFRÆÐISTOFA SIG. THORODDSEN S/F
Thoroddsen and Partners
ORKUSTOFNUN
ÞÓRISVATN
JARÐFRÆÐIKORT
GEOLOGICAL MAP
Mælikvarði Scale
0 1 2 3 4 5 km
11.11.'69 EGV/Gyða Tnr. 47 B. 332
Fnr. 9072



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ÞÓRISVATN
Jarðgrunnskort
Map of Superficial deposits

13.11.69 EGV/IS	Tnr 81 B-332	Fnr. 9107

EXHIBIT NO.2.01

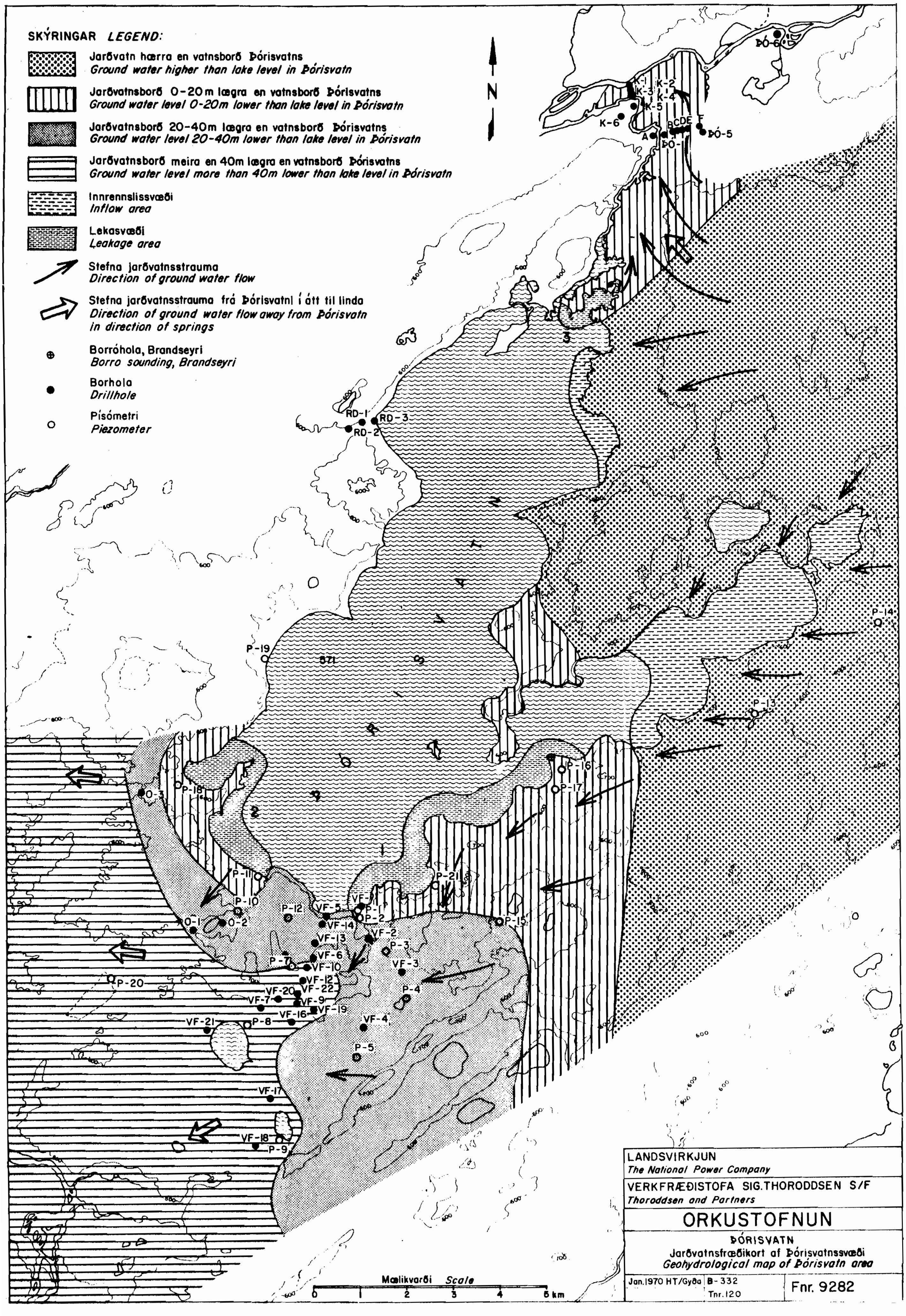
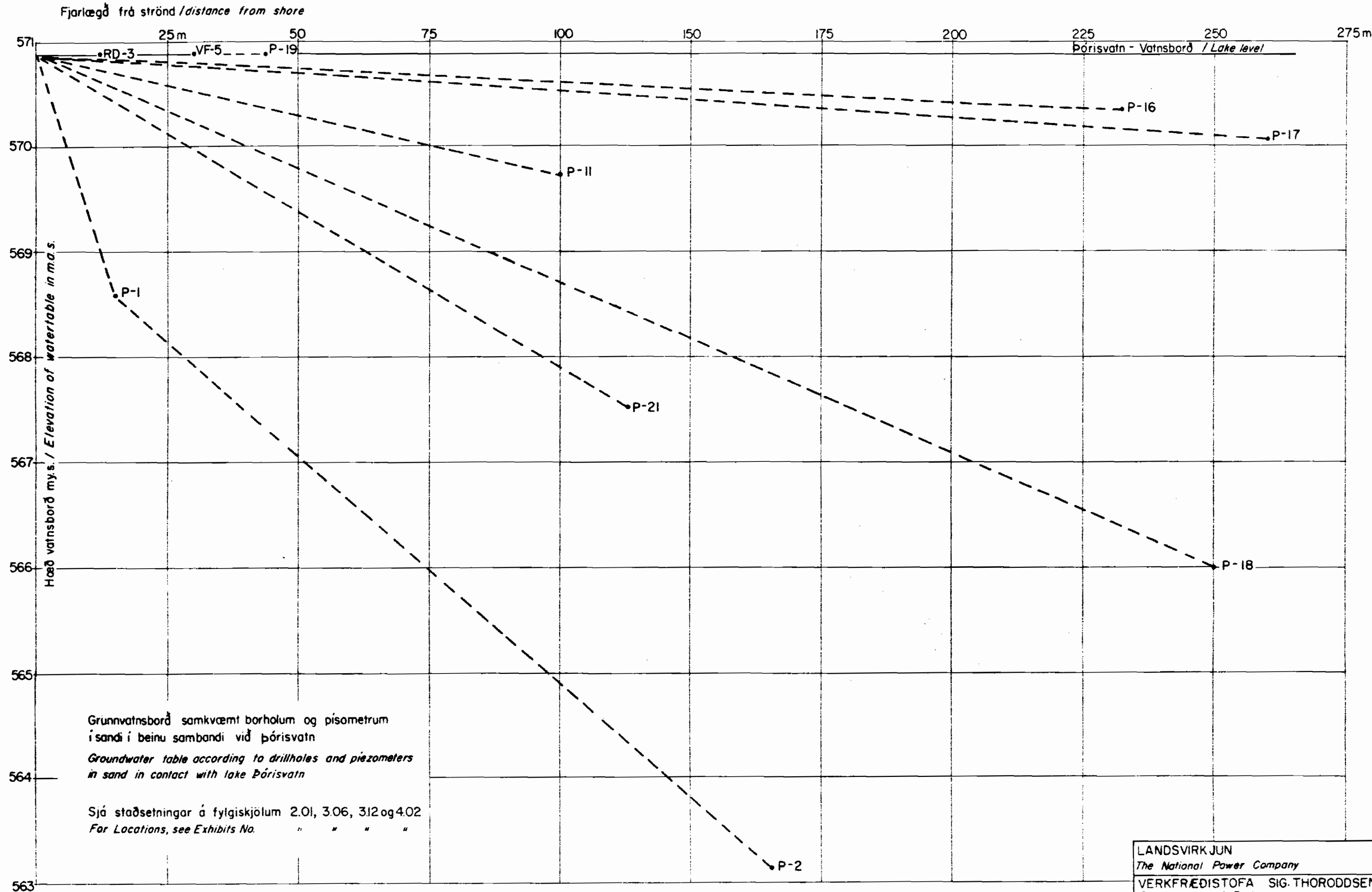


EXHIBIT NO.2.02



Grunnvatnsborð samkvæmt borholum og písometrum í sandi í beinu sambandi við Þórisvatn

Groundwater table according to drillholes and piezometers in sand in contact with lake Þórisvatn

Sjá staðsetningar á fylgiskjölum 2.01, 3.06, 3.12 og 4.02

For Locations, see Exhibits No. " " " "

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Thoroddsen and Partners

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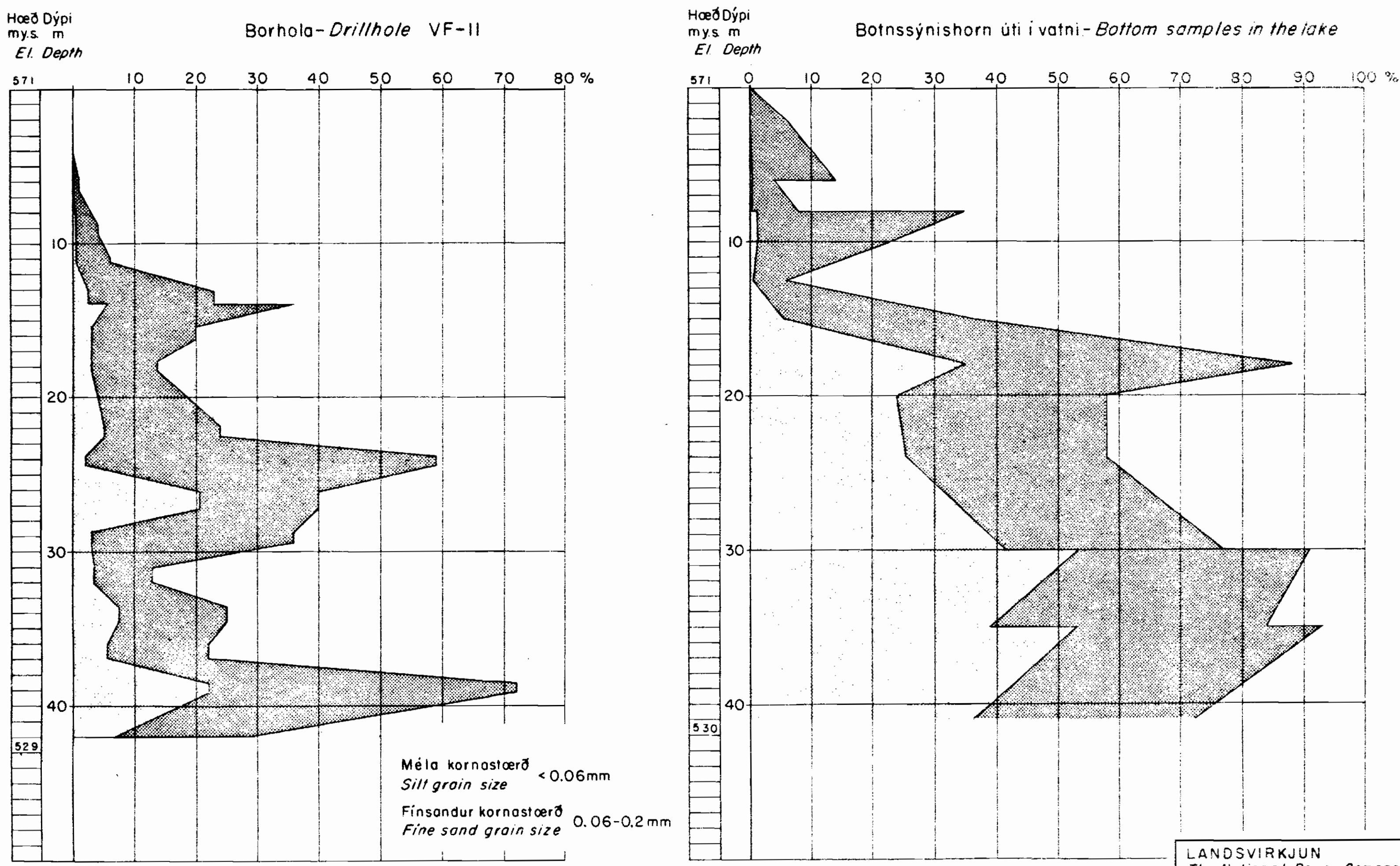
Grunnvatnsborð samkvæmt borholum og písometrum í sandi í beinu sambandi við Þórisvatn
Groundwater table according to drillholes and piezometers in sand in contact with lake Þórisvatn

Des. 69 HT/SJ. Tnr. 106 B-332 Fnr. 9201



SKÝRINGAR-*LEGEND*

Méla og leir-*Silt and clay*

Fínsandur-*Fine sand*

Staðsetningar á borholu VF-II og botnssýnishornum úti í vatni, sjá fylgiskjal 3.12

Location of Drillhole VF-II and Bottom Samples in the Lake, see Exhibit No. 3.12

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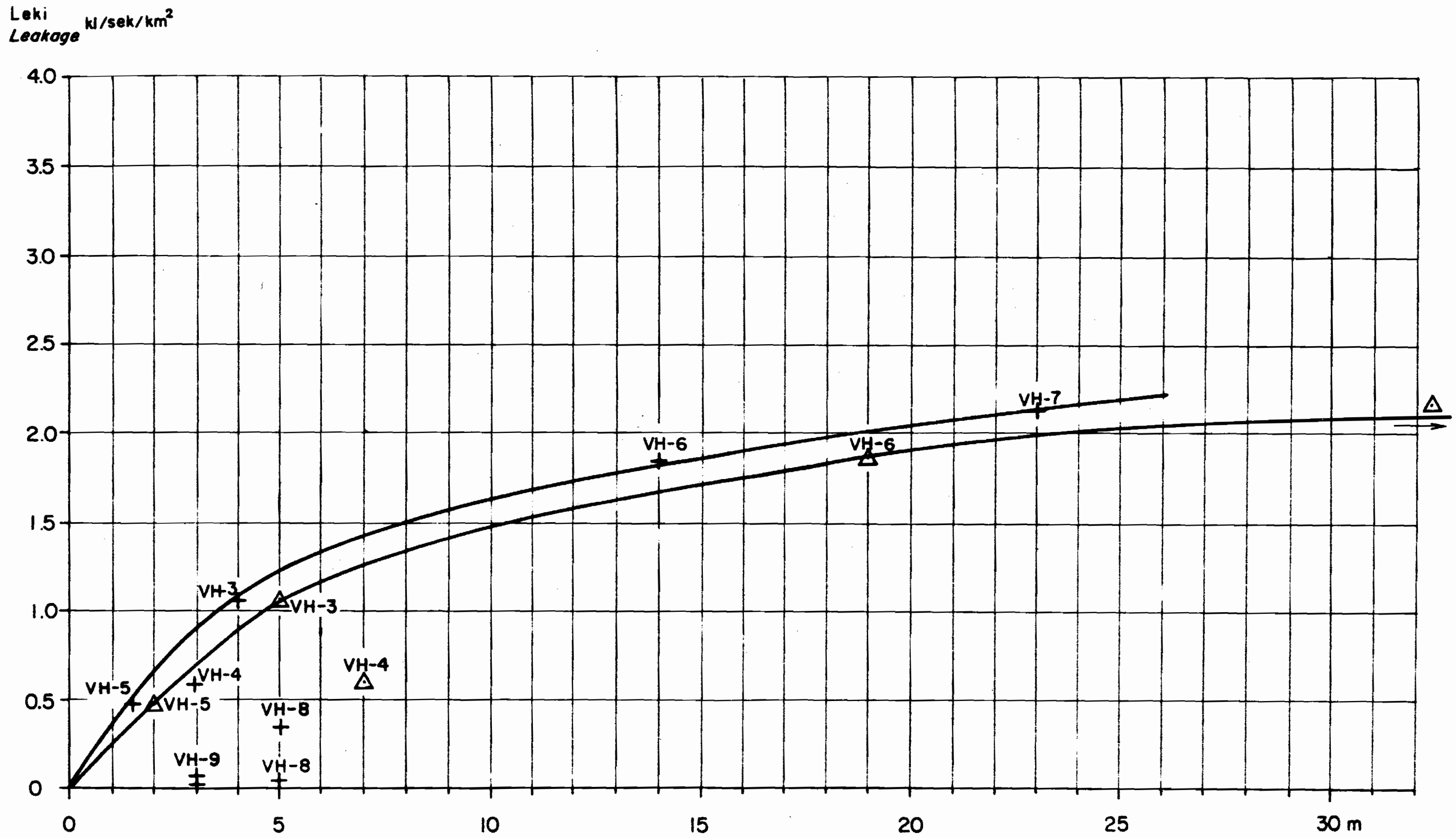
ÞÓRISVATN VATNSFELL
Fínsandur og méla í Þórisvatni
Fine sand and silt in Þórisvatn

12.11.'69 H.T./IS.	Tnr. 48 B-332	Fnr. 9073

EXHIBIT NO. 2.04



Sjá staðsetningar á fylgiskjali 3.06

For Location, see Exhibit No. "

SKÝRINGAR: *LEGEND:*

+ Lárétt gildi, hæðarmunur yfirborðs vatna og písómeterjarðvatns
Horizontal value, difference in elevation between surface water and piezometer ground water

△ Lárétt gildi, hæðarmunur písómeterjarðvatns og aðaljarðvatns
Horizontal value, difference in elevation between piezometer ground water and main ground water.

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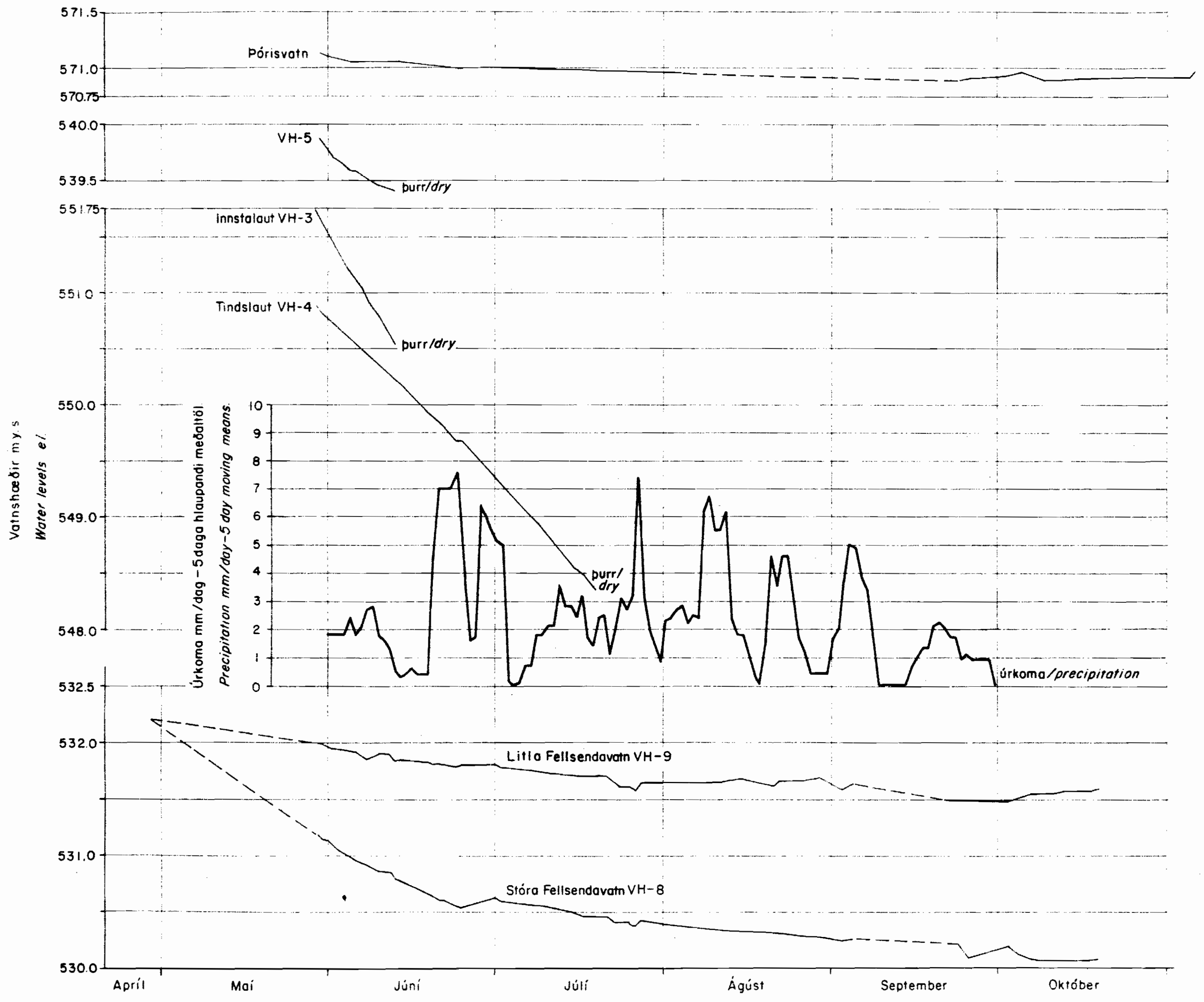
Thoroddsen and Partners

ORKUSTOFNUN
ÞÓRISVATN-VATNSFELL
SAMB. LEKA OG HÆÐARMISM. JARÐVATNSBORÐA
CORRELATION BETWEEN LEAKAGE AND DIFFERENCE IN ELEVATION OF GROUND WATER TABLES

19.11'69 PI/EK
Tnr. 91
B-332
Fnr. 9117



Sjá staðsetningar á fylgiskjali 3.06

For Locations, see Exhibit No. "

LANDSVIRKJUN *The National Power Company*		
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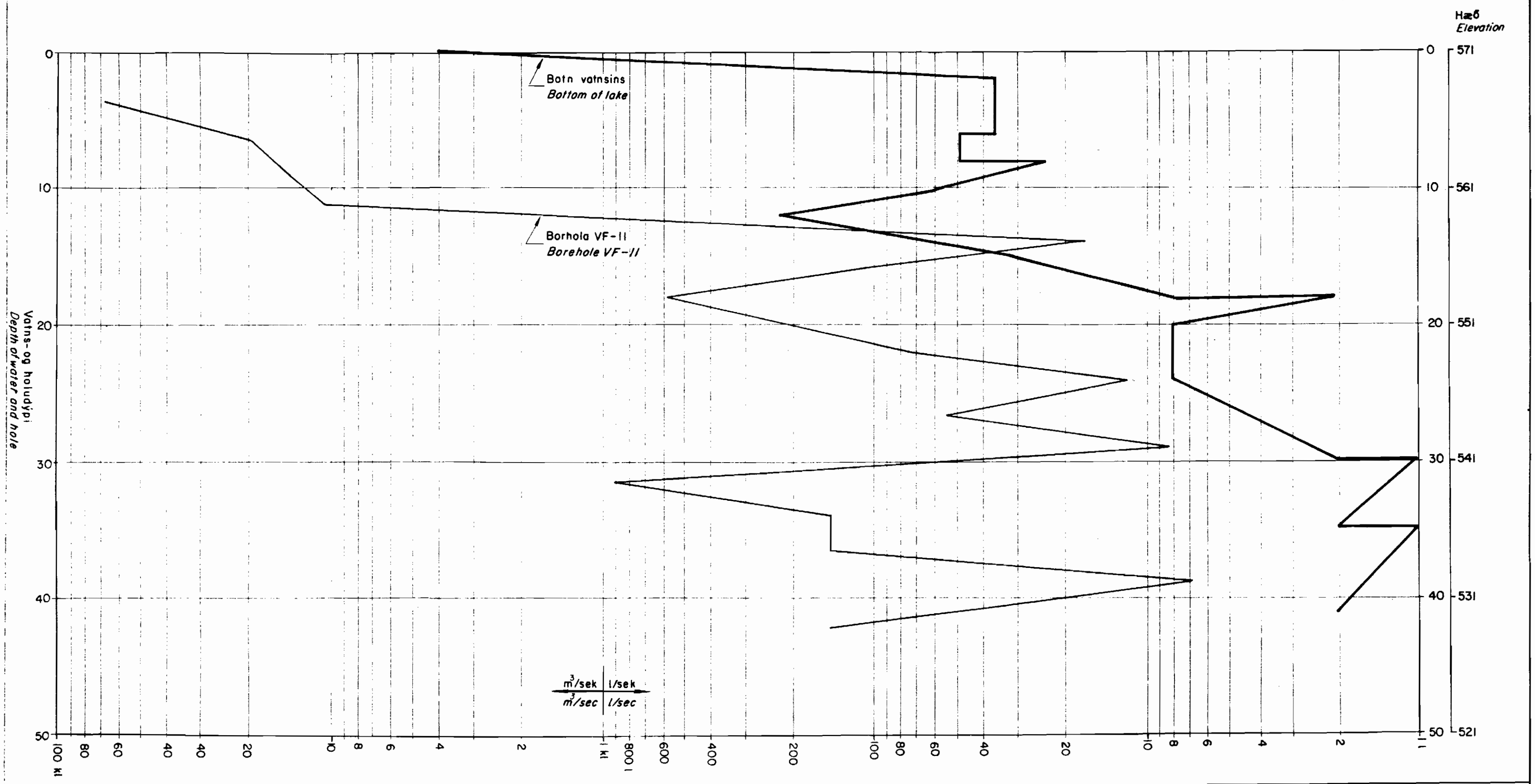
ORKUSTOFNUN		
ÞÓRISVATN VATNSFELL VATNSHÆÐIR OG ÚRKOMA *WATER LEVELS AND PRECIPITATION*		
18.11.'69 PI/EK	Tnr. 87 B-332	Fnr. 9113

EXHIBIT NO. 2.06



Leki á km² miðað við 2% jarðvatnshalla.
Leakage per km² at 2 per cent ground water gradient.

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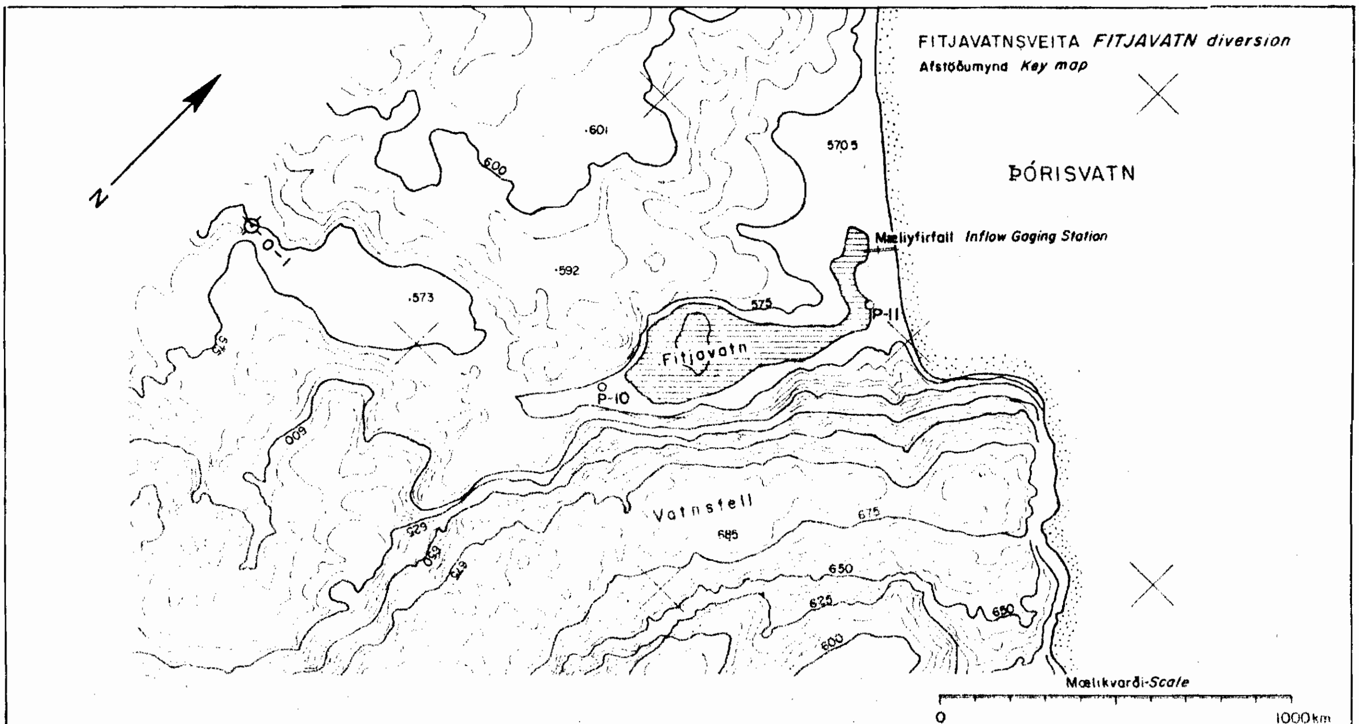
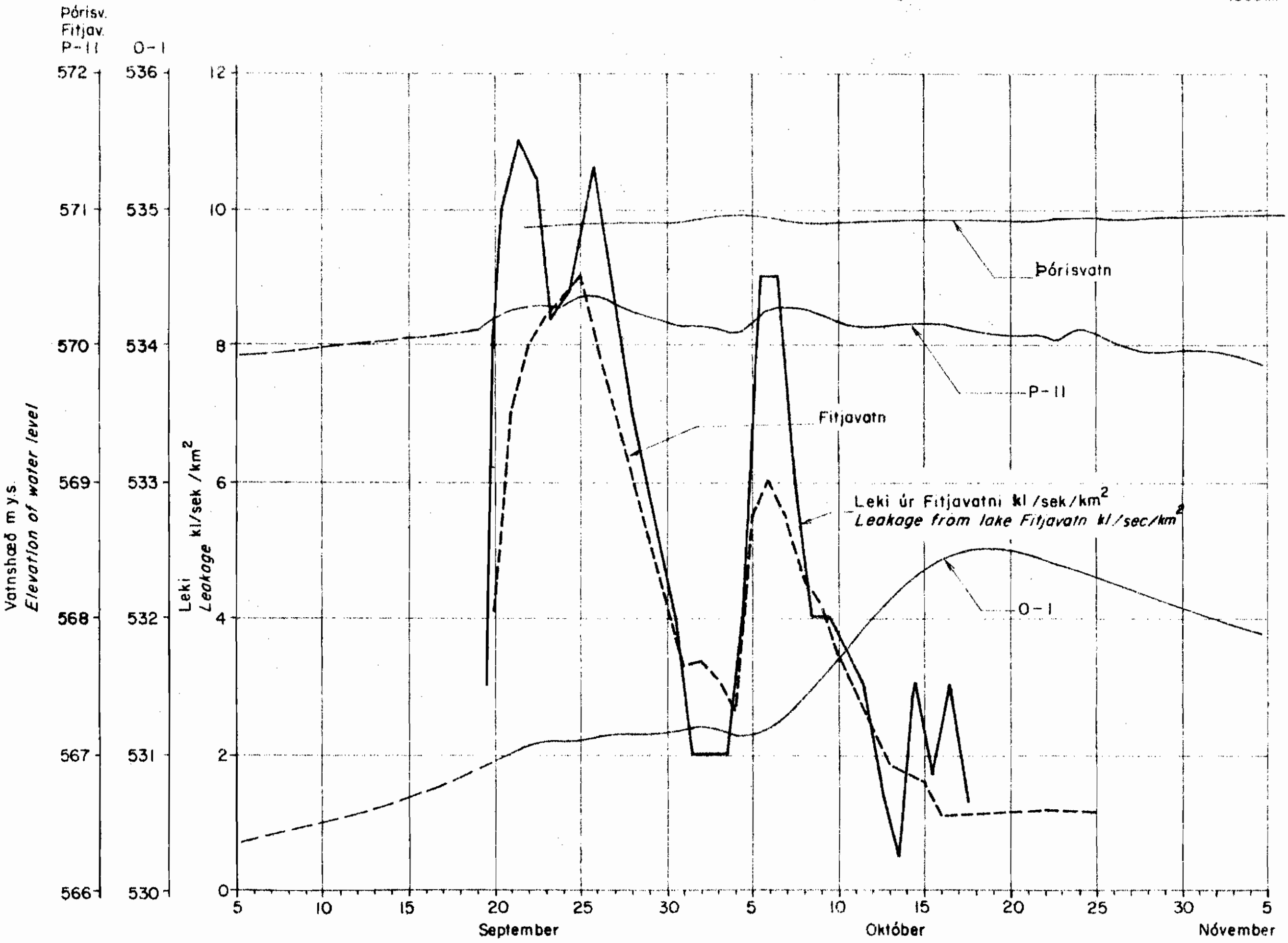
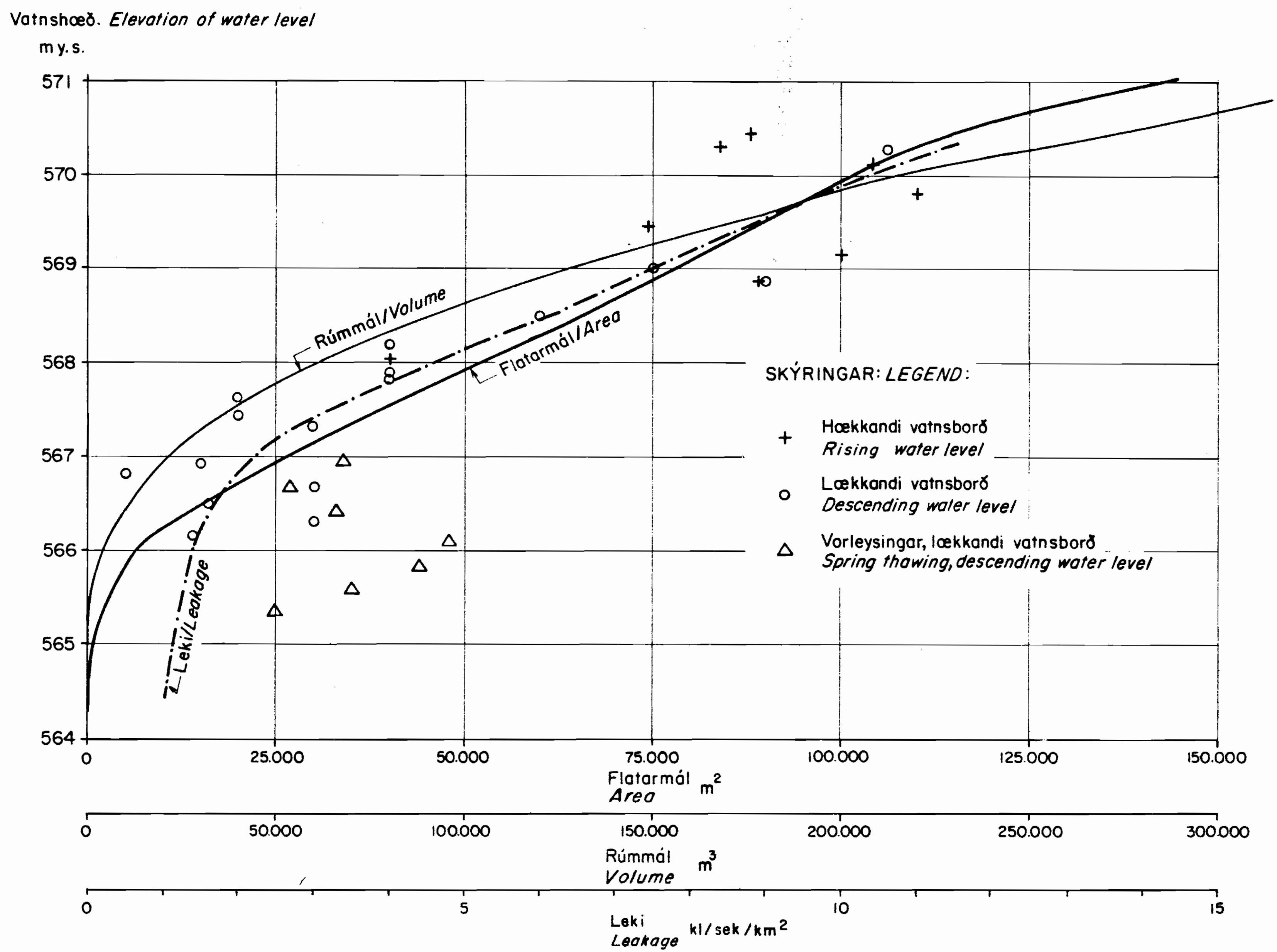
ORKUSTOFNUN ÞÓRISVATN Leki gegnum set. *Leakage through sediments.*	
12.1.'70 H.T./EK.	Tnr. 109 B-332
	Fnr. 9262





LANDSVIRKJUN *The National Power Company*	
VERKFRÆÐISTOFA SIG. THORODDSEN S/F *Thoroddsen and Partners*	
ORKUSTOFNUN	
ÞÓRISVATN-VATNSFELL FITJAVATNSVEITA, Vatnshæðir og leki. *FITJAVATN DIVERSION Water levels and leakage*	
12.11.'69 PI/EK Tnr. 46 B-332	Fnr. 9070

EXHIBIT NO. 2.08



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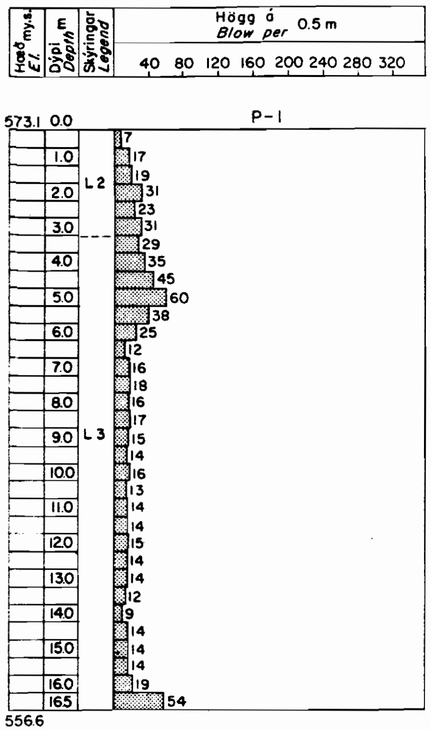
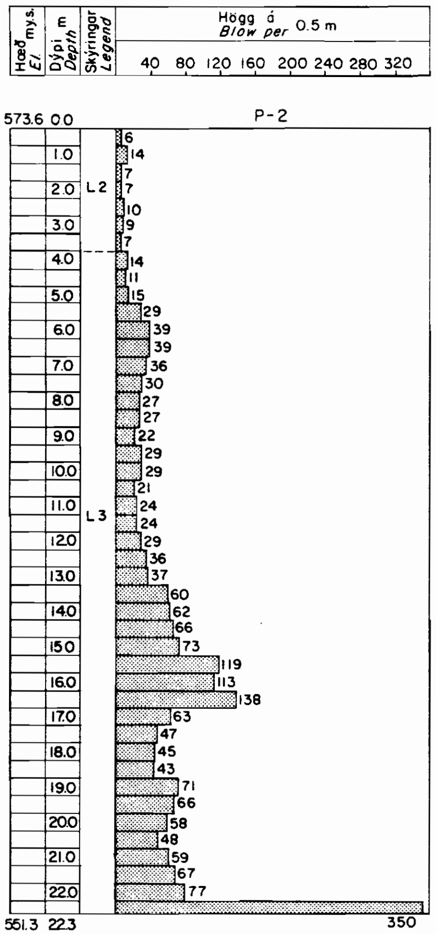
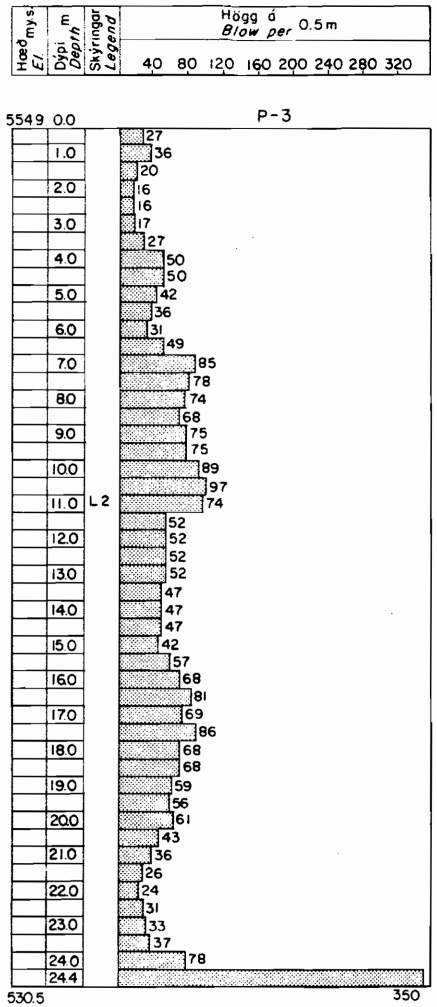
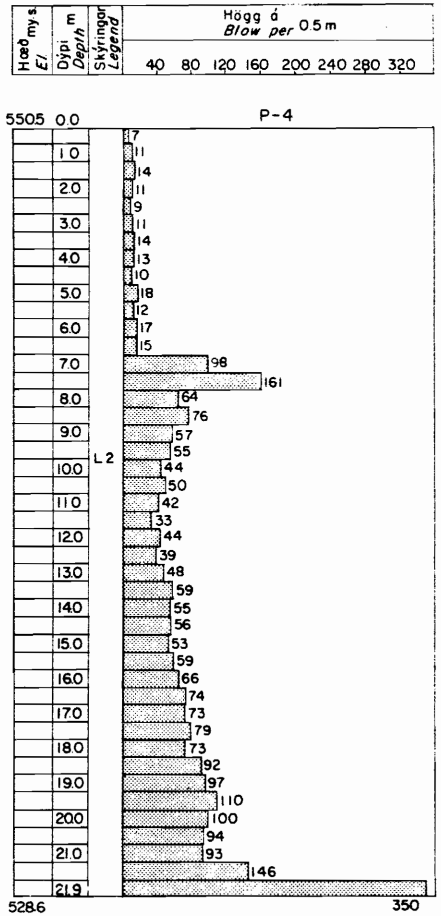
	ORKUSTOFNUN	11.11'69 P.I./E.K.
	ÞÓRISVATN-VATNSFELL	Tnr. 45
	FITJAVATNSVEITA. rúmmál, flatarmál, leki.	B-332
	FITJAVATN DIVERSION. volume, area, leakage.	Fnr. 9069









Staðsetningar sjá fylgiskjöl 2.01, 3.06, 3.12 og 3.13
Locations, see Exhibits No. " " " and "

L2 Sandur, mest aðfokinn vikur og aska
Sand, mostly Winddrifted Tephra

L3 Strandmyndanir og vatnaset
Beach and Lake Deposits

Þvermál borstanga – *Rod diameter 32 mm*
Þyngd lóðs – *Hammer weight 65 kg*
Fall lóðs – *Hammer drop 1 m*

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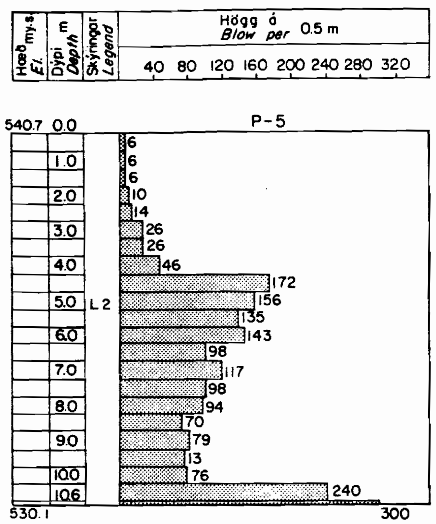
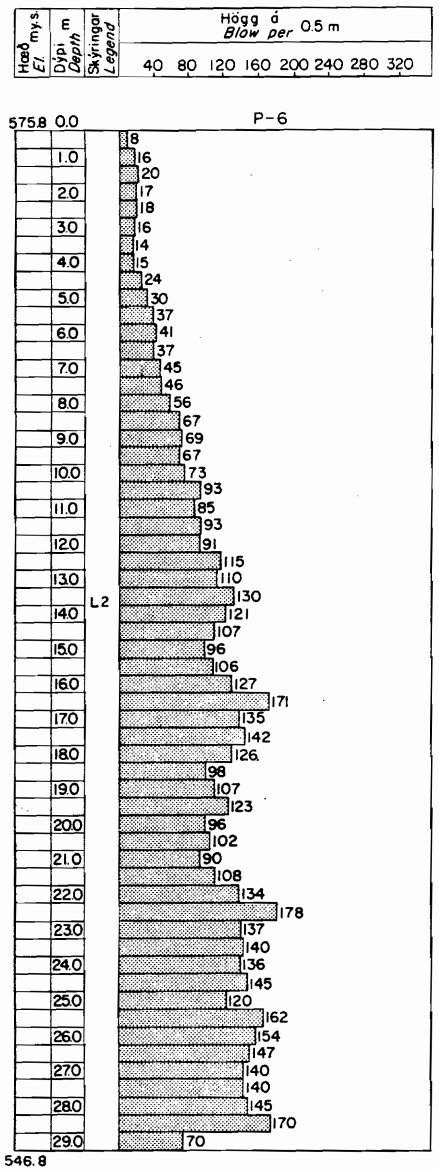
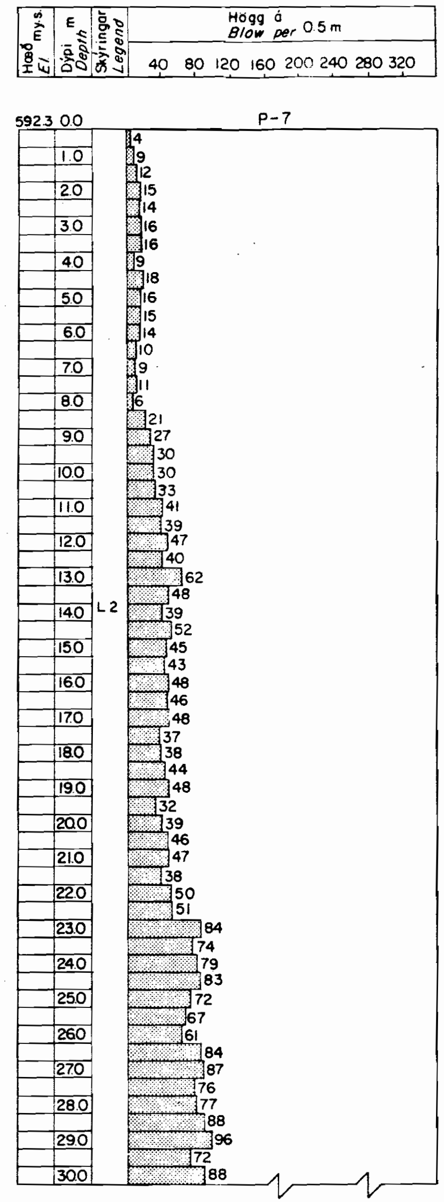
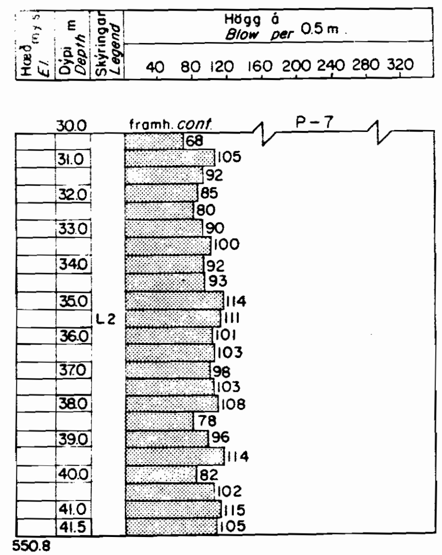
ÞÓRISVATN
Pisometrar P-1 — P-4
Piezometers " "

Nov. '69 HT/EK	Tnr. 61	Fnr. 9087
Bl. 1 of 6	Bb. 84 B-332	









Staðsetningar sjá fylgiskjöl 2.01, 3.06, 3.12 og 3.13
Locations, see Exhibits No. " " " and "

L2 Sandur, mest aðfokinn vikur og aska
Sand, mostly Winddrifted Tephra.

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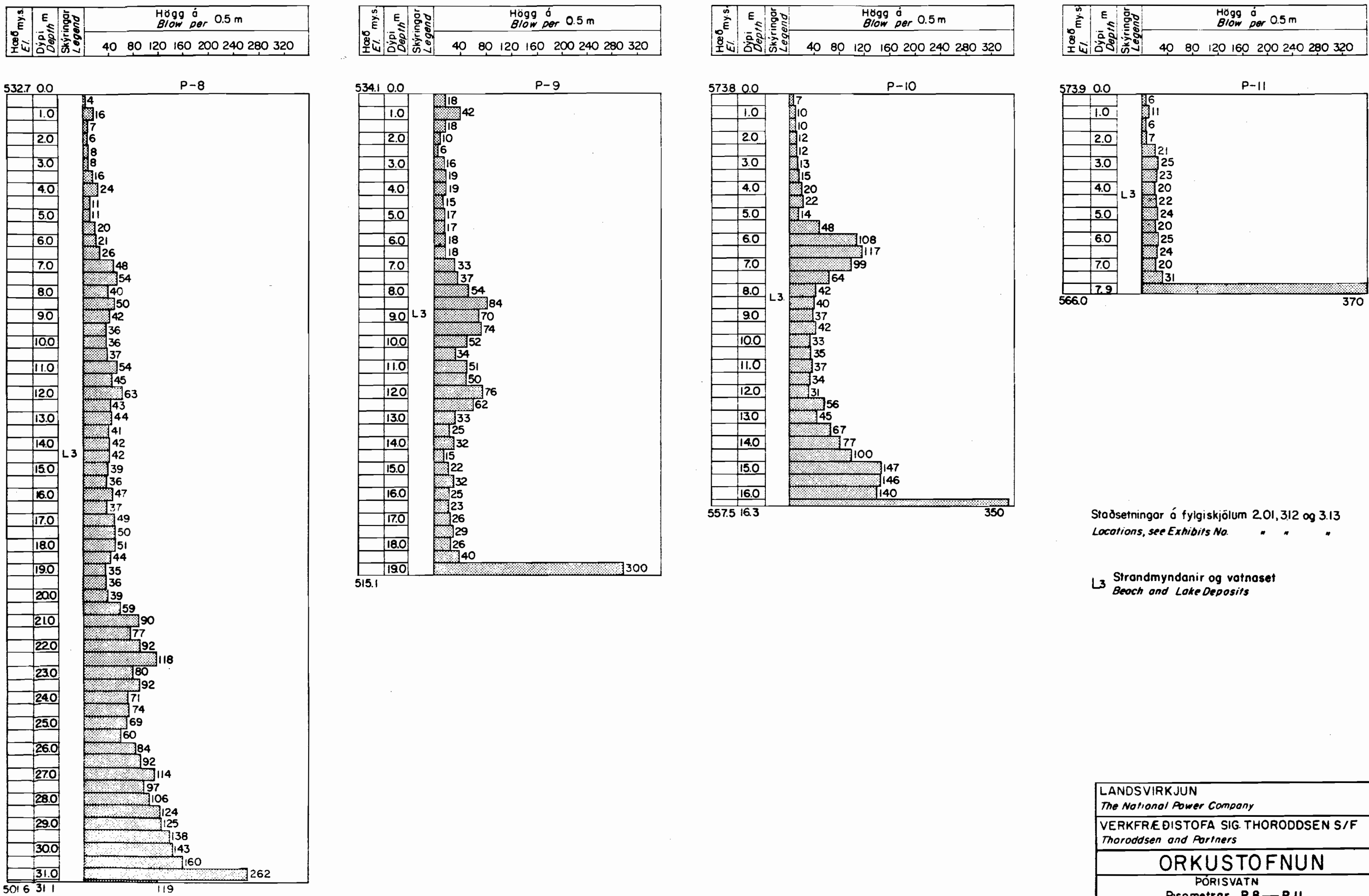
ÞÓRISVATN Pisometrar P-5 — P-7 *Piezometers " "*	
Nov. 69 HT/EK · Tnr. 62 · Bl 2 of 6 · Bb.85 B-332	Fnr. 9088

EXHIBIT NO. 2.11



Staðsetningar á fylgiskjölum 2.01, 3.12 og 3.13
Locations, see Exhibits No. " " "

L3 Strandmyndanir og vatnaset
Beach and Lake Deposits

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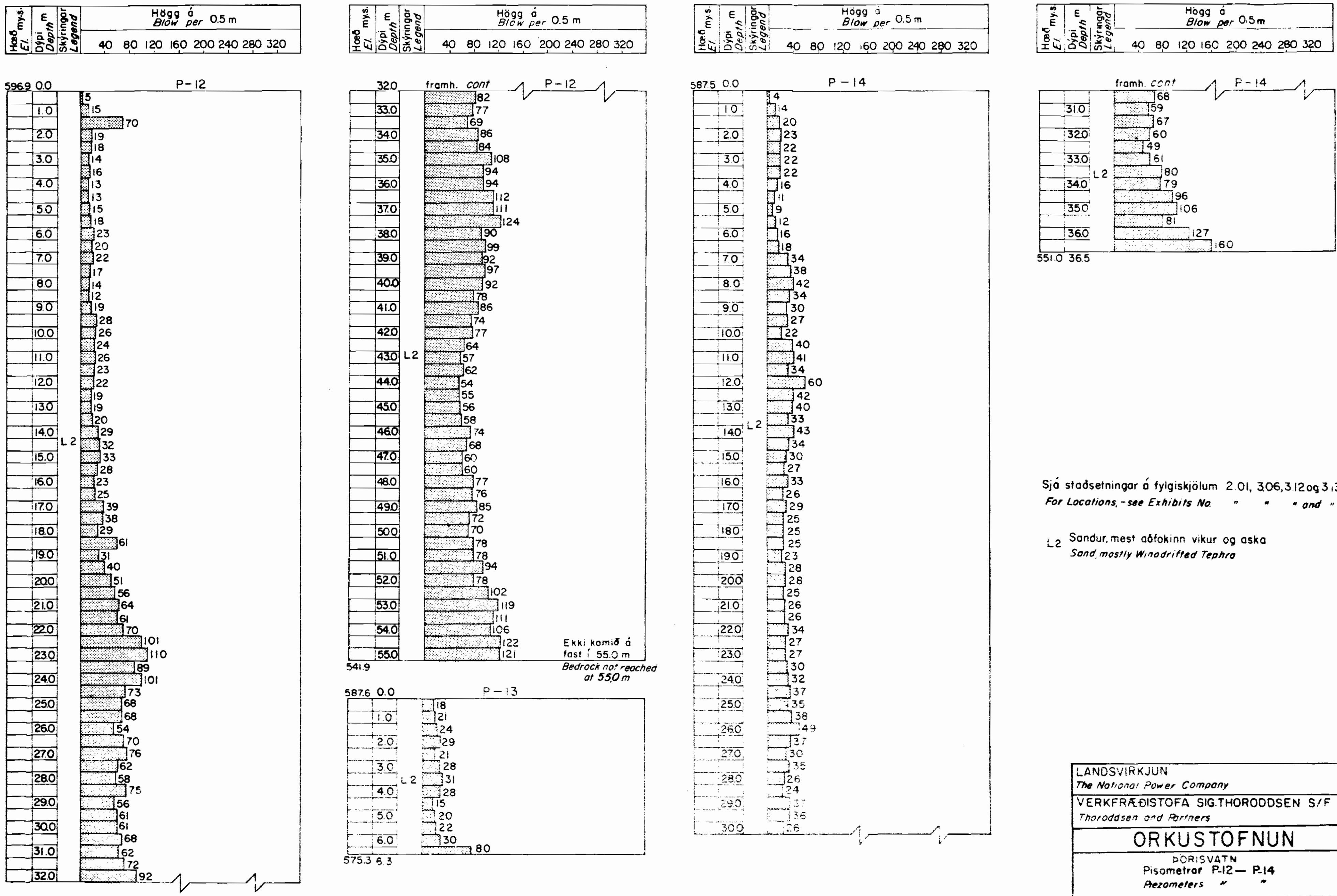
ÞÓRISVATN
Písometrar P.8 — P.11
Piezometers " "

Nov. '69 HT/EK	Tnr. 63	Fnr. 9089
BL. 3 of 6	Bb 86 B-332	



Sjá staðsetningar á fylgiskjölum 2.01, 3.06, 3.12 og 3.13
For Locations, - see Exhibits No " " " and "

L2 Sandur, mest aðfokinn vikur og aska
Sand, mostly Winodrifted Tephra

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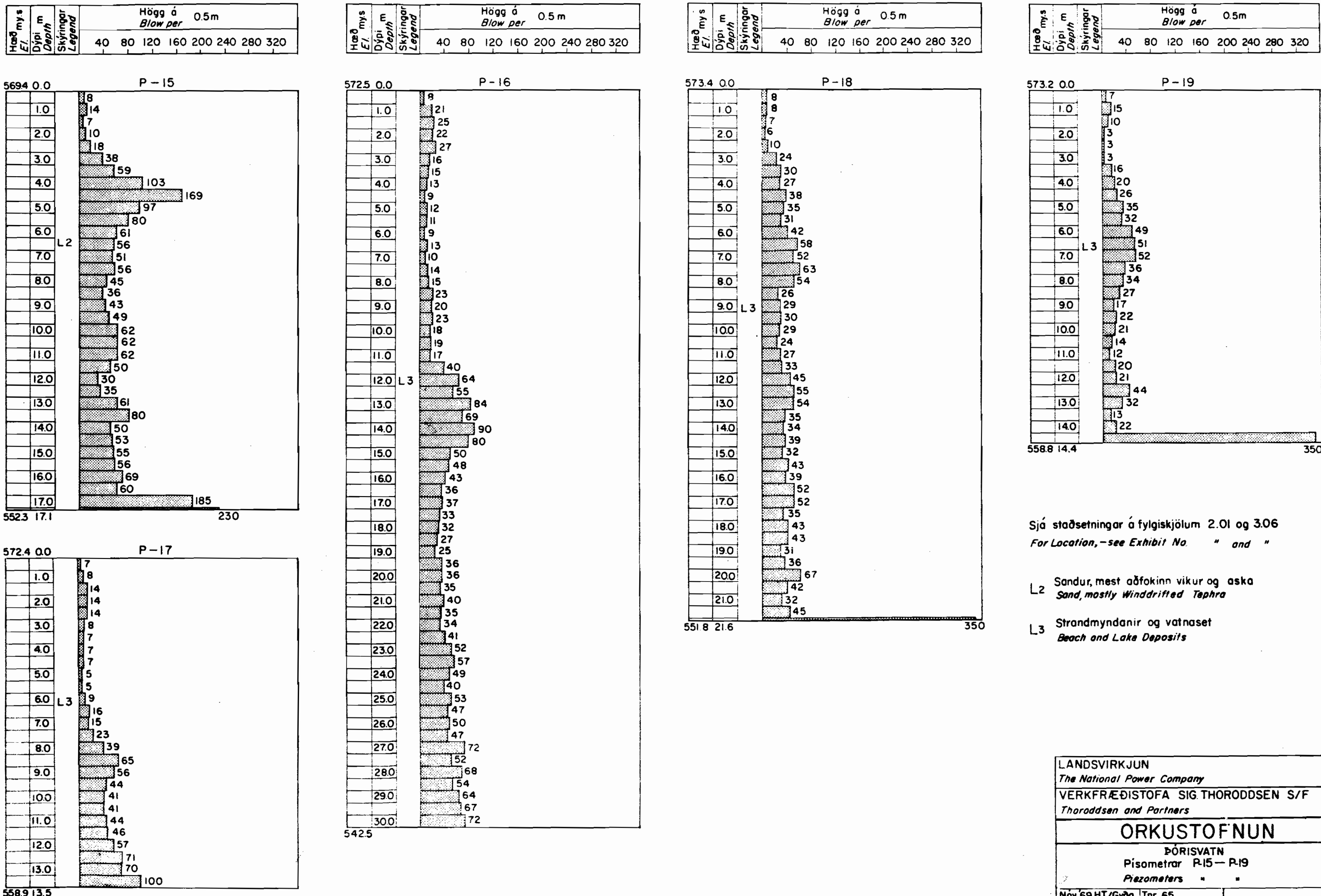
ÞÓRISVATN
Písometrar P-12 — P-14
Piezometers " "

Nov69 HT/EK | Tnr 64 | Bl 4 af 6 | Bb 87 B-332 | Fnr. 9090

EXHIBIT NO. 2.13



Sjá staðsetningar á fylgiskjölum 2.01 og 3.06
For Location, – see Exhibit No " and "

L2 Sandur, mest aðfokinn vikur og aska
Sand, mostly Winddrifted Tephra

L3 Strandmyndanir og vatnaset
Beach and Lake Deposits

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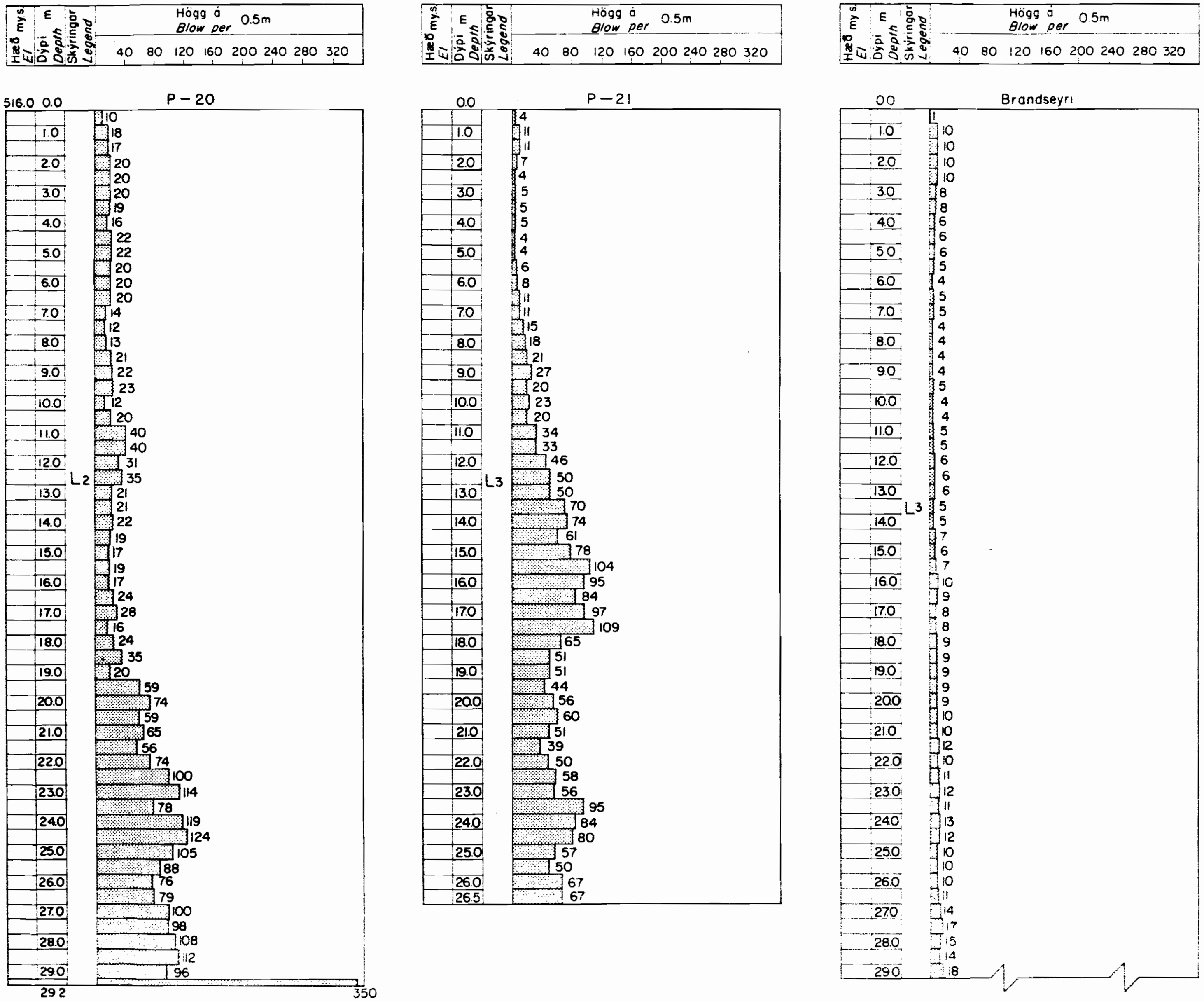
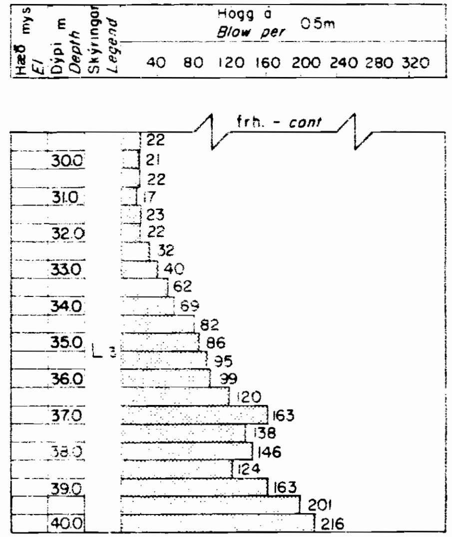
ÞÓRISVATN
Pisometrar P.15 — P.19
Piezometers " "

Nóv. 69 HT/Gyða	Tnr. 65	Fnr. 9091
Bl. 5 af 6	Bb.88 B-332	





Sjá staðsetningar á fylgiskjölum 1.03, 2.01, 3.06 og 3.12

For Locations,– see Exhibits No " " " and "

L2 Sandur, mest aðfokinn vikur og aska
Sand, mostly Winddrifted Tephra

L3 Strandmyndanir og vatnaset
Beach and Lake Deposits

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ÞÓRISVATN

Písometrar P-20, P-21 og borrahola Brandseyri
Piezometers " " and Borro Sound "

21/12'69 HT/SJ Tnr. 104
B: 6 of 6 Ac 05 B 332
Fnr 9196