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BOREHOLE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELL SV-14, SVARTSENGI, SW-ICELAND

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ABSTRACT

This report describes the stratigraphic sequence and the alteration in drillhole SV-14 in the Svartsengi high-temperature field, SW-Iceland. The stratigraphic column consists of a hyaloclastite formation. This was formed under the ice sheet as a result of the quenching of magma in water. It consists consequently of a mixture of vitroclastic glass and partially crystalline basalt. The hyaloclastite formation is divided into three types, the first type, the hyaloclastite tuff, is dominantly composed of perlitic glass, the second type is the hyaloclastite breccia made up of similar amounts of perlitic glass and partially crystallized basalt and the third type is the basaltic breccia which consists of a majority of partially crystallized basalt and minor perlitic glass. Three alteration zones are divided in the well, the zeolite smectite zone, the mixed layer clay zone and the chlorite zone. Aquifers in this well were located on the basis of borehole measurements and records of circulation losses.

1. INTRODUCTION

1.1 General information

Iceland lies astride the Mid-Atlantic Ridge which represents the constructive boundary of the European and the American plates. The main geological formations of Iceland are shown in Figure 1. The oldest formation is Tertiary (3-16 m.y.) and consists of a lava succession in general dipping gently towards the volcanic zones. The second formation is of Quaternary, Plio-Pleistocene age (0.7-3 m.y.). The succession consists of alternating sequences of lavas and hyaloclastites. The former is formed during the interglacial periods whereas the hyaloclastites were formed as a result of subglacial eruptions of the ice ages. The third and youngest formation is contained within the neovolcanic zone and is composed of Upper-Pleistocene and Postglacial formations (< 0.7 m.y.). As seen in Figure 1 this zone delineates the rift zones. The rifting within the neovolcanic zone is mainly confined to distinct fissure swarms. Generally, a central volcano forms at the central part of each fissure swarm. These volcanoes are the foci of magmatic activity within the fissure swarms and it has been shown from studies in the deeply eroded

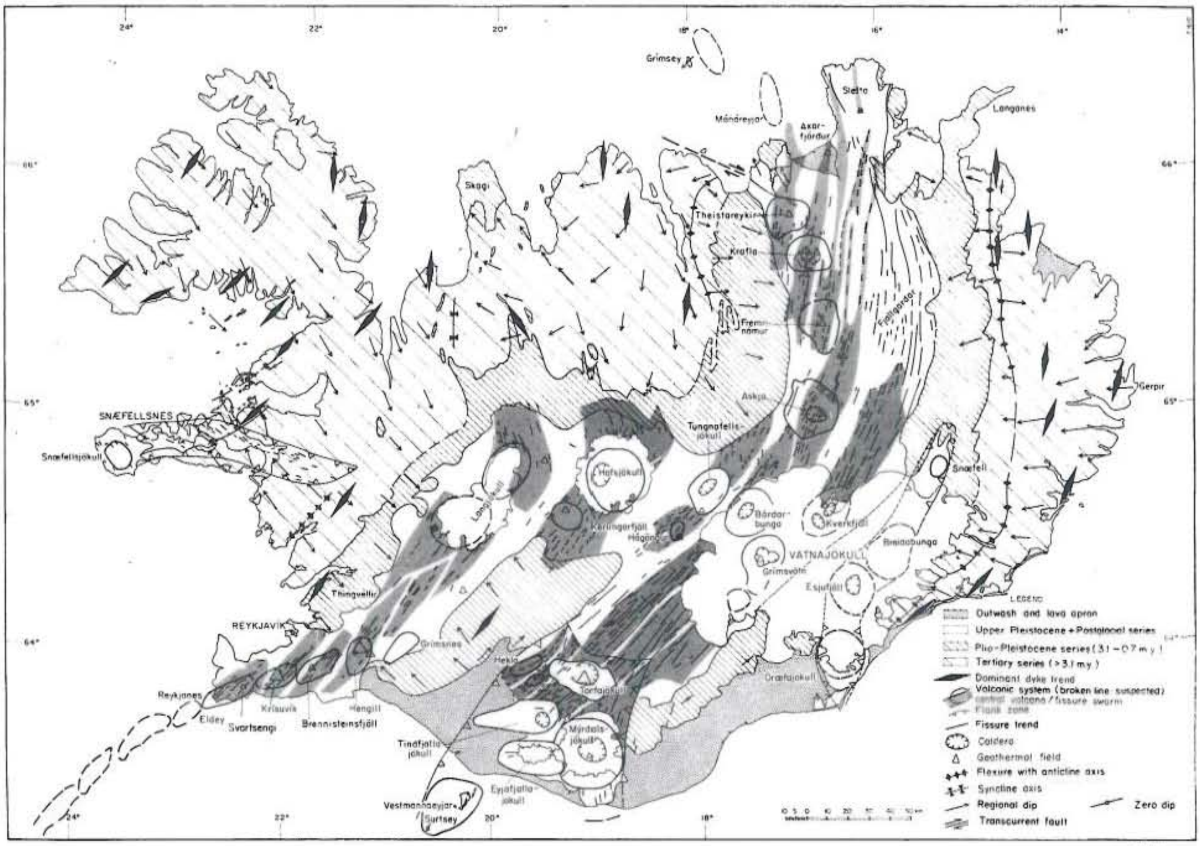

FIGURE 1: Geological map of Iceland (Saemundsson, 1979)

regions (i.e. in the Tertiary and Quaternary regions) that a high percentage of intrusions occur in the core of these volcanoes (Saemundsson, 1979). The high-temperature areas are confined largely to the central volcanoes of the active volcanic rift zones, and are thought to draw heat mainly from local accumulations of igneous intrusions emplaced at a shallow level in the crust (Fridleifsson, 1979).

The Svartsengi area is located on the Reykjanes Peninsula, approximately 50 km southwest of the capital Reykjavik and covers the Svartsengi geothermal field, the lava fields surrounding it, and the pillow lava piles of Hagafell, Lágafell and Thorbjarnarfell and the table mountain of Svartsengisfell. The Svartsengi high-temperature geothermal field is producing 100 MW_{th} and 16 MW_{el} for the communities in the region. The geothermal field has a very high degree of faulting caused by an active fissure swarm cutting across the field, but surface manifestations are few and surface alteration is of rather small extent.

Previous work done in the area consists of geologialc mapping by Kuthan (1943), Jón Jónsson (1978), Freysteinn Sigurdsson (1985) and Haukur Jóhannesson (1989). Hjalti Franzson (1990) mapped the surface alteration and structural lineations of the geothermal field. The surface alteration zones have been classified into high-, medium- and low-intensity alteration zones. High-intensity alteration is found where extensive formations of clay occur; medium-intensity alteration is characterized by extensive deposition of silica, in the form of opal crusts, and/or aragonite, and low-intensity alteration is characteristic of slight deposition of silica, also in the form of opal crusts. Active manifestations are characterized by hot soil and steaming ground (Franzson, 1990).

The geothermal areas in Iceland are divided into two distinct groups (Pálmason et al., 1979). The low-temperature areas are in Quaternary and Tertiary rock formations, and the high-temperature areas are in the active volcanic zones. In the low-temperature areas the temperatures are below 150°C at 1 km depth, whereas in the high-temperature areas the temperatures are higher than 200°C at this depth.

1.2 The geology of the Svartsengi area

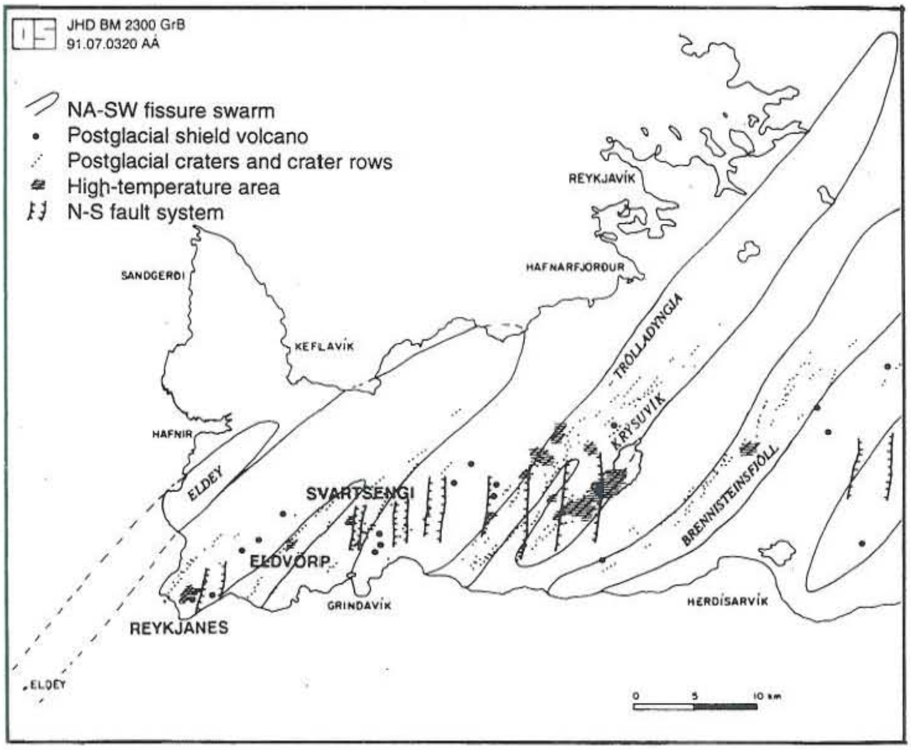

FIGURE 2: A structural map of the outer Reykjanes Peninsula, showing volcanic systems, fracture systems and high-temperature areas (Jóhannesson, 1989)

The Grindavík swarm is the second westernmost fissure swarm on the Reykjanes Peninsula (Figure 2). About 30 eruptions are believed to have occurred within the swarm during Holocene age (Postglacial) and are mostly fissure lavas (Jakobsson, et al., 1978) The Svartsengi high-temperature field lies within the Grindavík fissure swarm. The production is located to the north of Thorbjörn mountain and west of the Svartsengisfell mountains. The oldest rock formations outcrop at Thorbjörn and Svartsengisfell mountains, consisting, to a large extent, of pillow lava and some hyaloclastite. The second main geological surface formation consists of postglacial lava flows which entirely cover the high-temperature area. These lavas are both of aa and pahoehoe types. Two small lava craters are found at the northern foot of Thorbjörn mountain. The lava issued from these craters is likely to be found underlying the topmost lava to the north and east. The two youngest lavas largely cover the Svartsengi area, the northern one derived from an approximately 10 km long fissure to the east of Svartsengisfell, and the lava flow to the south derived from a short fissure west of Thorbjörn. These lavas are mostly of aa type (Jónsson, 1978).

1.3 The Svartsengi high-temperature field

Active surface geothermal features are lacking and the hydrothermal alteration is insignificant, mostly represented by patches of clay alteration in the hyaloclastite formations in the northern slopes of Thorbjörn mountain and western part of Svartsengisfell (Jónsson, 1978). The area of hydrothermal alteration has been roughly estimated as 1-2 km^2 (Arnórsson et al., 1975). Before exploitation, steam was only seen rising from fractures in the lava west of Svartsengisfell in certain weather conditions (Jónsson, 1978).

On the Reykjanes Peninsula the cold groundwater movement is greatly controlled by tectonics and is, in fact, characterized by a very high permeability of the bedrock causing a low groundwater level in spite of high infiltration. The groundwater in the region is confined to a 50-55 m thick lens floating on seawater in the central part of the peninsula, which thins out towards the coastline.

Resistivity in the ground is extra low due to the salinity of the ground water. In areas of geothermal activity it is even lower due to increasing temperatures. Discrimination between the effects of temperature and salinity is sometimes difficult. From resistivity measurements the outer boundary of the Svartsengi high-temperature field has been defined, and the geothermal area is estimated to be 6-7 km^2 at 600 m depth b.s.l. and increasing downwards (Georgsson, 1984).

The temperature profiles are rather similar in the Svartsengi drillholes. Between 40 and 230 m the temperature ranges from 40 to 70°C, but increases sharply below 230 m to about 180°C at 320 m. From there the temperature continues to increase to about 235°C at about 500 m below sea level below which it remains nearly constant.

1.4 Location of the well SV-14

Well SV-14 was located about 150 m south of well SV-10, about 40 m from well SV-3 and about 50 m west of the main road to the seaside village, Grindavik. The main intension of the project was to sink the well into the steam cap area to utilize it for electrical production. Figure 3 shows the location in relation to other well and the power plant in Svartsengi.

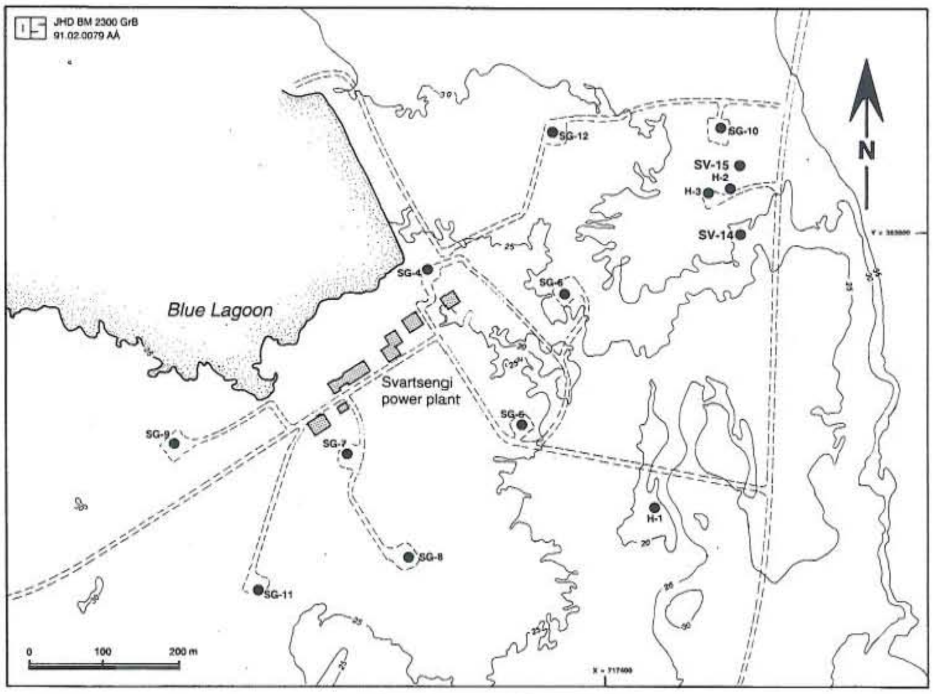

FIGURE 3: The Svartsengi power plant and location of wells (Björnsson and Steingrímsson, 1991)

2. STRATIGRAPHY OF WELL SV-14

2.1 Introduction

Relatively detailed cutting analyses along with various other borehole logs were used to assess the geothermal system into which SV-14 was drilled. During drilling, rock cuttings were taken at a 2 m interval and properly labelled. The circulation fluid was monitored every four hours and under some circumstances more often. The penetration rate was calculated for every 2 m interval. Temperature logs were done during drilling to locate aquifers and assess the condition of the well. After the drill string was pulled out of the borehole at the end of drilling, geophysical logs were conducted. Regular temperature and pressure measurements were conducted during the warming-up period of the well.

The cuttings are very reliable indicator of the thermal history of the reservoir. The samples from the field, after being properly logged, are transported to a petrographic laboratory. At the laboratory, the samples are air-dried for proper safekeeping and storage. Before cutting analysis the samples in the boxes are wetted by pouring water on to them. Wetting the cuttings is convenient for enhancing the visibility of the rock types and minerals. The wet samples are then placed under binoculars for investigation. Essential features to be noted during binocular study are as follows: Rock type(s), grain size(s), rock fabric(s), original mineralogy, alteration mineralogy and intensity, colour(s), presence or evidence of faulting, size and shape of drill chips, and types and amounts of contaminants. Examination was done using a Wild Heerbrugg binocular microscope with a magnification of 6-80x. Initial information obtained included stratigraphy, alteration mineralogy and evidence of permeabilities.

In addition to binocular microscopic study, thin sections for petrographic study were made in order to expand or confirm preliminary findings of the cuttings. Selected thin-section samples were analysed using a Leitz Wetzlar petrographic microscope. Moreover, X-ray diffraction analyses were done to confirm and identify the types of clay minerals present in the cuttings.

All of the data gathered from cutting analyses and borehole measurements were combined and assessed to explain the geothermal system in which the well was drilled.

2.2 Drilling of well SV-14

The SV-14 was drilled in the Svartsengi geothermal field to mine steam from the steam cap. The hole was completed in 33 working days or between January 1st 1993 and February 20th 1993. First stage was percussion drilling with a 23" hammer down to 34 m depth and the well was cased with an 18 5/8" casing. Then a larger drillrig (Narfi) was installed on the well. First it was drilled down to 100,4 m with a 17 ½" bit, and cased to 99 m with a 13 3/8" casing and cemented. Drilling was continued with a 12 1/4" bit down to 197 m depth and the well cased with a 9 5/8" casing to 195 m and the casing cemented. The production part of the well was finally drilled with a 8 ½" bit down to 612 m depth and a slotted liner placed in that part of the well down to 598 m. During drilling, the well inclination was monitored and the results are shown in Table 1.

TABLE 1: SV-14, well inclination

Depth (m)	Inclination from vertical (m)	Horizontal accumulative deviation (m)
95	0.2	0.2
165	2.0	1.3
250	3.8	5.6
400	4.0	15.8
550	4.9	27.4
610		32.4

2.3 The stratigraphy of well SV-14

Cuttings analysis made it possible to detect a presence of hyaloclastite formation and divide it into three different units (Figure 4). The hyaloclastite was formed under an ice sheet as a result of the quenching of magma in water. It consists, consequently, of a mixture of vitroclastic glass and partially crystalline basalt. The hyaloclastite unit is divided into three lithological types. The first type, the hyaloclastite tuff, is predominantly composed of perlitic glass. The second type is the hyaloclastite breccia made up of similar amounts of perlitic glass and partially crystallized basalt. The third type is the basaltic breccia which consists of a majority of partially crystallized basalt and minor perlitic glass. Petrographically the hyaloclastite unit shows a similar grading in crystallinity from pure vitroclastic near opaque glass to holocrystalline basalt, the latter of mostly granular texture and only rarely showing sub-ophitic texture.

These three lithological types show a variance from one depth to another due to different alteration. A plausible explanation may be different permeability in similar lithological units, which affects the alteration processes. Figure 4 shows the detailed stratigraphy and penetration rate of well SV-14.

2.4 Volcanic succession from the cuttings

Depth	**Description**
0-14	No cuttings.
14-28	Altered tuff and fresh fine- to medium-grained basalt. Hydrothermal alteration minerals like pyrite, calcite, and chalcedony (quartz).
28-32	Tuff-breccia, dark colour, fine-grained matrix and medium- in the crystals. Few fragments with oxidation, the majority of fragments with vesicles.
32-36	No cuttings.
36-62	Pillow-lava, medium-grained, with plagioclase phenocrystals, pyrite micro-crystalline at alteration mineral. Some fragments with vesicles with clay phenocrystals or chalcedony filling.
62-66	Basaltic-breccia, dark colour, fine grain, with veins of calcite and chalcedony. Vesicles with clay inside, pyrite micro-crystalline and some basaltic fragments with oxidation.
66-72	Tuff-breccia, dark colour, medium-fine-grained, vesicles with clay filling, few pyrite.
72-88	Basaltic-breccia, gray colour, medium-fine-grained, with vesicles with clay inside, some plagioclase porphyritic, basaltic fragments, few quartz fragments and pyrite micro-crystalline.
88-104	Tuff-breccia, brown colour, medium-fine grain, with vesicles, with clay, calcite and chalcedony fillings, some basaltic fragments with plagioclase and pyrite.
104-106	No cuttings.
106-176	Pillow-lava, gray colour, medium-fine-grained, with a few vesicles, the majority with clay and pyrite.
176-180	Basaltic-breccia, gray colour, with pyrite and few plagioclase phenocrists, some basaltic fragments with vesicles with clay, no oxidation and few zeolites.
180-192	Basaltic-lava altered, few vesicles with clay and chalcedony filled, few zeolites.
192-198	Basaltic-breccia, very altered, with vesicles filled with clay, few pyrite, calcite.
198-206	No cuttings.
206-208	Tuff-altered, brown colour, with some vesicles clay and calcite fillings, there are pyrite micro-crystalline and few plagioclase. Some zeolite fragments.
208-218	Basaltic-breccia, gray colour, medium-fine grain, some calcite fragments, no pyrite but some vesicles filled with clay.
218-224	Tuff-breccia, with vesicles filled by clay inside, a little oxidation, few calcite and chalcedony fillings.
224-266	Basaltic-breccia, brown colour, calcite, pyrite and vesicles with clay, Some basaltic fragments are oxidized.
266-274	Tuff-breccia, brown colour, fine grain, with vesicles with clay inside, pyrite along with a little oxidation and calcite.

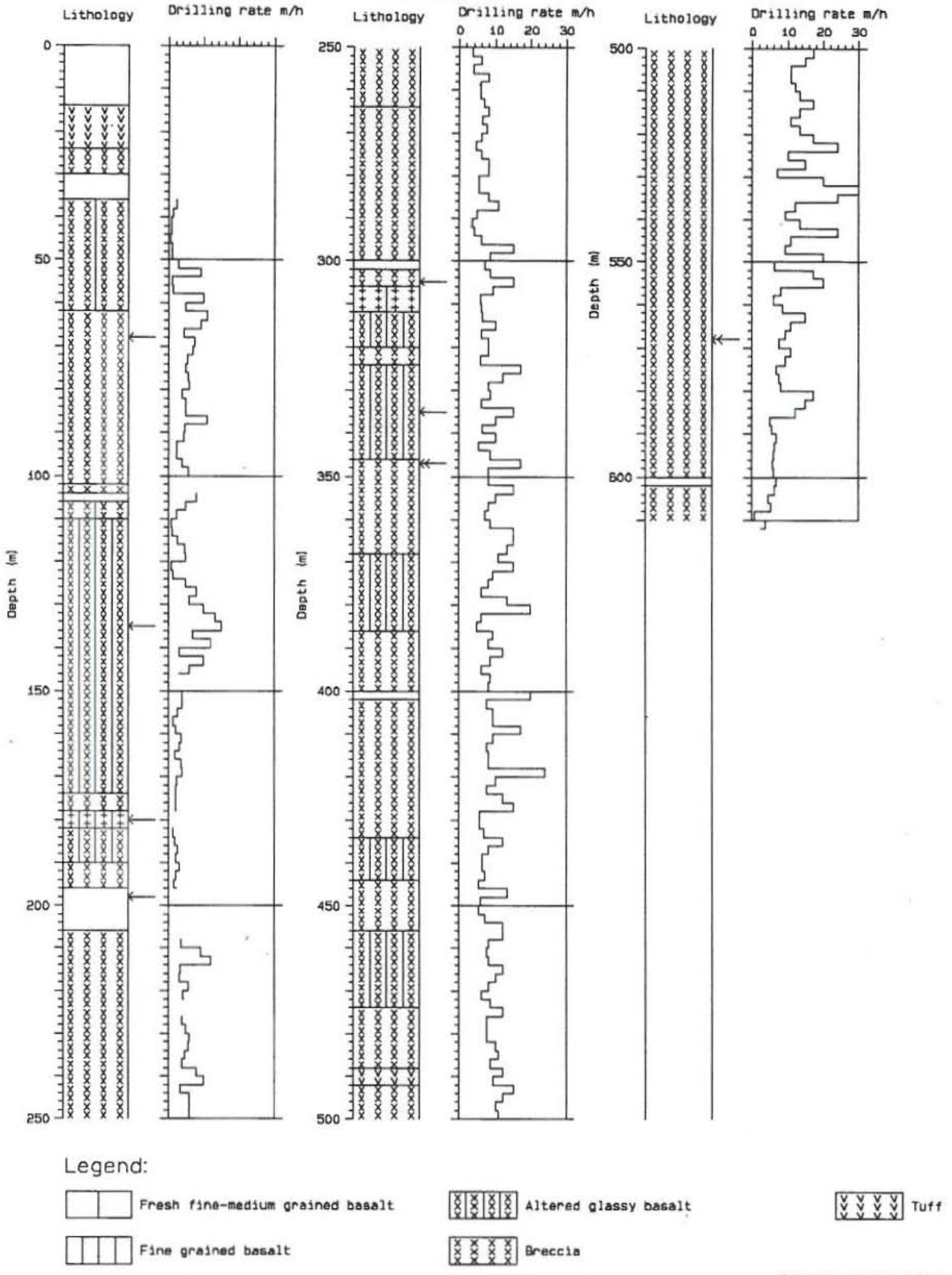

FIGURE 4: Detailed stratigraphy and penetration rate of well SV-14, Svartsengi

274-302	Basaltic-breccia, brown colour, medium-fine-grained, some fragments are altered and with white colouration. The basaltic fragments have vesicles with clay fillings, some calcite fragments, a little oxidation and a little pyrite.
302-304	No cuttings.

304-308	Basaltic-breccia, brown colour, medium-fine-grained. Some fragments altered with white colouration. The basaltic fragments have vesicles with clay, calcite fillings, a little oxidation grade and a little pyrite.
308-314	Basaltic-lava, very altered, with pyrite, calcite and few heulandite crystals.
314-348	Pillow-lava, medium altered, some vesicles with clay, some pyrite micro-crystalline, a few calcite.
348-370	Basaltic-breccia, very altered, with calcite and pyrite and slight oxidation, some vesicles clay filling and rare chalcedony.
370-388	Pillow-lava, brown colour, variable alteration, some vesicles have clay fillings, few pyrite micro-crystalline, there are calcite and plagioclase.
388-402	Basaltic-breccia, altered, medium-fine-grained, with few vesicles filled with clay, few calcite, most pyrite micro-crystalline, a little oxidation and some zeolites.
402-404	No cuttings.
404-436	Basaltic-breccia, very altered, fine-grained, white colour, a little oxidation, pyrite microcrystalline, some vesicles with clay or calcite inside and some zeolite crystals.
436-446	Pillow-lava, dark colour, fine-grained, some fragments completely altered. There are vesicles with clay filling and a little calcite.
446-458	Basaltic-breccia, with oxidation and some vesicles with clay fillings, chalcedony and micro pyrite crystalline.
458-478	Pillow-lava, dark colour, fine-grained, few vesicles with clay fillings, some zeolites a few micro pyrite crystalline, some quantity of calcite.
478-490	Basaltic-breccia, very altered, fine-grained, with vesicles with clay fillings, some calcite, quartz and pyrite.
490-494	Tuff-altered, with pyrite and calcite.
494-508	Tuff-breccia, with basaltic lava fragments, very altered. Vesicles with clay fillings, few grades of oxidation, some of pyrite and calcite.
508-514	Basaltic-breccia, very altered, formed by basaltic lava fragments with variable alteration. Few vesicles with clay inside, and some pyrite, calcite and zeolite.
514-602	Tuff-breccia, very altered with some zeolite, pyrite, calcite, chalcedony, opal and a little quartz. A little oxidation present, quantity of vesicles with clay fillings.
602-604	No cuttings.
604-612	Tuff-breccia, very altered with zeolite, pyrite, calcite, chalcedony, opal and quartz, some quantity of vesicles with clay fillings, some oxidation present.

3. HYDROTHERMAL ALTERATION IN WELL SV-14

3.1 Analytical techniques

The X-ray diffractometer (XRD) is an extremely valuable instrument for identifying minerals and can be used, under some circumstances, to provide qualitative and quantitative information. It is especially good for identifying clay and zeolite minerals but is expensive. It is capable of detecting subtle differences in the thermal characteristics of clays.

Each clay mineral group is characterized by a particular type of layer structure and interlayer material. Consequently, the basalt reflections give very useful indications of the mineral present in a clay sample. There are considerable limitations to an analysis based only on these data. In the first place, most natural clays are mixtures of several clay minerals and a number of accessory minerals. Reflections from clays are usually broad because the crystals are thin and the layer stacking is frequently disordered. This, together with the large number of minerals frequently present, leads to overlapping reflections and few observable reflections from less abundant components. It is, therefore, usual to examine clay specimens before and after various treatments that alter the diffraction patterns of the components. The most common are treatments with polar liquids of low volatility, such as ethylene glycol to aid the identification of smectites, and various heat treatments that collapse swelling minerals by dehydrating the interlayer material and destroying or transforming minerals such as kaolinite and hydroxides. These treatments are also valuable in elucidating the nature of the components of interstratified minerals. After drillcutting analysis, it was possible to know where clay was most abundant in the well. Therefore, twenty-one samples were selected, corresponding to the twenty-one different depths.

As mentioned above, XRD is the most common method for clay analysis. Each sample undergoes three different treatments. The first round of samples are untreated; they are usually analysed directly after preparation, but in some circumstances they are kept at constant humidity for several hours. The second round of samples undergoes a special glycol treatment to see if they can swell or not. They are installed in a dessicator for at least 24 hours (see Appendix). The third round of samples is heated for one hour at a temperature of 500-550°C.

The result of the XRD analysis is most important for interpreting the rock formation temperature when referring to mineral alteration. It also provides fundamental data for the construction of alteration zones.

3.2 Petrographic analysis

Identification of hydrothermal minerals can be used to comment upon present and past conditions in a geothermal reservoir. Thus, for example, mineralogical estimates of subsurface temperatures can be available shortly after samples are recovered and this information can be used to help make decisions and plans without the long waiting period needed for a well to stabilize thermally. However, it is important to compare alteration- and measured temperature for further knowledge of the reservoir's character.

In the petrographic study, thirty-two samples were collected for extensive examination. The study was divided into two main categories, i.e. a study of primary rocks and a study of secondary minerals. The occurrence of calcite, quartz, feldspar and clay minerals in the well show the alteration grade dominant in the area. Chabazite and scolecite are rare, but other minerals, like stilbite, chalcedony, sphene, albite, anhydrite and mixed-layer clay, appear principally in the deep section. Table 2 shows the results of the petrographic analysis in well SV-14.

3.3 Alteration in well SV-14

Considerable alteration data have been assembled from the geothermal wells in Iceland, both within the Svartsengi field and from other fields. Only those data which show temperature variation, permeability and porosity within and outside the high-temperature reservoir will be discussed here. Alteration has been used extensively in Iceland to assess the temperature (past and present) in the hydrothermal systems. In this particular well the upper boundary of the mixed layered clays (about 200°C) occurs at about 400 m depth in the area of the deeper wells but reaches up to 200 m depth in well SG-10 in the east. Epidote, which indicates a minimum formation temperature of 240-250°C, appears at about 600 m depth. Alteration belts in the Svartsengi field have been considered as representative a fair correlation with the presently measured formation temperature, though perhaps near the lower limit. The alteration temperature is further discussed below in connection with the fluid inclusion studies.

Figure 5 shows the areas of surface alteration and active manifestations in the Svartsengi area; the alteration zones have been classified into high-, medium- and low-intensity alteration zones. High-

TABLE 2: Results of petrographic thin-sections from well SV-14 in Svartsengi

Depth (m)	Rocks	IA	MINERALS																		Sequences in time
			Primary																		
			Ov	Px	Pg	Ore	Gl	Ca	Qc	Qz	Cb	Sc	Stb	Sph	Ab	Fel	Anh	Sm	L	Ch	
62	pillow lava	med.	x	x	x	x	x	x	x	x	x										Ca, Qc,Ca,Qc,Ch
74	basalt breccia	med.	x	x	x	x	x	x		x			x			x				x	Ca,Ch,Ca,Ch,Ca
92	tuff breccia	med.	x	x	x	x	x	x		x			x			x				x	Ca,Ch,Ca,Ch,Ca,Ch
130	pillow lava	med.	x	x	x	x	x	x		x			x			x				x	
146	pillow lava	med.	x	x	x	x	x	x		x			x							x	
178	basalt breccia	med.	x	x	x	x	x	x		x			x			x				x	
186	basalt lava	med.	x	x	x	x	x	x		x			x			x	x			x	
196	basalt breccia	high	x	x	x	x	x	x		x			x			x	x			x	
208	tuff	high	x	x	x	x	x	x		x		x	x				x		x		Sc,MLC,Ca
246	basalt breccia	med.	x	x	x	x	x	x		x			x							x	
294	basalt breccia	high	x	x	x	x		x		x			x			x			x	x	
304	basalt breccia	high	x	x	x	x		x		x						x			x	x	Ca,Ch,Ca
332	pillow lava	high	x	x	x	x		x		x			x	x		x				x	Ch,Ca,MLC
346	pillow lava	high	x	x	x	x	x	x		x				x		x				x	Ca,MLC,Ca,MLC
352	basalt breccia	high	x	x	x	x	x	x		x				x						x	
388	pillow lava	high	x	x	x	x		x		x			x	x	x	x				x	
418	basalt breccia	high	x	x	x	x	x	x		x		x				x					
434	basalt breccia	med.	x	x	x	x	x	x		x				x		x			x	x	MLC,Ca
444	pillow lava	med.	x	x	x	x	x	x		x											Ca, Ch, Gl
464	pillow lava	med.	x	x	x	x	x	x		x			x			x	x			x	Ca,Cl,Ch
486	basalt breccia	high	x	x	x	x	x			x			x		x	x			x	x	
494	tuff breccia	high	x	x	x	x	x	x		x						x			x	x	
508	tuff breccia	high	x	x	x	x	x	x		x					x	x			x	x	
516	tuff breccia	med.	x	x	x	x	x	x		x			x		x	x				x	Fel,Qz,Ca,MLC
524	tuff breccia	high	x	x	x	x	x	x		x				x	x	x				x	Ca,MLC,Qz
528	tuff breccia	med.		x	x	x	x	x		x			x		x	x	x			x	Ca,MLC,Ch.
552	tuff breccia	high	x	x	x	x	x	x		x		x				x				x	Ca,MLC,Ch.
560	tuff breccia	high	x	x	x	x	x	x		x						x	x		x	x	Ca,MLC,Qz
572	tuff breccia	high	x	x	x	x	x	x		x						x		x		x	Ca,MLC,Ch
610	tuff breccia	high	x	x	x	x	x	x		x				x		x			x	x	Fel,Ca,MLC,Ch

Ov: Olivine
Px: Pyroxene
Pg: Plagioclase
Ore: Ore
Gl: Glass
Ca: Calcite
Qc: Chalcedony
Qz: Quartz
Cb: Chabasite
Sc: Scolesite
Stb: Stilbite
Sph: Sphene
Ab: Albite
Fel: Feldspar
Anh: Anhydrite
Sm: Smectite
MLC: Mixed layer clay
Ch: Chlorite
IA: Intensity of alteration

intensity alteration is found where extensive formation of clay occurs; medium-intensity alteration is characterized by extensive depositions of silica, in the form of opal crusts, and/or aragonite, and low-intensity alteration is characteristized by slight deposition of silica, also in the form of opal crusts. Active manifestations are characterized by hot soils and steaming ground (Pullinger, 1991).

Highly altered earth seems to be characteristic of fossil fumaroles, where the rock is altered to clays, usually smectite and kaolinite, by low pH geothermal fluids. Medium- and low-intensity alteration zones are characterized by depositions of opal and/or aragonite and a distinction is made between the two zones by the amount of deposition of either mineral. Aragonite deposition indicates that hydrothermal activity in the past was in the form of hot springs, probably of carbonate character. The deposition of opal also indicates hot springs and water flow of a neutral alkali chloride composition (Kifua, 1986).

The low- and medium-intensity alteration zones were probably active during late glacial times, when the ridges of Svartsengisfell and Thorbjarnarfell were covered by water. At this time there probably existed a transient geothermal system caused by the heat in the pillow lava and hyaloclastite mounds superimposed on the regional geothermal system. Fluids travelled through fracture systems and the permeable parts of the pillow mounds, depositing opal and aragonite. In some places like Selháls, the fluids reached the surface, probably through fractures, forming hot springs that deposited either silica, if the composition of the waters was alkaline, or aragonite if the water was of carbonate character.

The present active geothermal manifestations occur as hot soils and steaming ground in an area surrounding wells SG-2, SG-3, SG-10 and SV-14. Soil temperature measurements were taken in different locations of the active manifestations, giving temperatures in the range of 30-100°C at 0.5 m depth. There seem to be two upflows, one on the east side of the main road to Grindavik, where the temperatures are found to be between 77-99°C, and the other next to well SG-10, where temperatures at 0.1 m depth are found to be in the range of 95-100°C. In this area, the surface activity has probably increased after exploitation of the geothermal field began. If the right geological conditions exist, it will be possible for the steam cap pressure to overcome the overlying lithostatic pressure and produce a phreatic explosion similar to those experienced in the Kawerau geothermal field in New Zealand.

The shape of the upper part of hydrothermal systems can be assessed by contouring the upper limit of alteration minerals and projecting that onto the surface of the field. That can imply the geological nature of the hydrothermal aquifers. Contours of several alteration minerals have been plotted in that way, and those which appear above 600 m depth imply a similar shape of the system (Franzson 1990).

A correlation of alteration and temperature tell whether an equilibrium condition prevails in the hydrothermal system. That has been assumed for Svartsengi (Franzson 1983). A correlation of temperature distribution above 400 m depth and alteration indicates that the same permeable structures control the main hydrothermal upflow, i.e. an upflow in the northeast around the shallow wells (SG-2, SG-3 and SG-10) and a NNW-SSE structure in the central part of the field. A correlation between temperature and the upper boundary of the mixed-layered clays indicates that a cooling has occurred, where in well SG-8 measured temperature is only about 100°C but should, according to alteration, lie in the region of 200°C. The difference between measured and alteration temperatures decreases rapidly downwards and is insignificant at about 600 m depth, at the upper boundary of the epidote zone (alteration 240-250°C and temperature about 235°C). Although cooling is evident, the close similarity of the alteration and temperature anomalies infers that the same hydrothermal structures are operating in both instances.

3.4 Alteration of primary minerals

The primary mineral constituents of the rocks penetrated in well SV-14 are: plagioclase, olivine, pyroxene, iron oxides and glass. These show differential resistance to alteration as a consequence of

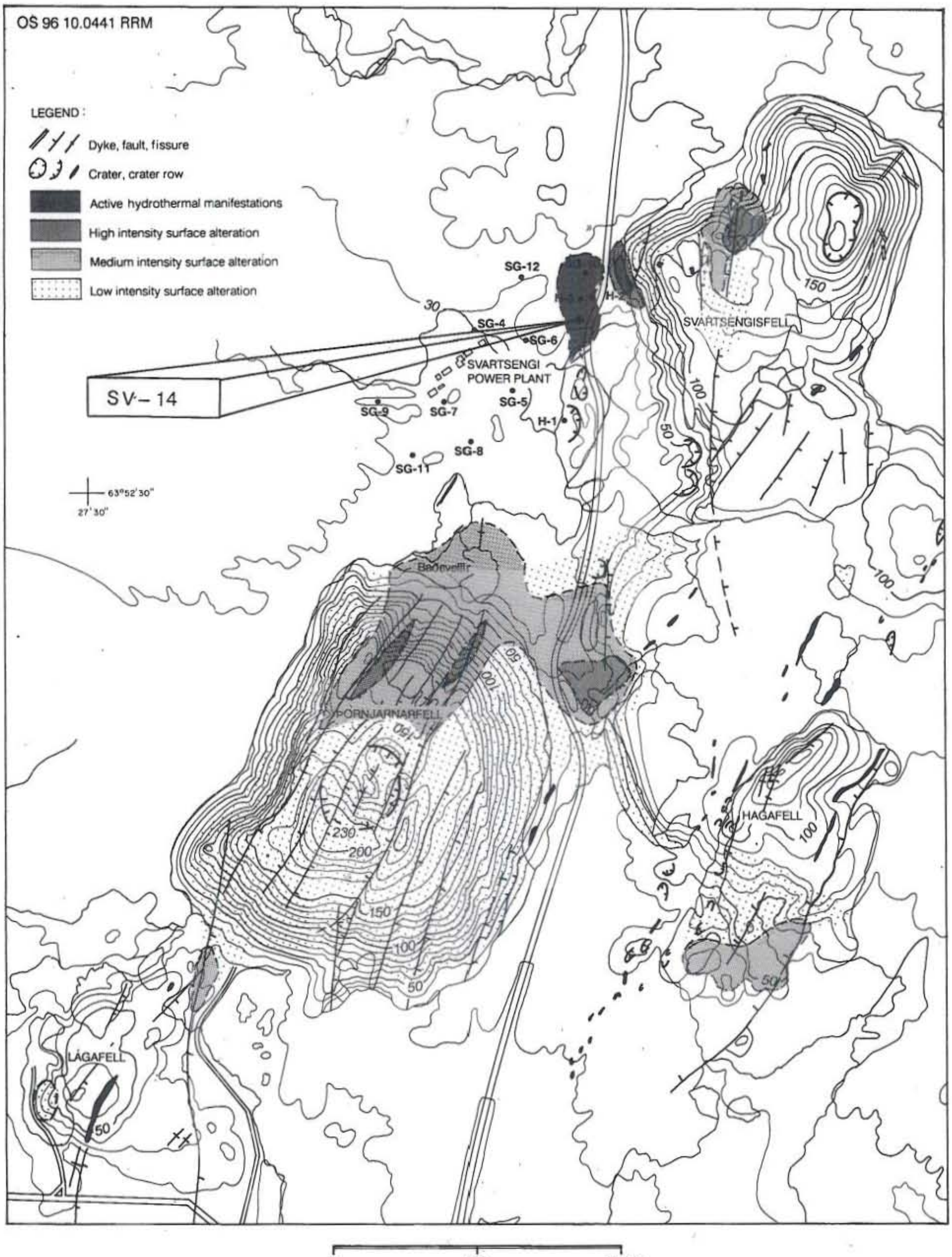

FIGURE 5: Surface hydrothermal alteration in Svartsengi (Pullinger, 1991)

temperature, permeability and geothermal fluid circulation in the rock.

Glass is also commonly found, formed during rapid cooling of the magma. Interacting with the invading hydrothermal fluid, the above constituents undergo transformation in a rare, partial or complete manner in response to a changing alteration environment.

The grade of preservation of primary textures is a function of formation permeability and the type, abundance, and grain size of primary minerals (Lonker et al., 1993). Under the influence of hydrothermal fluids and temperature, these minerals alter to similar and/or different alteration minerals as follows:

1. Glass alters easily;
2. Olivine starts to alter above 130°C;
3. Pyroxene is relatively resistant to hydrothermal alteration;
4. Plagioclase is also relatively resistant to hydrothermal alteration;
5. Iron oxide minerals alter mainly to other iron oxides, sphene and sulphide (usually pyrite).

In general, the order of decreasing susceptibility to alteration is glass, olivine, plagioclase and pyroxene. In this well, fresh basaltic glass occurs until 330 m. Calcite and clay minerals are the most common replacement minerals of glass in this well. Olivine appears in practically all the well, (primary mineral) but always the alteration grades change, depending on the conditions. They are normally smectites which then convert to higher clay minerals with increasing temperature and depth of burial. Pyroxene was observed in all the wells but starts to disintegrate at around 486 m. Limited albite was seen in this section at 388 m. Ironoxides or minerals were first observed to alter to sphene in this section at 330 m. It was recognized by a reaction rim at the edges which displayed yellow to red brown colours.

3.5 Distribution of hydrothermal alteration minerals

Figure 6 shows the distribution of alteration minerals in well SV-14. The entire depth penetrated by the drill hole is characterized by the presence of clays, calcite, quartz, zeolite, pyrite and other minerals of rare occurrence. These occur as replacement minerals, as vein fillings along fractures and disseminations, e.g. pyrite in the groundmass. Clay is common as an alteration product of volcanic glasses. Calcite showed the widest range of occurrences in fractures as fillings or interstitial minerals. Quartz was typically observed as a secondary vein mineral and cavity fill. Pyrite is widespread, disseminated in matrices and veins and sometimes also the major sulphide in quartz veins.

Calcite is the most common alteration mineral with a formation temperature extending up to 270°C (Kristmannsdóttir, 1978). However, its formation depends essentially on how the interplay of temperature, load pressure, and concentration of free CO_2 in the solution affects the solubility of calcite and also on the availability of Ca^{2+} ions in the solutions (Steiner, 1977). Calcite in well SV-14 showed a wide range of occurrences especially among the hyaloclastites but seldom in denser holocrystalline basaltic lava. The calcite observed is generally of two types; as a normal rhombohedral calcite and with a bladed morphology, commonly called "platy calcite". The first type is usually indiscriminately distributed in the interstitial pore-spaces of the rock matrix and cavities, whereas platy calcite was observed filling up fractures and as intergrowth with other minerals.

Chalcedony is a secondary mineral in the cavities of igneous rocks and is often associated with quartz, opal and the zeolites. It is the principal constituent of charts and jaspers. The temperature range of chalcedony seems to be lower than that of quartz. It is present from the top to the bottom of the well.

Quartz is seldom found as groundmass alteration but was rather abundant as open-space fillings, often as crystal growth in the clay-lined or calcite-filled vesicles or as intergrowth with calcite. Quartz formation is most notable directly above the zones of circulation loss below 246 and 300 m.

Zeolites are hydrous calcium aluminum silicates that commonly occur as secondary minerals in rock cavities, especially basalt (Kerr, 1959). They are widespread as fillings from top to bottom. They are often associated with calcite, quartz and rarely with pyrite. There are two dominant groups of

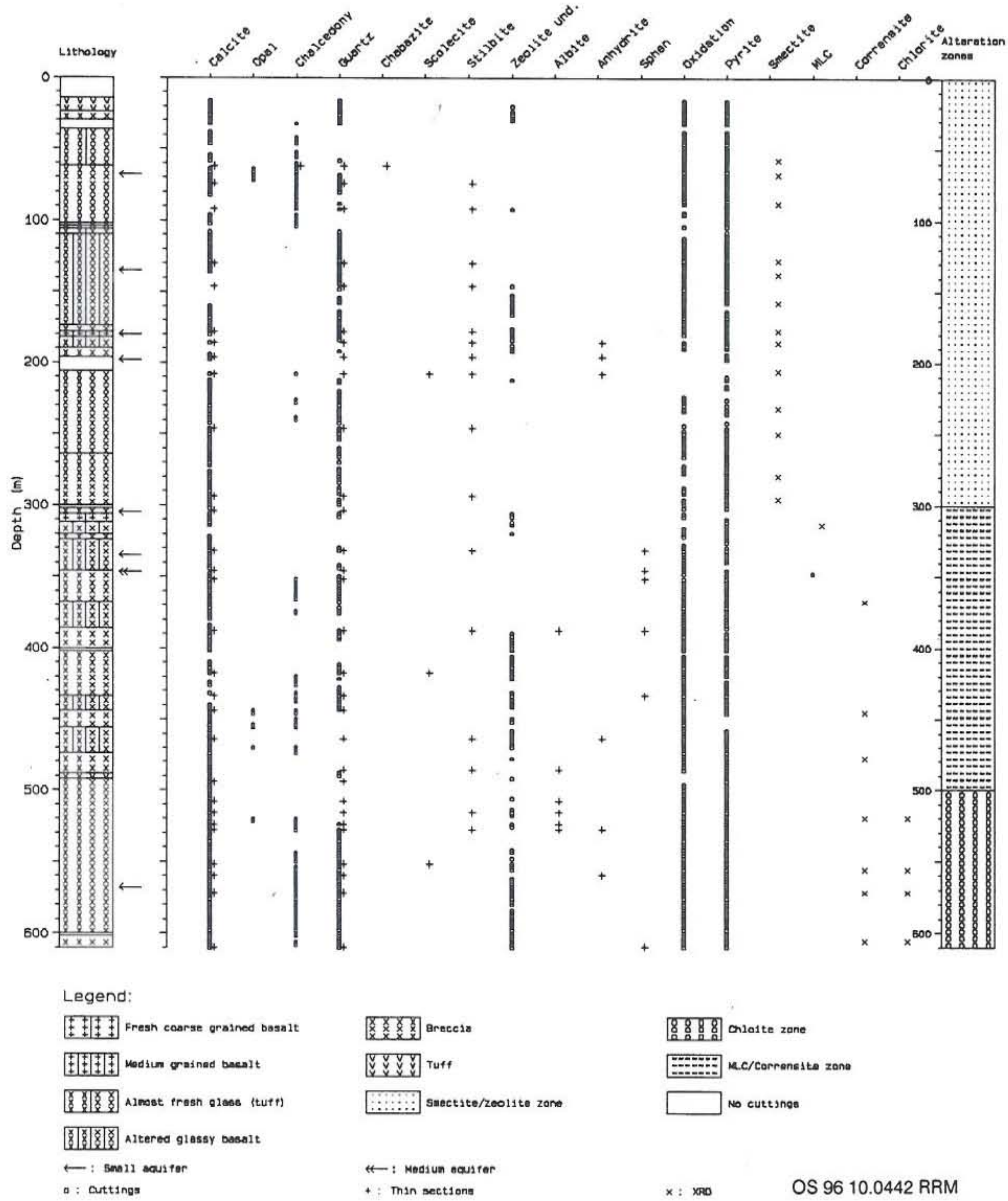

FIGURE 6: Distribution of hydrothermal alteration minerals in well SV-14, Svartsengi

zeolites identified by XRD, binocular and petrographic analysis. These groups are the heulandite-stilbite group (T = 90-110°C) and the modernite-laumontite group (T = 90-200°C).

Chabazite is restricted to the upper 62 m of this well. In cuttings it is recognized in vesicles down to about 120 m by its euhedral rhombouhedral crystals that approach the cube, and distinguish it from the other low-temperature zeolites.

Scolecite appears in the stretch between 200-560 m, found in cavities or vesicles.

Stilbite is a zeolite seen in caves and fractures of igneous rocks. Usual associates are calcite, heulandite and other zeolites. It appears practically in all the wells, but the most concentration is at 74-332 m.

Sphene is a widely distributed accessory mineral in crystallized rocks and in such metamorphic rocks as gneisses and schists. In the well it appears from 332 to 612 m.

Albite was observed in partially altered plagioclase in thin section, it was possible to see from 388 m down to 520 m. It was differentiated from balsam by its lower refractive index and was distinguished from wairakite by the latter's cross-thatched twinning.

Anhydrite occurs in sedimentary beds. It is often encountered in deep drilling but near the surface it is usually altered to gypsum. It often occurs with halite and is common in salt mines. In salt domes it is often found as cap rock. In SV-14 it is found infrequently, and appears only in the stretch 186-560 m.

Pyrite is the most common sulphide occurring as disseminations and fracture-fillings. The fine-grained disseminated pyrite is generally less abundant in the basaltic lava than in the hyaloclastites. Relative abundance of pyrite has turned out to be very useful in assessing permeability in Icelandic hydrothermal systems. A relative increase in of pyrite in the groundmass was observed, as well as in the quartz veins at 96-234 m. Under a binocular microscope it is easily identified with its distinctive brass yellow colour and metallic luster. This is common as euhedral crystals often cube yielding square, rectangular, triangular or even hexagonal outlines. Under oxidizing conditions pyrite may alter to limonite.

Clay minerals are the most voluminous alteration minerals. They alter basalt glass, olivine, and partly plagioclase and are found as vesicle and vein fillings. The clay minerals are usually fine-grained and poorly crystalline. Clays in well SV-14 are mainly smectite and corrensite (swelling chlorite). The clays in this well also showed textural generation from fine-grained to coarse-grained as the well gets deeper. Fine-grained variety is typical in the shallow level to approximately half of the well's depth. Textural variations from fine-grained to medium-grained and to coarse-grained is observed in the remaining parts of the well. The coarser variety of clay was observed to have a pleochroic yellowish brown colour. This textural evolution is suggestive of increasing temperature with depth. Table 3 shows the XRD results for clay samples in well SV-14.

Smectite was observed under the binocular microscope as a brownish green, poorly crystalline mineral and thinly lined the walls of the cavities. In thin-section, it appeared brownish with low birefringence with occasionally a reddish tinge due to oxidation. On XRD it has peaks commonly occurring between 13.5 to 15 Å (constant humidity), 16.3 to 17 Å when treated with glycol and collapsing to 10 Å when heated to 500 to 550°C. It is seen down to 300 m depth. In the stereo microscope, it appears as brownish-green, poorly-crystallized masses lining openings. In thin-sections, it appears brownish, with low birefringence.

Mixed-layer clays (MLC) usually respond to XRD peaks of 15-17 Å (at constant humidity) expanding to 29-31 Å (glycolate) and collapsing to 12-14 Å when heated up to 500-550°C. Evidence of certain mixed-layer clays occurrences for this well was based on standard Icelandic mixed-layer clay calibration with peaks to 12.8-14.6 Å (at constant humidity), peaks at constant humidity to 16 Å when treated with glycol and with a breakdown to 12 Å when heated to 500-550°C. A probable trace of mixed layer clays was detected as a narrow belt just below the smectite-zeolite zone at 314 m depth.

Corrensite (swelling chlorite) is another variety of chlorite and occurs in this well. It shows a similar character as chlorite at constant humidity when heated, but swells at glycol saturation. It was first identified at 368 m and from there to the bottom of the well.

Chlorite is characterized by XRD by peaks 14.2 -14.5 Å (constant humidity) with another at 7-8 Å, all of which remain unchanged with glycolation and heating to 550°C. Chlorite was first seen at 520 m.

TABLE 3: XRD results for clay samples in well SV-14

Depth (m)	Untreated d (Å)	Ethylene glycol d (Å)	Heated d (Å)	Result
58	15.49	17.31	14.97, 10.39	Smectite
68	14.24	16.98	9.69	Smectite
88	14.97, 8.01	17.31, 8.55, 7.65	9.69	Smectite
128	14.97, 7.69	15.22, 7.68	9.82	Smectite
138	14.97, 7.69	16.20	9.56	Smectite
158	14.72, 7.69	15.49, 7.70	9.82	Smectite
178	14.01	16.98, 7.70	9.75	Smectite
186	15.49	16.98, 8.49, 7.58	9.95	Smectite
206	15.22, 9.02	16.59, 8.92, 7.58	9.95	Smectite
232	13.67	17.05	9.86	Smectite
250	13.67	16.72	9.88	Smectite
280	13.46	17.11	9.82	Smectite
296	13.14	16.98	9.82	Smectite
314	15.49, 7.31	30.43, 15.17, 7.30	12.41	MLC
368	14.72	31.5, 15.22,7.49, 7.24	14.02	Corrensite
446	14.72	31.75, 17.24	14.43	Corrensite
478	14.38	31.5, 17.66, 7.78, 7.13	14.11	Corrensite
520	14.48, 7.19	32.0, 16.98, 14.47, 7.67, 7.19	14.48, 7.25	Corrensite, chlorite
556	14.48, 8.18	31.5, 14.71, 7.63, 7.14	14.48	Corrensite, chlorite
572	14.48	16.66, 14.98, 7.68, 7.14	14.72	Corrensite, chlorite
606	14.72, 7.19	16.66, 14.81, 7.14	14.24	Corrensite, chlorite

Other minerals: The beginning of albitization in plagioclase is found in several samples and appears to be nearly unrelated to depth. Newly formed potash feldspar is found sporadically in all the holes. Haematite is most common in the uppermost tuffaceous layers.

3.6 Alteration zones

The degree of hydrothermal alteration and the amount of hydrothermal minerals formed in a geothermal reservoir depend largely on the following parameters: 1) the type and permeability of the rock; 2) the temperature and chemical composition of the fluid, and 3) the duration of the geothermal activity; the latter being related to the age of magmatic activity (Kristmannsdóttir, 1978; Elders et al., 1979; Browne, 1984; and Reyes, 1990).

According to Browne (1984), the minerals commonly used as geothermometers are the zeolites, clays, epidote and amphiboles. In Icelandic geothermal fields, most zeolites are common before 100°C and disappear before 200°C (laumontite, mordenite). Wairakite, just as in Cerro Prieto, Mexico, starts appearing at 180°C and is recorded up to 300°C (Kristmannsdóttir, 1978; Elders et al., 1979). In the present study, chlorite was found to occur from 500 m. Therefore, the chlorite recorded seems to represent the conditions at 230-250°C.

The intensity and type of alteration usually reveal the degree of permeability, past or present. Minerals such as adularia and albite are often related to permeable zones, especially if they are present individually in association with quartz and calcite (e.g. at Tongonan, Philippines and in all New Zealand geothermal fields). This relationship is only valid if these minerals occur in veins and fractures (Browne, 1984). If they are, however, altering plagioclase, this relationship does not hold. However, from the present study, it is evident that plagioclase reveals two kinds of changes by hydrothermal fluids, namely: replacement by any other mineral through dissolution, and alteration by albitization. The former was observed in the phenocrysts, whereas the latter was restricted to the laths only. Otherwise, the albitization of plagioclase occurs within a wide range of temperatures (Reyes, 1990). It has been observed that in zones where both albite and adularia occur together, the permeability of the rock tends to decrease through selfsealing.

The original mineralogy of the rock seems to have a minor effect on the type of secondary mineral assemblage in permeable zones and where temperatures exceed 250°C. It is controlled mostly by the porosity/permeability.

Three alteration zones divide well SV-14: The zeolite smectite zone, to 220 m depth and corresponding to temperature of 200°C, the MLC/corrensite zone, to 500 m depth and with a temperature interval of 200-230°C and the chlorite zone, to 612 m depth and with temperatures over 230°C but below 250°C (Figure 6).

3.7 Deposition sequence

The diagnostic examination of cuttings and thin-sections under the microscope is the main tool for the determination of the chronological order of rock-mineral and mineral-mineral interaction in the well. Deposition is best observed occurring as full, partial or rare in cavities, fractures and interstitial spaces of the groundmass as it undergoes transformation in response to different changes in the environmental deposition. Clay is the major hydrothermal alteration lining walls of the vesicles and fractures. Table 4 shows the hydrothermal mineral evolution of well SV-14 commonly observed in most of the thin-sections.

TABLE 4: Sequence of hydrothermal mineral deposition

Depth	Depositional sequence
62	Calcite-chalcedony-smectite-(quartz ?)
74	Calcite-smectite-calcite-smectite-calcite
92	Calcite-smectite-calcite-smectite-calcite-smectite
208	Scolecite-fine-grained smectite-calcite
294	Calcite-smectite-quartz
304	Calcite-MLC-calcite
332	MLC-calcite-MLC
346	Calcite-corrensite-calcite-corrensite
418	Corrensite-calcite-corrensite
434	Corrensite-calcite
444	Calcite-corrensite
464	Calcite-corrensite
508	Corrensite-calcite-corrensite
516	Quartz-calcite-corrensite
524	Calcite-corrensite-quartz
528	Calcite-corrensite
552	Calcite-corrensite-chlorite
560	Calcite-corrensite-quartz
572	Calcite-corrensite-chlorite
582	Calcite-corrensite-chlorite
600	Quartz-calcite-corrensite-chlorite
610	Calcite-corrensite-chlorite

4. AQUIFERS

Aquifers are defined as a permeable zone or zones within a well that can be related to a single geological structure such as an intrusion, fault, or stratigraphic boundary. Aquifers in the boreholes have been assessed based on circulation losses or gains, temperature logs (during drilling, heating up and discharge), alteration and other methods. The data base for each aquifer is quite variable from one well to another as previously discussed. Aquifers are divided into three categories, i.e. small, medium, and large aquifers. In some instances high permeability occurs more or less continuously over a large depth interval in a well, interpreted as representing a single aquifer.

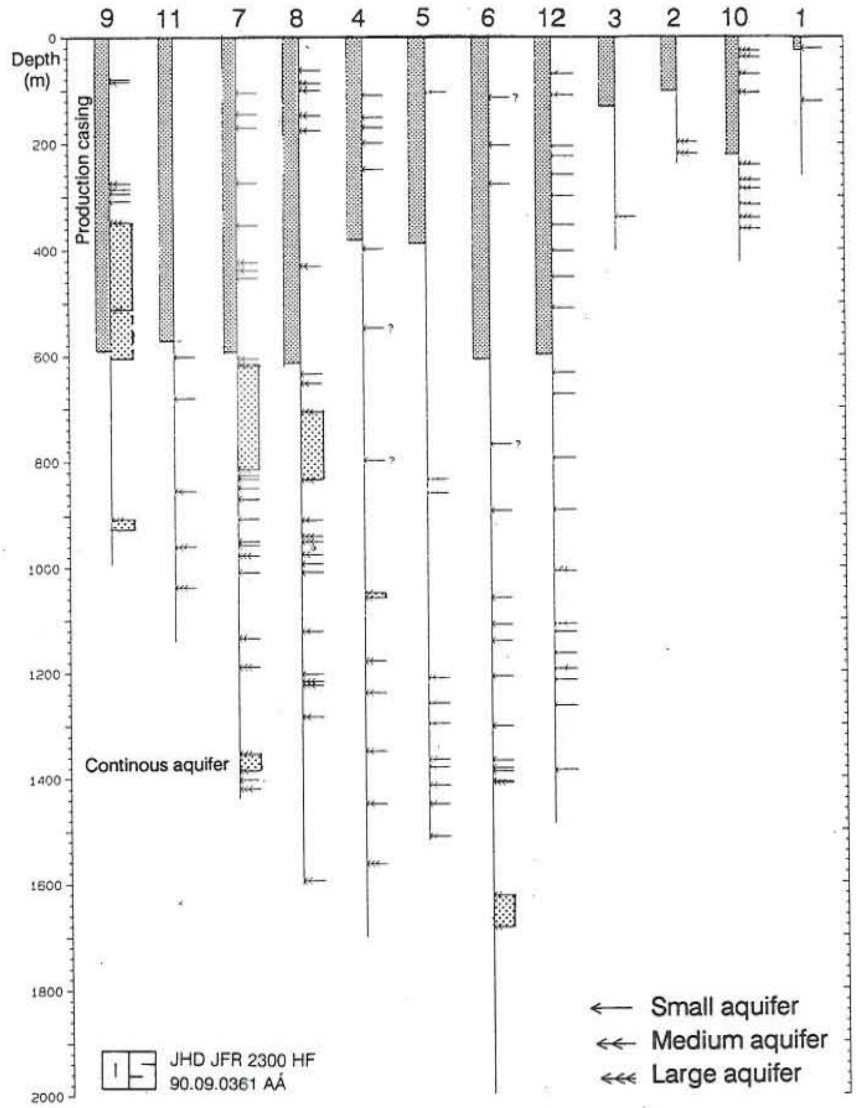

FIGURE 7: Distribution of aquifers in the Svartsengi wells (Franzson, 1990)

Figure 7 shows the distribution of aquifers in all the wells drilled in Svartsengi, both in the production part and behind the casings. It shows a very variable aquifer distribution from one well to another. The majority of aquifers correspond to well SV-14, coinciding with aquifers that appear in well SG-10, but there are some differences when compared with the location and level of aquifers in wells SG-2 and 3. This phenomenon may be due to the presence of perlitic glass in the hyaloclastite unit, changing the permeability characteristics of the rock and prohibiting fluid circulation.

Figure 8 shows the relationship of the aquifers and the geology for each 100 m depth interval in the reservoir. The relationship is mainly of three types: In the upper part of the strata the aquifers are mainly connected to stratification boundaries. These become rare below 500 m. The boundaries are sub-horizontal planes below 500 m, and are probably fed from below by sub-vertical feeders. The location of aquifers derived from the temperature logs are listed in Table 5.

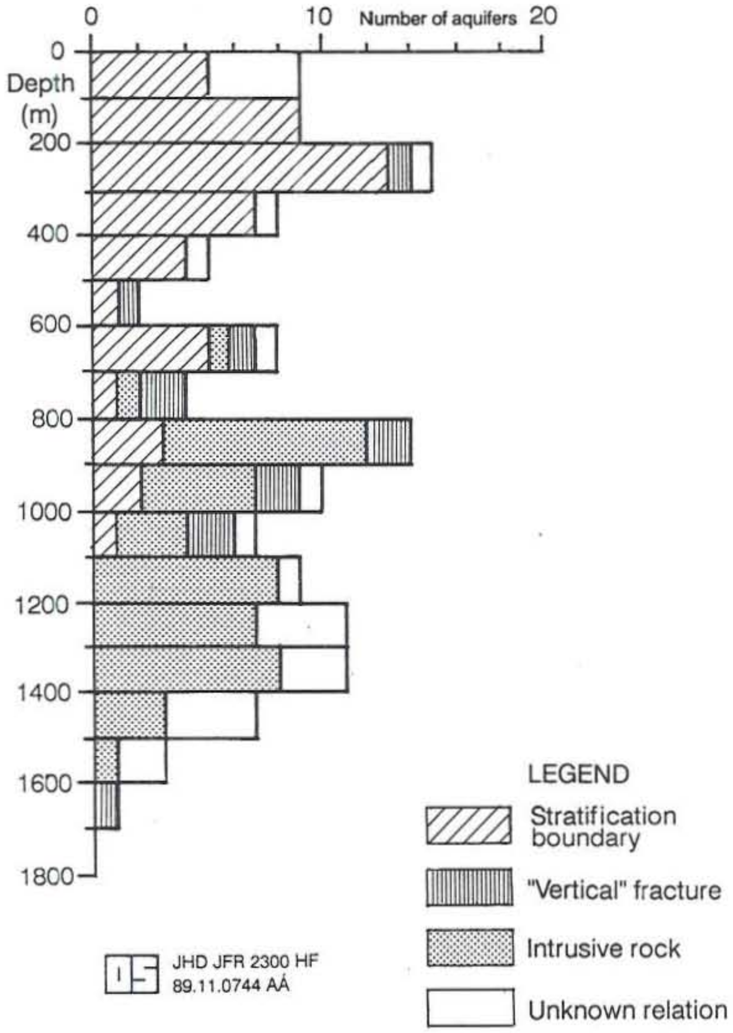

FIGURE 8: Relationship between aquifers and geology for each 100 m depth interval in the Svartsengi reservoir (Franzson, 1990)

TABLE 5: Location of aquifers in well SV-14

Depth (m)	**Methods used**	**Rock**	**Alteration**
68	Temperature log.	Pillow lava	Weakly altered
135-145	Temperature log.	Pillow lava	Medium altered
180	Temperature log.	Basaltic breccia	Medium altered
190-205	Temperature log. (circulation loss)	No cuttings	
305	Temperature log.	Basaltic breccia	Highly altered
335	Temperature log.	Pillow lava	Highly altered
340-350	Temperature log. (circulation loss)	Pillow lava	Medium altered
568-612	Temperature log. (circulation loss)	Tuff breccia	Highly altered

5. CONCLUSIONS

The main conclusions of this report are as follows:

1. The oldest formation in the Svartsengi high-temperature area consists of extensive of pillow lava as a part of hyaloclastites.

2. The stratigraphy of well SV-14 is formed by a hyaloclastite formation, which was formed under the ice sheet as a result of the quenching of magma in water; this formation is divided into three lithological units, hyaloclastite tuff, hyaloclastite breccia and pillow lava.

3. According to circulation losses/gain during drilling, eight aquifers were intersected. The lowest aquifer, which is the main production aquifer in the hole, was intersected at 568 m.

4. The geothermal alteration shows a progressive intensity with depth. Smectite and zeolites were identified in the upper part and close to the bottom chlorite was seen.

5. Three alteration zones, are found in well SV-14:
   The zeolite-smectite zone, to 220 m depth and corresponding to 100°C temperature;
   The mixed layer clay zone, to 500 m depth and corresponding to 230°C temperature;
   The chlorite zone, to 612 m depth and corresponding to the boiling point curve.

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APPENDIX: XRD-analytical techniques

Procedure 1: For zeolite and other hydrothermal mineral analysis

1. Under the binocular microscope, hand pick grain filling either vesicles or veins from the cuttings contained in the rectangular plastic box. The sampling depth is dependent on the worker's purpose and objectives. There is no strict rule on the sampling methodology. The amount of samples should be more than enough to fill up the sample window used in XRD.

2. Crush the sample in an agate bowl to a grain size of 5-10 microns. Acetone is added to prevent loss of sample while powdering.

3. Fill the sample window slot with an appropriate amount of powdered sample, then press a glass slide against the sample in a slot to make it firm, flat and level.

4. Run the sample from 4-60°.

Procedure 2: For clay mineral analysis

1. Place approximately two teaspoons of drill cuttings into a test tube, wash out dust with distilled water. Fill the tubes 2/3 with distilled water and plug with rubber stoppers. Place the tube in a mechanical shaker 4-8 hours, depending on the alteration grade of the samples.

2. Remove the tubes from the shaker and allow to settle for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pipette a few mm from each tube, halfway below the level of the sample, and place about ten drops on a labelled glass slide. Avoid having the samples thick. Make a duplicate for each sample and let dry at room temperature overnight.

3. Place one set of samples in a desiccator containing Glycol ($C_2H_6O_2$) solution and the other set in a desiccator containing $CaCl_22H_2O$. Store at room temperature for at least 24 hours. Thick samples will need a longer time in the desiccator, at least 48 hours.

4. Run both sets of samples from 2-14° on the XRD.

5. Place one set of samples (normally the glycolated one) on an asbestos plate and heat in a preheated oven at 500-550°C. The exact location of individual samples on asbestos plate must be known before heating because labelling will disappear during the heating process. Cool the samples sufficiently before further treatment.

6. Run the samples from 2-14° on the XRD.