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INTEGRATED HYDROLOGICAL SURVEY OF A FRESHWATER LENS

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Paper presented at the
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F. Sigurðsson, F. Thorarinsson, S.P. Snorrason, K. Ágústsson
and G. Sigbjarnarson.

National Energy Authority, Department of Economic Geology.
REYKJAVIK, ICELAND

Abstract

A comprehensive hydrogeological survey was carried out in the western half of Reykjanes peninsular for Sudurnes Regional Heating Thermal-Plant, which will need more than 300 l/sec of freshwater for its operation, extraxted from less than 50 m thick groundwater lens floating on seawater. The present paper deals with how a synthesis of geological, geophysical, geochemical as well as hydrogeological methods have been successfully used to obtain a basis for a digital model to estimate a safe yield of the basin. The research has pointed out the most yielding exploitation sites as well as the danger of intermixing with the underlying sea-water or water from known or previously unknown geothermal areas.

Introduction

Since 1975, geohydrological studies of fresh groundwater have been carried out on the western part of the Reykjanes peninsula and are still continued (Fig. 1). The aim of this survey is to provide Hitaveita Sudurnesja (Sudurnes Regional Heating) with ample fresh water to be heated with thermal brine and steam from boreholes at the geothermal area Svartsengi (F. THORARINSSON et al., 1976).

The geohydrological conditions on the western half of the Reykjanes peninsula are rather extreme. The very high permeability of the bedrock causes a low groundwater level in spite of high infiltration (about 800 mm/year, resulting from a precipitation about 1300 mm/year, evapotranspiration 400-500 mm/year and lacking surface run-off). The fresh-water occurs therefore confined to a thin lens, 50-55 m in the main exploitation area floating on sea-water. This implies the danger of seawater intrusions in pumped wells. The exploitation of the area in question must therefore progress cautiously and neccessitates a thorough preparatory geohydrological survey.

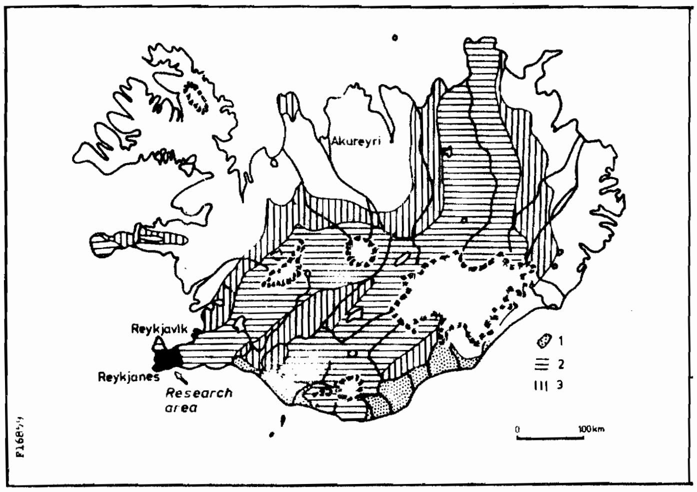

Fig. 1

Location of the research area within the Neovolcanic zone of Iceland:

1. Recent glaciofluvial deposits.
2. Neopleistocene volcanics.
3. Eopleistocene volcanics.

The survey methods are on one hand surface exploration, geological, geophysical and hydrological (run-off at the seashore), and on the other, exploration in boreholes and the few available natural waterholes in the area, this including temperature and water level measurements, resistivity logging and chemical analysis of water. These methods are similar to those successfully applied to the nearby and similar Straumsvík area (F. SIGURÐSSON 1976).

The results of this survey should make a comprehensive basis for a quantitative hydrological model (J. INGIMARSSON et al. 1978), which makes it possible to estimate the safe-yield of the basin and the different exploitation sites, especially as regards pollution by seawater.

Geology.

The Reykjanes peninsula is a part of the "Neovolcanic Zone" in Iceland (Fig. 1), connecting the Reykjanes-ridge and the "Western Volcanic Zone". The formations are therefore almost entirely volcanic in origion and of neopleistocene age (Fig. 2). The volcanic formation falls into three categories: Marginal dolerites, hyaloclastite mountains and lavas.

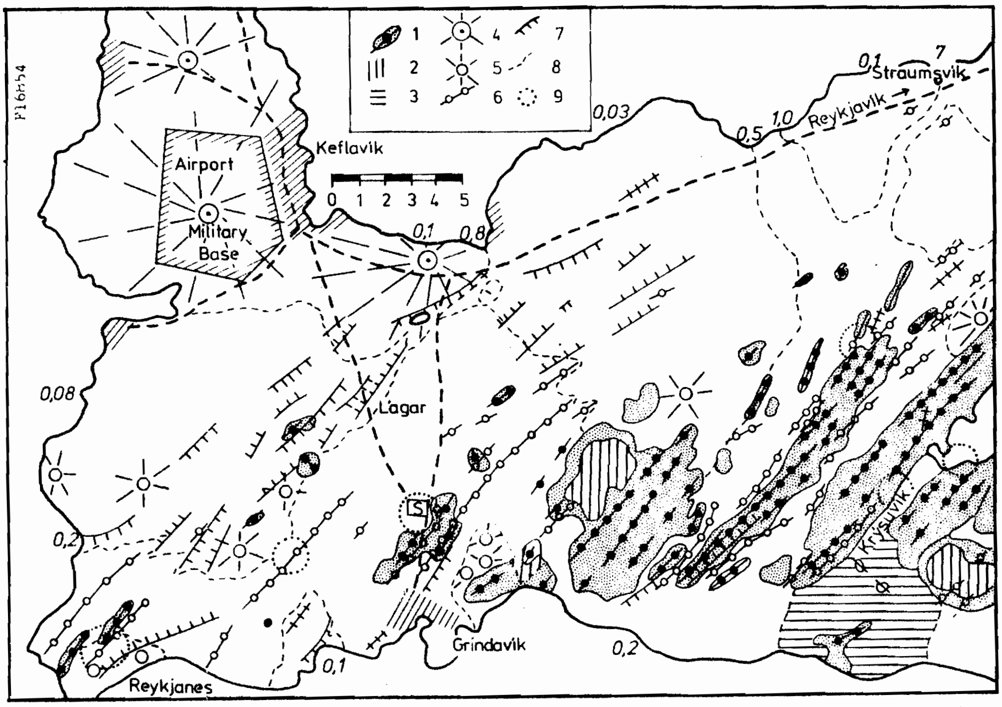

Fig. 2 The geological structure of the western Reykjanes peninsula:
1. Hyaloclastite ridges. 2. Lava caps on table mountains.
3. Interglacial lavas. 4. Interglacial shield volcanoes.
5. Postglacial shield volcanoes.
6. Postglacial eruptive fissures. 7. Main tectonic faults.
8. Boundaries of lavas from postglacial shield volcanoes.
9. Geothermal areas.
The numbers at the coast denote the out-flow in l/m.s.

The dolerites are principially believed to stem from shield-volcano eruptions (JON JONSSON 1965, 1972; F. SIGURÐSSON 1976; F. THORARINSSON et al. 1976). Sedimentary interbedding is scarce in the dolerit lava-pile and glaciation has reduced the permeability considerably, resulting in relatively high ground water levels in the dolerites.

The hyaloclastic mountains are believed to be formed in sub-glacial eruptions, and they are similarily situated as post-glacial eruption sites. The hyaloclastite formation consists of pillow-lava and various hyaloclastites grading into tuffs, and forms mountainous clusters and ridges. The pillow-lava can be highly permeable, but the permeability of the hyaloclastites decreases drastically with increasing tuff content, in spite of increased porosity. The hyaloclastite mountains usually give ris to relatively high ground water levels (F. SIGUÐRSSON 1976; F. THORARINSSON et al. 1976).

The young lavas are post-glacial, and little or none humus or soil covers them, as yet. They are highly permeable, especially when associated wtih a high portion of scoria. Wherever this young lava formation, mostly by tectonic causes, reaches below sea level, ground water levels consequently are relatively low.

The ground water movement is greatly affected by the tectonics. The numerous open fissures channel ground water flow in their direction, while the also numerous faults resist flow perpendicular to this direction. Tectonic grabens, where young lavas reach below sea level, run parallel to faults and channel ground water flow in that direction. The direction of faults and fissures thus creates anisotropy in the ground water flow, which otherwise is directed by rock bodies.

There are two main tectonic systems or directions in this area: N 30-40°E, the direction of recent volcanism and hyaloclastite ridges, and N 60°-70°E, which runs along the northern edge of the volcanic zone and is probably related to the upbuilding of volcanic material in the volcanic zone. As shown by the distribution and discharge of springs and run-off at the seashore, all main water outlets on the Reykjanes peninsula are situated where the latter tectonic system is intersected by landforms i.e. bays, tectonic depressions, lava-filled valleys and such (e.g. Vogavík, 2 m^3/s; Vatnsleysuvík, 1.5 m^3/s, Straumsvík 7.5 m^3/s, Heiðmörk, 3-4 m^3/s). The observed run-off at the seashore supports our ideas about ground water movements on the western half of the Reykjanes peninsula, derived from other observations and data (fig. 2) (JON JONSSON, 1965; F. SIGURÐSSON, 1976; F. Thorarinsson et al., 1976; Á. HJARTARSON, Th. HAFSTAÐ, 1977).

Ground water levels and thickness of fresh water lens.

Ground water levels have been measured in a few boreholes for more than two years (Fig. 3). Annual variation is considerable, and so are short period fluctuations, which can be correlated to variations in infiltration. Mean water level at Lágar is about 1.5 m above sealevel. Two holes have been drilled in the main exploitation area through the fresh water lens (Fig. 3), and it appears that the

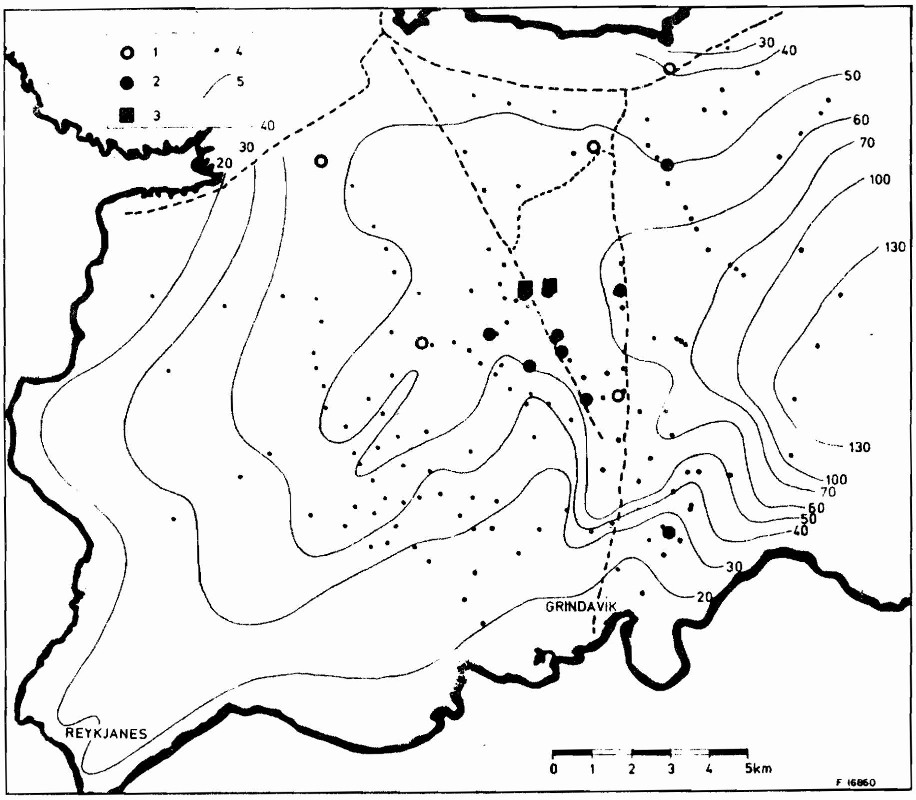

Fig. 3 Locations of geoelectrical soundings; measured thickness of the fresh-water lens: 1-3: Wells: 1. Wells older than two years. 2. Wells younger than two years. 3. Drillholes through the fresh water lens. 4. Geoelectrical soundings. 5. Isolines of thickness of the lens.

fresh water lens down to the middle of the underlying zone of mixing with sea water is about 54 m thick but the whole mixing zone is 16 m thick. The reason why the depth down to the middle of the mixing zone is chosen as a reference point rather than the thickness of the actually fresh water, which is 46 m, is that the height of water level above sea level is proportional to the first rather than the second. "The fresh water lens" will henceforth refer to the lens down to the middle of the mixing zone.

Geoelectrical Soundings.

In connection with the geothermal project in Svartsengi, over 160 vertical soundings (VES) have been carried out, and about 100 of those (Fig. 3) were specificially aimed at measuring the thickness and resistivity of the fresh water lens. The VES curves thus obtained, generally can be described by a three layer model (table 1).

TABLE 1.

		Resitstivity	Thickness
Layer 1.	Dry rock, above water table	5000-20000 Ω m	20-60 m
Layer 2.	Fresh water lens in rock	300-2500 Ω m	20-80 m
Layer 3.	Seawater in rock	3-20 Ω m	

Those familiar with electrical prospecting will immediately realize, how negligent the influence of layer 2 is on the VES curve. Since inhomogenity in the lava, especially at the surface, creates a noise effect of some 5-10%, conventional interpretation by a visual comparison with a set of mastercurves is rendered useless.

We have made this comparison with the help of a computer by calculating a set of 100 normalized mastercurves. (Layer 1: $h_1=1$, $\rho_1=1, \rho_3= 0,001$ and only h_2 and ρ_2 vary, and compared each VES curve with this set. Since the parameters of layer 1 in each VES curve are reatively easy to determine and the resistivity of layer 3 can be taken as zero, this comparison is straight forward and simple. For every VES curve, the computer prints out the error of fitness with each mastercurve, and isolines of error can be drawn on that sheet, h_2 and ρ_2 being the ordinate and abscissa on that diagram. This has the advantage of allowing qualitative information, such as geological knowledge, to be integrated into the final interpretation of the VES curve.

The interpretation is in fact threefold: thickness of the fresh water lens, resistivity of the lens and resistivity in layer 3 (seawater in rock).

The thickness calculated from the VES curves is somewhat smaller than the actual thickness as measured in boreholes. This would stem from the VES curves responding to the increasing salt concentration at the top of the mixing zone, rather than the higher concentrations of seawater at the bottom of the zone, and is to be expected.

In the Lágar area, this difference appears to be about 10%. A correction is made for this in the subsequent discussion. Some variation in the interpretated thickness is observed, but this difference is rarely significant between closely situated measurements. On the basis of this data and measured water levels in boreholes, a map was constructed showing isolines for the thickness of the fresh water lens (Fig. 3).

The resistivity values for the lens (Fig. 4) can not be uniquely correlated to different rock bodies or geological formations, but the general distribution of these values agrees tolerably with the stratigraphy expected from the geological information and also agrees with the measured thickness of the lens (Fig. 3).

In those spots, where resistivity in layer 3 is less than 5 Ω m, resistivity in layer 2 is often reduced as compared to surrounding areas. These spots are also indicated, by temperature and salinity measurements and chemical analysis of fresh water, as geothermal areas, known or probable (fig. 4.).

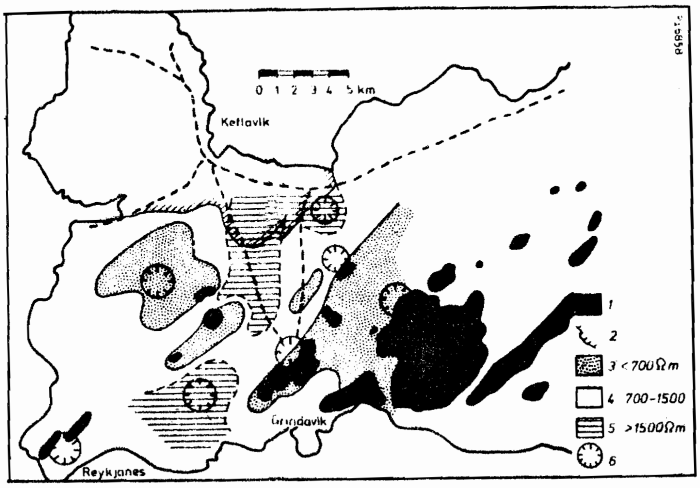

Fig. 4

Resistivity in the freshwater lens

1. Hyaloclastite at the surface
2. Surficial limits of interglacial lavas.
3. Resistivity <700 Ωm,
4. Resistivity 700-1500 Ωm.
5. Resistivity >1500 Ωm.
6. Known and assumed geothermal areas

Temperature and salinity measurements.

Temperature and water resistivity measurements in wells have been carried out at 30 sites for about two years (Fig. 5). These measurements were irregular, but generally done once a month. Annual

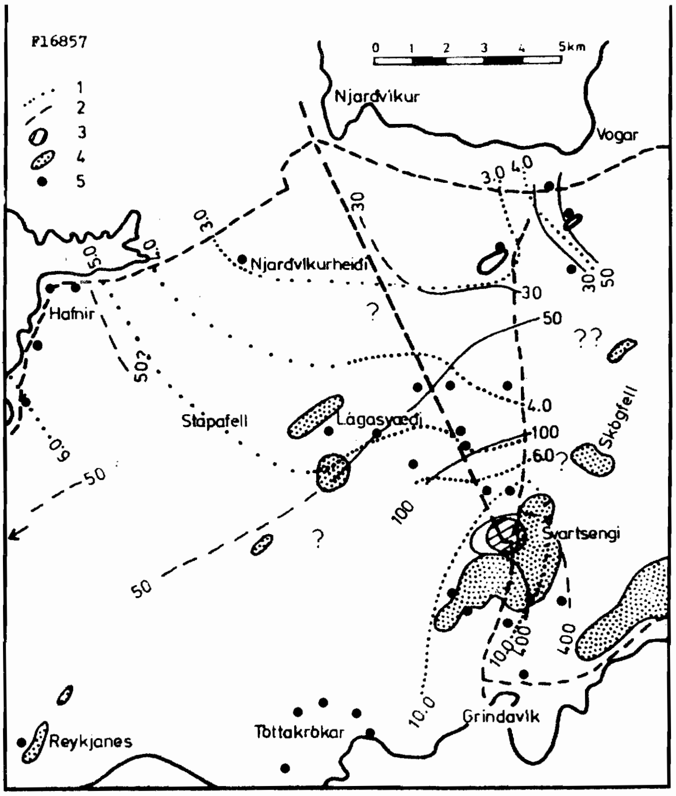

Fig. 5

Temperature and salinity in wells:

1. Isolines in °C of temperature
2. Isolines of estimated cloride content. in ppm.
3. Svartsengi geothermal area.
4. Hyaloclastite at surface.
5. Wells.

variation is common but in some cases meteorologically induced fluctatiions or effects from the pumping of nearby boreholes were observed (F. SIGURÐSSON et al., 1977; F. SIGURÐSSON, 1977). By comparing water resistivity measurements with analysed chloride contents in the water, the resistivity measurements can be interpreted as chloride contents in water.

Generally, temperature rises (3-4° to 6°C) and salinity increases (30 ppm Cl^- to about 200 ppm Cl^-) going from the northwest to the southeast (Fig. 5). Isolines of temperature and salinity make possible a division of the basin into sub-basins with different properties as discussed later. The chemical analysis of fresh water support this division and make it somewhat more detailed in places.

In the light of these divisions and their properties, assumptions may be made about movement, mixing and even origin of individual ground water streams. Special attention is drawn to the effects of the geothermal area at Svartsengi. The difference in properties between some of the sub-basins can be, or even must be, explained with hidden geothermal areas with no surface manifestations (Fig. 4).

Chemical analysis of water.

The chemical composition of the fresh water has these sources: The chemical composition of rain water; the injection of seawater, airborne or diffused from the mixing zone; ion exchange between rock and water, increasing the ratio of cations and SiO_2 to Cl^-; injection of thermal brine (S. ARNÓRSSON et al., 1975) and other similar geothermal influences, decreasing the ratios of Mg^{++} and SO_4^{--} to the total ion contents. Chemical analysis of rain water from the area are not yet available and analysis of rain water from Keldnaholt, Reykjavík, are considered instead. A marked difference between sub-basins and the influence of different chemical sources is most clearly seen in the chloride content and the ratios between chemical components (Table 2).

In the northern part of the research area, ion exchange between water and rock is the dominant feature, but the influence of seawater and thermal brine injection increases to the SSE, towards the geothermal area at Svartsengi (Fig. 6). Seawater injection is clearly indicated SW of the geothermal area, and thermal brine injection SE of it.

TABLE 2.

Sample, type or site	Cl^- ppm	$(K^+/_{Cl^-})$ x 100	$(Mg^{++}/_{Cl^-})$ x 100	$(SO^{--}/_{Cl^-})$ x 100	$(SiO_2/_{Cl^-})$ x 100
Rain water	7	4	13	57	4
Seawater	19000	2.0	6.7	13	0.0
Thermal brine	12000	7.9	0.0	0.3	3.8
Njardvíkurheidi	25	6	20	40	35
HSK-13	25	4	7	40	35
HSK-5/6	40	2.5	10	25	30
HSK-2/4	75	2	10	15	20
Snorrast.tjarnir	70	2.5	10	20	15
HSK-12	160	2	7	15	10
HSK-7	400	2.5	5	10	10

Location of wells are shown in Fig. 7

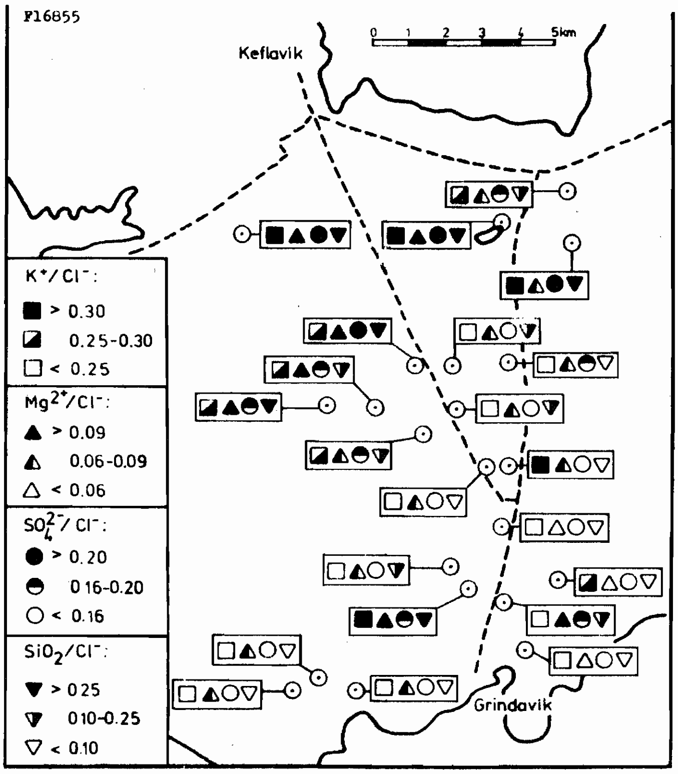

Fig. 6

Chemistry of water in wells; ratio between chemical components.

Divison of the ground water basin.

The research area is, to a first approximation, one ground water basin. It is convenient, though, to divide it into sub-basins, on

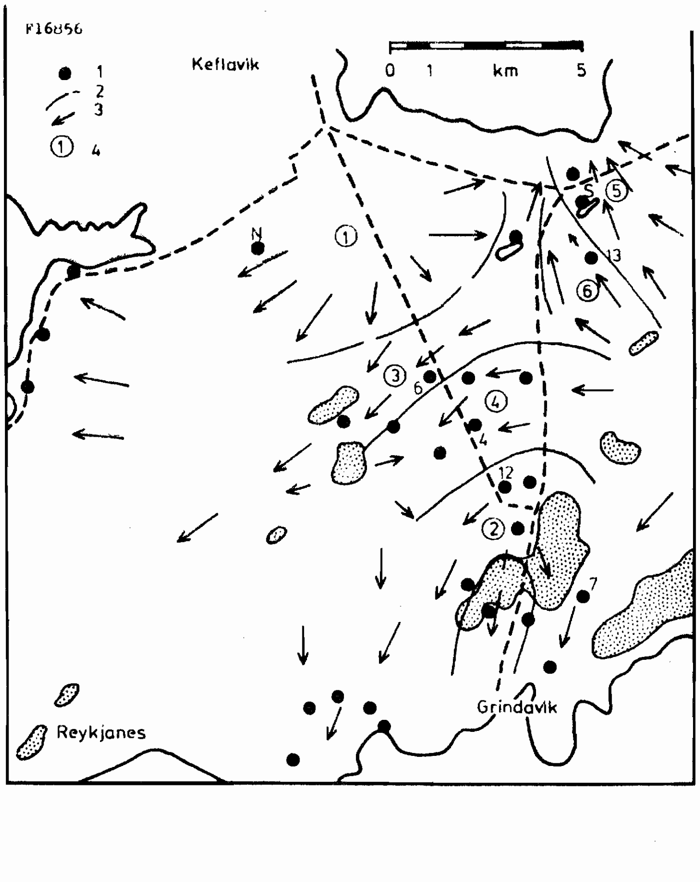

Fig. 7

The divison of the groundwater regime in sub basins and postulated flow of groundwater:

1. Wells. Numbers refer to Table 2.
2. Boundaries of sub-basins.
3. Flow directions.
4. Number of sub-bsins; see text.

the basis of different properties. These sub-basins may or may not fit the usual definition of a ground water basin (TODD, 1959, pr. 31).

Ground water levels indicate a sub-basin (1) in the dolerites on the northern part of the research area, a sub-basin without any inflow (numbers refer to Fig. 7.) The surroundings of the geothermal area at Svartsengi form a sub-basin (2), which is clearly under a geothermal influence and is drained to the SSW. Between these two sub-basins are two others, (3), (4), each rather constant in salinity and chemical composition, but temperature increases in both these sub-basins towards WSW, though not equally (Fig. 5). This probably indicates very little mixing between them, but the chemistry of the southernmost sub-basin (4) may be influenced by a geothermal area farther to the east. That same geothermal area might have some influence in the NW corner of the research area (5). Between these two might be yet another sub-basin (6) with no inflow, being probably on the watershed between catchment areas. West of the main research area, near the coast, some indications may be found of an influcence from a hidden geothermal area (Fig. 4).

This division into sub-basins and the postulated flow of ground water (Fig. 7) and position of boundaries of catchment areas agrees with the thickness of the fresh water lens, as calculated from VES curves (Fig. 3). Again, the thickness agrees with the probable stratigraphy of the research area.

Basis for a mathematical model.

Since the conclusions drawn from various surveys fit reasonably well together, it ought to be possible to define a basis for a mathematical hydrological model of the whole basin with considerable certainty. Based on our then present knowledge such a model was constructed, early in 1977, but it did not fit well enough with data acquired later. A new basis for a model was therefore set up in april 1978, and a new model will be constructed this summer.

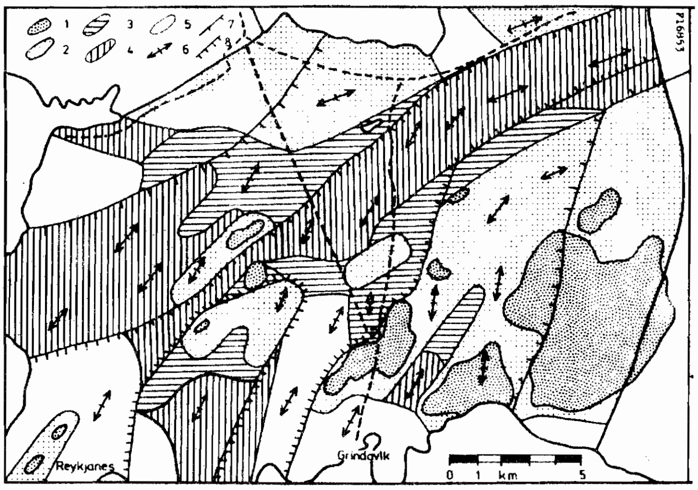

Fig. 8

The hydrogeological base for the hydrological model:
1. Hyaloclastite at surface. 2-5. Permeability of rock bodies:
2. Low.
3. Rather low.
4. High.
5. Very high.
6. Direction of anistropy.
7. Boundaries of anisotropic areas.

This new basis consists of the classification and location of rock bodies of various permeabilities and includes the anisotropy caused by the tectonic (Fig. 8).

Discussion

The investigation referred above is a part of the system of the investigations and the exploitation of the ground water basin (Fig. 9).

The information gained from the hydrogeological survey is threefold.

1. Properties of the aquifers.
2. Properties of the water.
3. Thickness of the freshwater lens.

Each group of information is independant of the others, and they can therefore be checked against each other to narrow the range

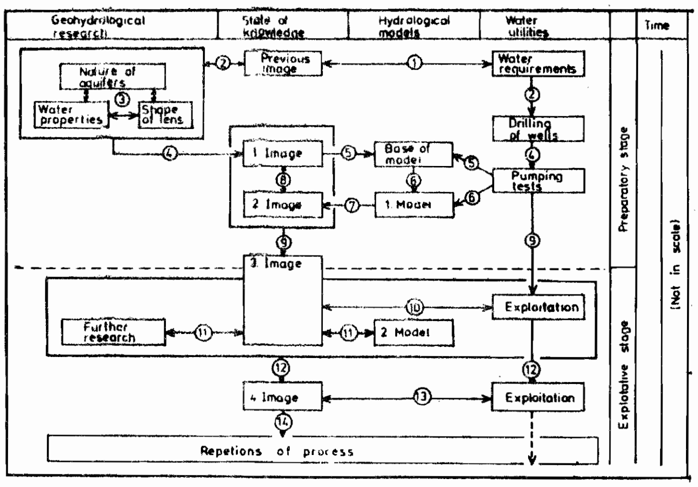

Fig. 9

Schematic connection between research and exploitation.

of possible conclusions. Since these conclusions are the basis for a mathematical model, the information can furthermore be checked against the output of that model and the choice of conclusions is further limited. Possible lack of information becomes evident at this stage. Further checking and conterchecking of this kind will continue as the exploitation progresses and more research is carried out. Thus improved ideas of safe yield and the general conditions of the basin should be developed continuously.

In this way, knowledge of the basin should keep pace with the exploitation and prevent an excessive overdraft. The investigation here referred only just prevented a shortage of water and then possibly the damage of aquifers and a close-down of the thermal plant for some time. This is now apparent, since previously the freshwater lens was assumed to be up to 150 m thick in the exploitation area (K. Ragnars and S. Arnorsson, 1974). Had this assumption been true, ground water could have flowed through the basin from the east to the west. This could have been in accordance with a possible interpretation of the investigation of deuterium-content in water in the Reykjanes peninsula (B. Árnason, 1976), but is now deemed extremely unlikely.

Acknowledgments:

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