

RESERVOIR GEOLOGY OF THE NESJAVELLIR HIGH-TEMPERATURE FIELD IN SW-ICELAND

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Abstract

The geological structures that affect the flow of geothermal fluid in the Nesjavellir system are deduced from variable data sources. The eruptive lithology consists of basaltic hyaloclastites and lava series. Intrusive rocks dissect the succession below about 800 m depth and become dominant part of the strata below 1500 m depth. The hydrothermal alteration depicts two outflow zones from the Hengill mountain, the main one lying on the east side of the Kyrdalshryggur ridge. The aquifers in the reservoir appear to be related to sub-vertical faults and eruptive fissures, stratigraphic boundaries of eruptive units in the upper 800 m and basalt and intermediate intrusive rocks below that depth.

1.0 Introduction

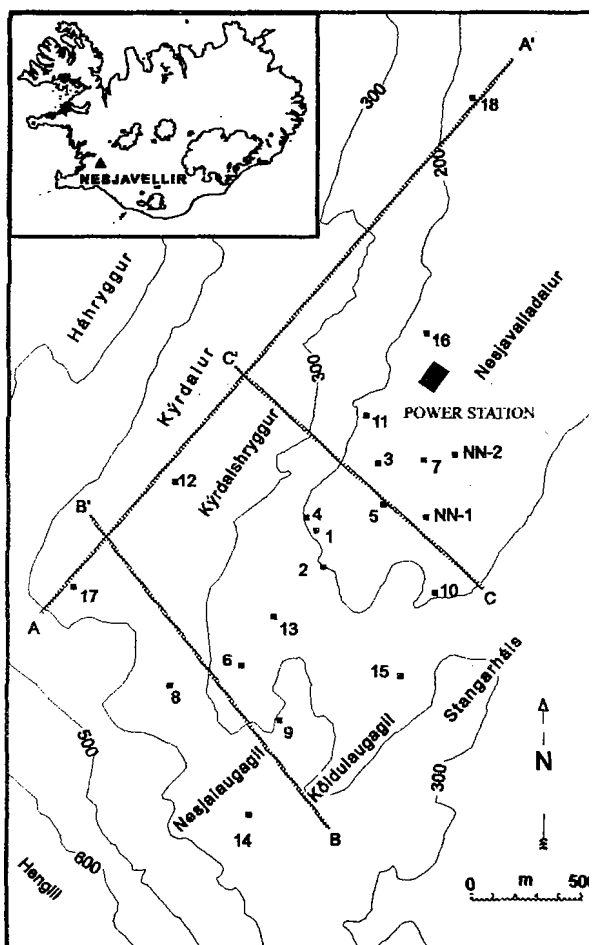


Figure 1. The Nesjavellir well field. The lithology cross section line A-A', and alteration cross sections along lines B-B' and C-C'.

Iceland lies within the rifting environment of the Mid-Atlantic Ridge. The Nesjavellir high-temperature field is on the northern perimeter of the Hengill geothermal area in the volcanic rift zone of SW-Iceland (Bjornsson *et al.* 1986). Hengill is one of the largest high-temperature areas in Iceland extending over some 25-30 km². The exploration of the Nesjavellir field spans about 4 decades, with the first 5 wells drilled in 1965-1972. Drilling was recommenced in 1982, after a decision to build a power plant had been taken, and in 1986 the 18th well was completed (fig. 1).

The Nesjavellir field has been extensively studied both by surface exploration methods and borehole studies, with numerous research reports and papers published. Publications in English include Bjornsson *et al.* (1986) who discussed results of geophysical surveys in the Hengill area, Stefansson (1985) and Bodvarsson *et al.* (1988) who presented results of temperature and pressure distribution and reservoir modelling of the field. Publications on geology and alteration in the reservoir include Tomasson and Kristmannsdottir (1974) who constructed the first geothermal model based on data from the first five wells. Franzson *et al.* (1986) reviewed the geothermal model with respect to geological data from 16 wells. Hreggvidsdottir (1987) studied the greenschist amphibolite facies transition, mainly in the deeper part of wells 7 and 11, and Steingrímsson *et al.* (1990) discussed the various evidences for a supercritical fluid at

the base of well 11. Schiffman and Fridleifsson (1991) studied the discrete smectite to chlorite transition in well 15.

The present paper is mainly based on data and interpretation from three reports on borehole geology of the 18 wells in the Nesjavellir field (Franzson 1988, 1993, 1994) which were made for the Reykjavik Municipal Heating Service which owns and operates the field. First the main character of the volcanic and intrusive succession is described, its alteration zones, faulting and aquifers, leading to a reservoir model.

2.0 Geology

The geological data is chiefly based on cutting analysis from samples taken at 2 m intervals in the wells, where the delay time of the cuttings in the well has been corrected for. The geophysical logs (caliper, n-n, nat-gamma, resistivity) were also extensively used to make the geological information as accurate as possible. The rocks in the reservoir which are totally made up of igneous rocks are dealt with in two parts; i.e. the accumulative eruptive sequence, and then intrusive rocks.

2.1 Eruptive sequence

The eruptive sequence is totally made up of rocks of basaltic composition. These can be divided on the basis of rock facies into sub-aerially erupted lavas and sub-glacially erupted hyaloclastites (pillow basalt, breccias, tuffs, and volcanoclastic sediments), and also petrographically, into basalt types (tholeiite, olivine tholeiite and porphyritic basalts). Figure 2 shows a simplified N-S cross section of the eruptive sequence to a depth of 1800 m b.s.l. Hyaloclastite formations are dominant down to 3-400 m b.s.l. but lavas dominate below. This lithological change may represent the base of the third last glacial and the onset of central volcanic activity in the Hengill area and puts thus a maximum age on the Hengill hydrothermal system. The underlying lava

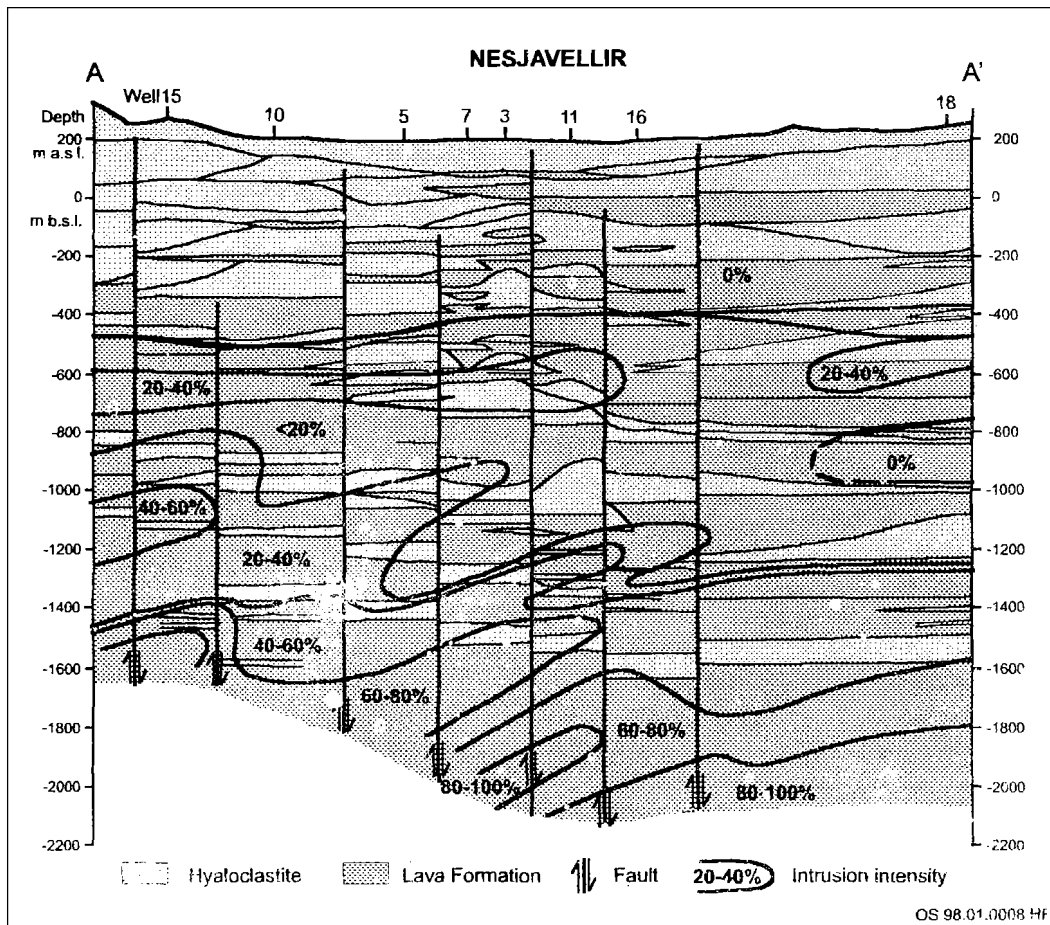


Figure 2. A N-S lithological cross section along line A-A' (c.f. fig. 2).

succession is believed to belong to the extinct Grensdalur central volcano some 5 km east of Hengill. It is possible to see up to 9 glacial (hyaloclastite) horizons in the c. 2 km thick eruptive sequence, which may infer a maximum age of 0.9 my at the base of the sequence.

2.2 Intrusive rocks

Intrusive rocks have been specifically mapped in all wells drilled after 1982 (wells 6 to 18). The intrusions have been divided into three groups; (i) relatively fresh basalt, (ii) altered basalt and (iii) intermediate-acid rocks.

The basaltic intrusive rocks are dominantly fine grained above 1400 m depth but are more doleritic below. The apparent thickness in the former group is about 5.5 m suggesting sheets or dykes, but the apparent thickness of the doleritic intrusions below is more difficult to ascertain as they are more commonly multiple. It is likely that they may become at least twice as thick as the ones above. The proportion of intrusions has been assessed from the detailed stratigraphic sections for each 200 m interval, and the cross-section on figure 2 shows the proportion of intrusions (%). The figure shows that intrusive rocks are rare above 400 m depth. The density of intrusions over the 400-1200 m (b.s.l.) depth interval is very variable but averages about 20%. Below that down to the base of the drilled reservoir the intrusion intensity increases markedly to above 60%. Below 1700 m they increase to above 80%, but that is based on data from three wells, of which only one reaches down to just over 2000 m depth. The concentration of intrusions appears to diminish towards north away from Hengill volcano. The correlation suggests that the majority of the intrusions lie sub-horizontally or dip 20-30° towards the central part of the Hengill volcano. A large proportion of the relatively fresh basalt intrusions are petrographically very similar and may belong to the same intrusive episode in the history of the Hengill central volcano. The near horizontal group of intrusions (fig. 2) in the 600-800 m depth interval are largely of this type.

These intrusions have often caused difficulties in drilling but are important to the geothermal system as aquifers (feed points) are commonly associated with them. Intrusions of intermediate composition in the Nesjavellir wells appear below 600 m depth. Although found at all depth intervals, they are most common at 600-800 m and 1000-1200 m depth intervals where they constitute about 15% of the succession. Well 11 which is the only one reaching below 2000 m depth b.s.l. has also about 25% of intermediate to acid rocks in 2100-2200 m depth range. The apparent thickness of the intermediate intrusions is quite variable. They are thickest at 1400-1600 m depth reaching a maximum thickness of 40 m. The average apparent thickness of 40 intrusions is about 12 m. Aquifers are commonly found associated with the intermediate intrusions, especially the thicker ones. It is possible to relate these horizons from one well to another. These show a dip of 14-24° towards the central part of the Hengill volcano in the south. Crosscutting relationships indicate that the relatively fresh basalt intrusions are younger than the intermediate ones.

3.0 Alteration

Hydrothermal alteration is very informative on various aspects of the geothermal system. Figure 3 shows schematically the alteration zones found in hydrothermal systems throughout Iceland along with the approximate maximum temperatures of the zonal boundaries. To the right alteration of the basaltic rocks at Nesjavellir is shown in relation to the alteration zones. It shows the glass and olivine to start altering near the upper boundary of the smectite-zeolite zone and both are completely altered near the upper boundary of the mixed layered clay zone. The more resistive plagioclase shows chloritic micro-veins near the upper boundary of the mixed layered clay zone. Albite alteration starts near the upper chlorite zone boundary. Epidote, sphene (titanite) and wairakite are notable alteration phases of plagioclase below the upper boundary of the chlorite-epidote zone. Magnetite-ilmenite alteration starts to give way to mostly sphene (titanite) alteration near the upper boundary of the chlorite zone. The pyroxene alteration has not been studied in detail, partly due to difficulties in assessing the extend of alteration. It, however, seems to alter at a similar rate as plagioclase. mainly to chlorite, and to amphibole at deeper levels. The extent of rock alteration varies somewhat within the alteration zones. Much of the eruptive volcanic sequence has been totally altered in the epidote-actinolite zone; while the intrusions are more resistant to alteration both because they are more dense and also because they are intruded in many cases at a late stage into the hydrothermal system. Indeed the extend of rock alteration seems to diminish at the base of the drilled hydrothermal system as has been observed in well NU-11 below 1800 m b.s.l.

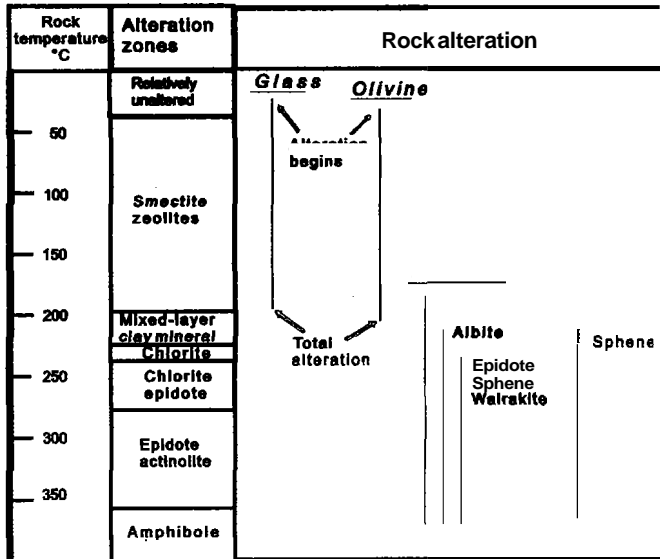


Figure 3. Temperature related alteration zones and rock alteration

occurs from well 3 to well 7, where e.g. the depth to the mixed layered clay zone deepens by 600 m over a distance of less than 200 m. By comparing figures 4 and 5 similar deepening of the alteration zones occurs towards north in the eastern part of the field.

A comparison between the temperatures indicated by alteration and present formation temperatures show that cooling has occurred at the outer perimeter of the field, especially west of Kyrðalshryggur ridge, while formation temperatures are higher than indicated from alteration in the southern and central parts of the field.

The alteration zones show a very uneven topography in the geothermal system in particular in the upper 1000 m of the succession as seen in the two E-W cross sections in figures 4 & 5. This depicts to some extent vertical and sub-horizontal permeability structures. The southern cross section (fig. 4) shows two such high-permeability zones; near well 8 and the other one between wells 9 and 14. The former coincides with the Kyrðalshryggur ridge. There chlorite is found at shallowest level. The eastern permeability zone is related to vertical fractures in the Koldulaugargil and Nesjalaugargil gullies (c.f. fig.1). In the northern cross section (fig. 5) the hydrothermal alteration associated with the eastern one has mostly disappeared, whereas the western one remains quite conspicuous and may have split into two parts. In that cross-section a distinct lowering of the alteration zone

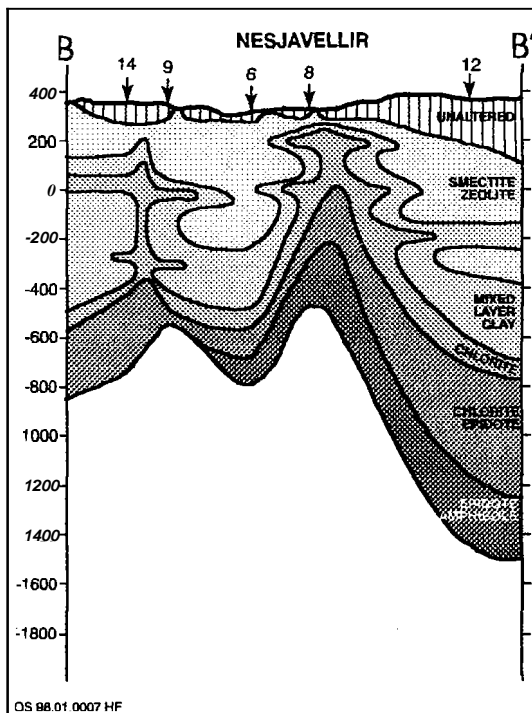


Figure 4. An E-W cross section of alteration zones along line B-B' (c.f. fig. 2).

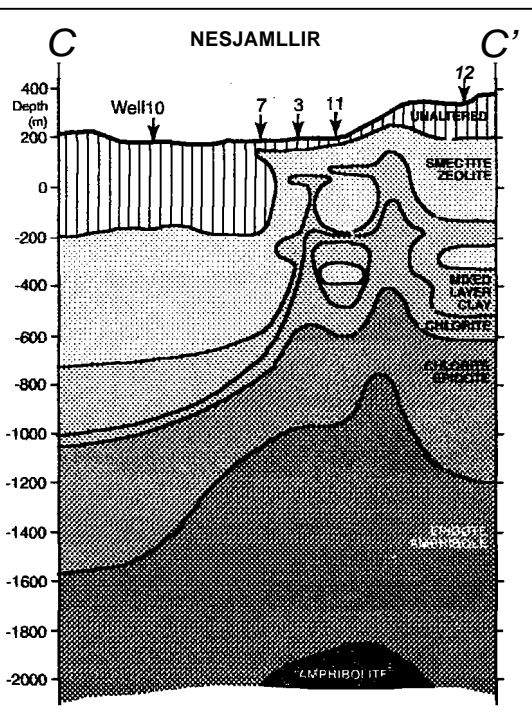


Figure 5. An E-W cross section of alteration zones along line C-C' (c.f. fig. 2).

4.0 Faults and eruptive fissures

The Nesjavellir field is situated within the intense fault and fissure swarm of the Hengill central volcano. Figure 6 shows the surface fractures and faults, and post-glacial eruptive fissures. Although striking dominantly NE-SW, indications are of N-S surface fractures in the SE-part of the field. Three post-glacial eruptive fissures are found within the well field the easternmost is approximately 8000 y while the western ones which follow

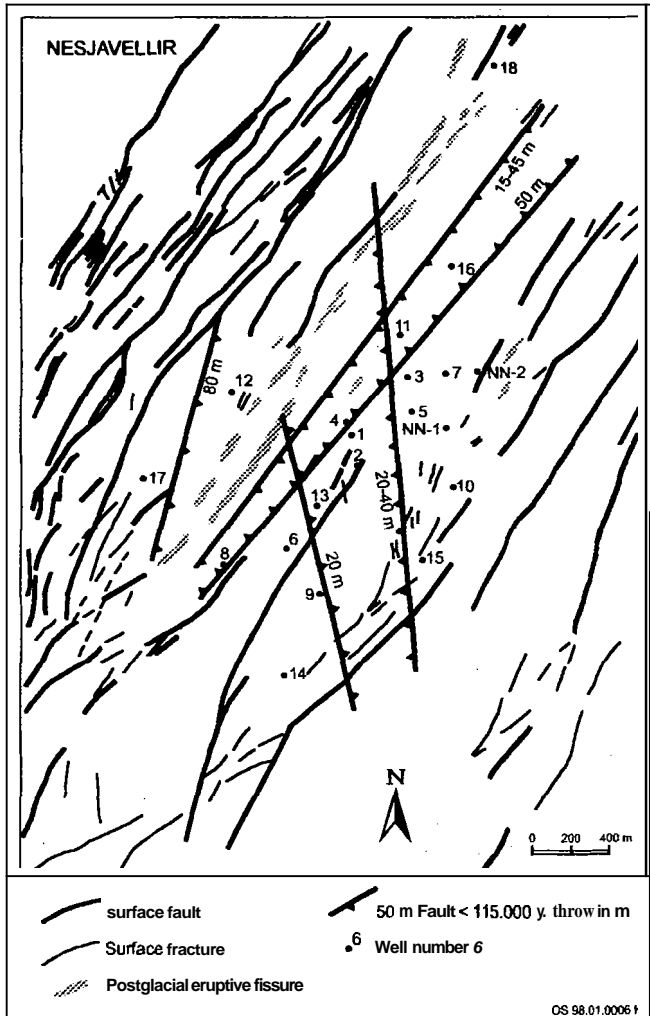


Figure 6. Surface faults, post-glacial fissures and buried faults younger than 115.000y based on borehole data.

the Kyrðalshryggur ridge have been dated at 5000 and 2000 y. As the lifetime of the fissure-swarm is probably more than 3×10^5 y, it infers that many of the faults and fractures have been buried by younger volcanics. Recognition of relatively dated horizontal formation boundaries is very useful in setting age constraints to faulting. Using such a boundary between last interglacial (lavas) and last glacial (Weichselian hyaloclastites) the following faults (thus younger than 115.000 y) are found and shown in figure 6: A notable NE-SW graben lies in the western part of the Nesjavellir valley, with fault throws up to 50 m. The graben faults seem to coalesce south of well 8. Three N-S trending faults dissect the Nesjavellir valley; the easternmost one shows a clear evidence of 20-40 m throw towards west, the central one has about 20 m throw towards east, and the one furthest to the west, between well 17 on one side and wells 6 and 12 on the other, has a throw of about 80 m to the east in the western part of the well field. NE-SW faults of this age in the eastern part of the field are likely to exist but are difficult to date due to the lack of a suitable horizon. Older faults (200-300.000 y) have been traced using older marker horizons but are not discussed here, except that a N-S fault component persists. An increase in the throw component with depth is observed in some cases, that either implies sustained fault movement with time, or that faults become more numerous at deeper levels.

4.0 Aquifers

The data used to locate aquifers (feed points) in wells are deduced mainly from temperature and pressure logs, circulation losses, alteration and geophysical/geological logs. These locations are then compared with the detailed lithology. Figure 7 summarises the average number and relative size of aquifers (feed points) found in each 200 m depth interval (data from 15 wells). The figure shows three main changes taking place with increasing depth. Aquifers are relatively common in the uppermost 600 m in the wells with relatively high permeability. In the next 400 m depth interval, aquifers become both fewer and smaller. From 1000 to 1400 m depth there is a conspicuous increase in the number and size of aquifers, below which the number decreases again but the aquifers continue to be relatively large. Figure 8 shows the apparent relation of aquifers with geological features. Three main factors seem to control the aquifers: Aquifers in the upper part seem to occur preferentially along boundaries between accumulative volcanic units. This type of permeability, however,

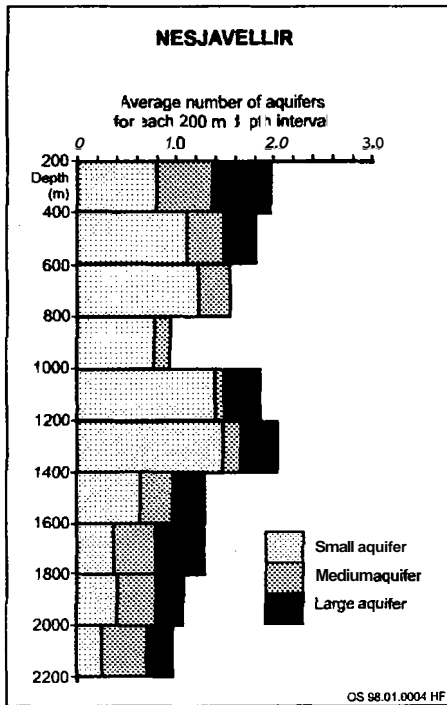


Figure 7. An average number of aquifers (feed points) over each 200 m depth interval in the Nesjavellir system.

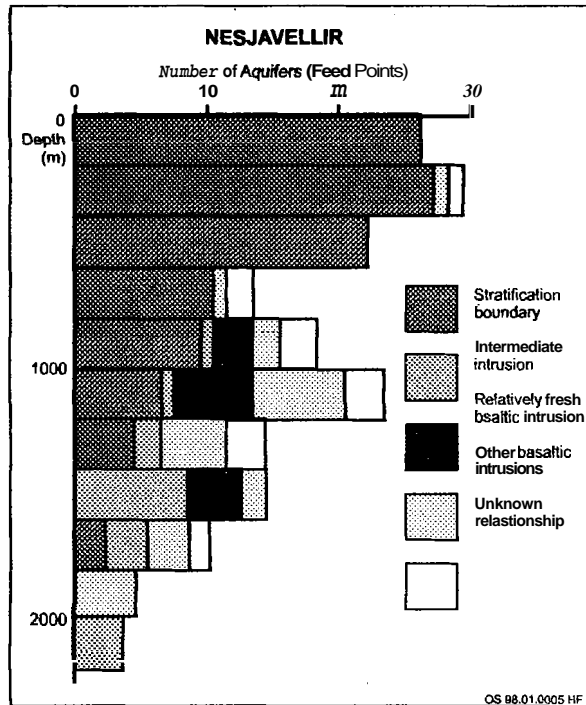


Figure 8. The geological control of aquifers

diminishes downwards and is becoming insignificant below 800 m depth. It is likely that the precipitation of alteration minerals and a rock load compaction contribute to the diminished primary permeability along the lithological boundaries. Permeability related to intrusive rocks becomes dominant below 900 m depth. The intrusive rocks are of three main types; relatively unaltered basalt intrusions, altered basalt intrusions and intrusions of intermediate composition. As mentioned above the relatively fresh basalt intrusions and the intermediate ones are sheet-like bodies dipping gently towards south under the Hengill volcano.

5.0 Conclusions

The prominent geological features that affect the geothermal flow in the Nesjavellir field are shown in figure 9. The main outflow zone from the Hengill geothermal system into the Nesjavellir wellfield towards north lies along sub-vertical faults and eruptive fissures on the east side of the Kyrðalshryggur ridge. These structures function also as a barrier to flow towards west into the Kyrðalur valley. The faults in Koldulaugargil and Nesjalaugagil provide another vertical outflow zone. The N-S faults, especially the easternmost one appears to function as a barrier to the north-eastward moving fluid. These main flow structures feed the permeable stratification boundaries in the upper part and below 800 m depth they feed the flowpaths along the intrusive boundaries. These intrusions are relatively unaltered and altered basalt intrusions and intrusions of intermediate composition. Both types appear to dip gently towards south into the Hengill mountain.

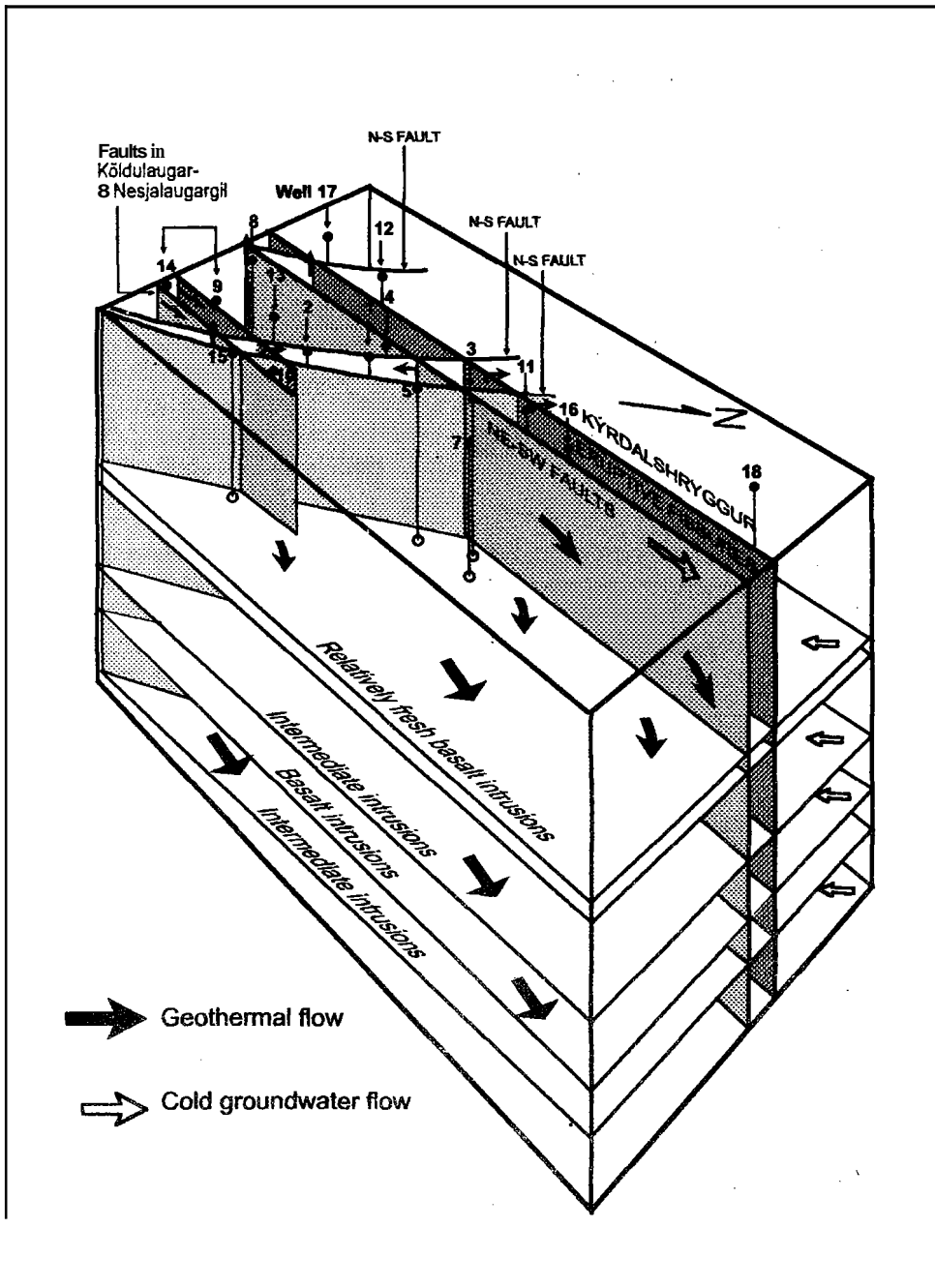


Figure 9. The geological model of the Nesjavellir reservoir.

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