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HYDROTHERMAL EVOLUTION OF THE NESJAVELLIR HIGH-TEMPERATURE SYSTEM, ICELAND

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ABSTRACT

The abundant vesicle and vein fillings in the Nesjavellir high-temperature field in SW-Iceland allows the thermal evolution to be studied. These time related sequences show a geothermal system evolving from a low-temperature condition to a high-temperature one, probably less that 100,000 years ago, associated with intrusives of dioritic composition. A progressive heating follows along NE-SW trending faults and eruptive fissures reaching a maxima, possibly ~5000 years ago. As the system cooled calcite was deposited. At present, the geothermal system is undergoing heating in southern part of the field, east of the Kyrdalsbrunir eruptive fissure.

1. INTRODUCTION

The Nesjavellir geothermal field is situated at the northern margin of the thermal anomaly associated with the Hengill central volcano in SW-Iceland. The field has been explored and utilised by The Reykjavik Energy, and the data presented here is a part of The National Energy Authorities (NEA) work for Reykjavik Energy.

Icelandic rocks, being largely of basaltic composition with subordinate amount of more evolved rocks, have variable porosities. Table 1 shows a range in primary porosity of about 150 extrusive and intrusive rock samples taken from a study of reservoir characteristics of varied composition in Iceland (Hjalti Franzson et al., 1998). The primary porosity was assessed through point counting in a petrographic microscope, which identifies pores greater than 30 µm. The table shows that Icelandic rocks are highly porous. These pores become gradually filled with alteration minerals. The scope of studying infilling sequences in Icelandic rocks is therefore ample, and extensive studies have been done on cuttings from geothermal wells.

This paper describes a petrographical study of mineral fillings in the Nesjavellir high-temperature geothermal field. These data combined with other relevant data, can be used to unravel the evolution of the thermal system.

2. THE NESJAVELLIR GEOTHERMAL SYTEM

2.1 Geothermal framework

The Nesjavellir high-T system is located at the northern edge of the thermal anomaly associated with the Hengill volcano. The approximate age of the volcano is about 3 x 10^5 years (Franzson, 1998) and the depth to the base of the volcano is found at approximately 600-800 m in boreholes at Nesjavellir. Figure 1 shows the salient features of the main permeability structures and crosssections of alteration zones in the northern and southern parts of the field. It shows that the main outflow zone from the Hengill geothermal system lies along the eastern side of sub-vertical volcanic fissures in Kýrdalsbrunir. These structures also act as a partial barrier to flow to the west across Kýrdalsbrunir. Another less conspicuous NE-SW outflow zone lies in the eastern part in Nesja- and Köldulaugargil (c.f. figure 1). N-S trending faults crossing the NE-SW structures appear to act as partial barriers to north-eastward flow. Other important permeability structures are shallow inclined diorite (older) and relatively unaltered sub-horizontal basalt intrusions (younger) below about 800 m depth. The hydrothermal alteration zones show, as clearly depicted to the left in figure 1, a close association with these permeability channels.

2.2 The study of mineral sequences.

The alteration zones shown in figure 1 are based on a combination of rock alteration intensity and secondary minerals deposited in the voids of the rocks.

A systematic study was made on the mineral sequences deposited from the geothermal fluids into the vesicles and veins (Franzson, 1994), during the exploration of the Nesjavellir field. A total of about 1100 observations (by binocular and petrographic microscopes) were made, in particular from wells 6, 7, 8, 9, 12 and 17, and less from other wells. Table 2 shows graphically the number of minerals found in these voids, where nearly 800 contain two minerals, and about 100 contain 3 minerals. Voids with 5 or more minerals are relatively rare and often represent repetitive deposition of same minerals. The relatively few observations with one mineral deposition is due to the biased search for a time relationships between different minerals.

Figure 2 shows the main conclusions of the study. The depositional sequence may be divided into the following six time related mineral assemblages, which are found throughout the geothermal reservoir, with the exception that assemblages V and VI may be less conspicuous at temperatures much above 300°C:

Assemblage I. This assemblage is partly based on the assumption that a low-temperature condition must have prevailed prior to the onset of high-temperature activity at the Hengill central volcano. Such a condition would include a 300-400 m thick cold groundwater layer underlain by a succession suffering a thermal gradient of 60-100°C/km. The alteration minerals could include limonite, opal, thin linings of clay (smectite), and low-temperature zeolites (e.g. Tómasson and Franzson, 1992). Indications of such deposition is circumstantial, other than limonite, clay linings and opal (later altered to chalcedony and quartz) are commonly observed, but zeolite deposition from this stage have probably been dissolved.

Assemblage II. The earliest indications of high-temperature alteration in the Nesjavellir system are associated with shallow inclined intermediate intrusions (diorites) (c.f. figure 1). The fingerprint of this alteration is K-feldspar (adularia) along with wollastonite. Amphibole (actinolite) is also distinctly associated with this intrusive episode, often forming a reaction rim around the primary pyroxene. The diorite intrusions are considered to be one of the main intrusive related aquifers in the Nesjavellir reservoir.

Assemblage III. It is difficult to separate this depositional episode from the previous one, and a more detailed study is needed. Epidote is the most prominent mineral in the assemblage along with chlorite, wollastonite, garnet, quartz, amphibole and sulfides.

Assemblage IV. The zeolite assemblage belonging to this category is quite conspicuous at Nesjavellir and may persist down to 1200 m depth at the outer margin of the geothermal system. This assemblage is believed to represent the upper part of assemblages II and III, and it is plausible that the oldest part of these may be a part of assemblage I. The order of mineral deposition from earlier to late found within this assemblage is (analcime >) thomsonite > (heulandite >/+) stilbite > scolecite/mesolite > mordenite > and laumontite. The main feature of this sequence is that the earliest ones are low-temperature zeolites and these are successively overlain by higher temperature varieties, laumontite being the last one. This zeolite trend indicates progressive heating within the geothermal system. A corresponding progressive heating in the lower part of the reservoir (Assemblage II + III) is not detected.

Assemblage V. A distinct change in alteration occurs at the onset of this depositional episode, especially in the zeolite rich part of the system (c.f. figure 2), where the zeolites show signs of breaking down and being replaced by other minerals. This change can be observed in all parts of the field, from the hottest well (no.8) at shallow level, to the coldest one (well 18). The first indication of this category is a clay deposition, either at the margin of the vesicles and underneath the zeolites, or on top of the zeolites. In the former instance one often can observe a coarsely crystallised clay force its way into the crystal structure of the zeolites. In the latter instance fine to medium crystallised clays are found on top of the zeolites especially in the lower temperature parts of the reservoir. Zeolites are partially to totally replaced in places, especially near zones of good permeability by quartz, wairakite, clay, calcite and laumontite (table 3). Quartz seems in most cases to have replaced the zeolites before wairakite.

Assemblage VI. The last mineral deposited in the Nesjavellir system is calcite, which is seen throughout the reservoir where temperatures are less than 290-300°C. In places, especially where calcite alteration is most pervasive, it is also found in older part of the time sequence but is in most cases interpreted as the calcite intruding the mineral layers.

Calcite shows a certain evolution in the upper few hundred meters. The earliest carbonates are radiating aragonite, which is succeeded at greater depth, and overlain by clay-rich carbonates. At still greater depth the radiating character disappears and the clay-rich carbonate is overlain by a normal calcite. The clay rich calcite variety has normally disappeared by 200°C.

Alteration zones, as shown in figure 1 summarise the overall character of the alteration minerals and reflect the maximum temperature reached at certain points in reservoir.

The temperature dependency of many of the alteration minerals (e.g. Pálmason et al. 1979., Franzson, 1998) allows temperature isolines to be drawn on figure 2, according to the minerals being formed at each depositional episode. It shows an overall increase in temperature with time to a maximum during deposition of assemblage V.

Calcite is of special importance as it is deposited closest to the present time in the geothermal system. It is difficult to assess the temperature of calcite deposition, except that it is not expected to form at temperatures surpassing c. 290°C. Fluid inclusion homogenisation temperatures on calcites from wells 17, 18 and 9 are shown in figure 3 along with boiling point-, alteration-, and present formation temperature curves. Ice-melting temperatures (T_m) of some of these calcite fluid inclusions were also measured and yielded Tm-ice 0.2°C or less, indicating low salinities and CO_2 contents of the geothermal fluids. Wells 17 and 18 show similar behaviour, with respect to that T_h values spread over a considerable temperature range. Primary inclusions, where identified, tended to yield higher temperatures than the secondary ones. The calcite in these two wells thus show cooling, both during and after the calcite deposition, which spans nicely the temperature difference between the alteration- and formation temperature curves. Although calcite hosted fluid inclusions in well 9 show a broad spread of T_h values, its relation with measured and alteration curves is different, because the T_h values are lower than the present formation temperature. Inclusions in quartz were measured along with calcite and these showed the highest T_h values, coinciding with the temperature of the boiling point curve. Paragenetically quartz (figure 2) formed earlier than calcite, and therefore represents an earlier thermal environment. Convincing evidence was found in well 9 of calcite deposition on top of finely radiating zeolites. Subsequent heating resulted in zeolite dissolution leaving behind an empty mould in the calcite The evidence from well 9 therefore shows that the calcite was deposited at lower temperature than the upper stability limit of the zeolite, which may be a little over 200°C (Pálmason et al., 1979). The evidence is therefore compelling that the calcite deposition throughout the Nesjavellir system is related to cooling in the reservoir caused by an inflow of colder groundwater becoming progressively oversaturated by calcite as it gains heat from the surrounding rock. There is, however, further evidence that heating has succeeded the cooling episode in certain parts of the field.

3. DISCUSSION

The proposed age of the Hengill volcano of about 3 x 10^5 years (Franzson, 1998) puts an upper limit on the age of the hydrothermal system. Furthermore, it puts a constraint on the change in surface elevation of the volcano during its lifetime. The surface at the onset of the volcano is now present at a depth of some 600 m below the present surface. This is indicated as the palaeosurface on figure 2.

The alteration temperature curve is, as seen in figure 2, mainly based on temperatures from depositional episodes 5, 3, and 4 to a lesser extent. On the other hand the formation temperature curves in the wells on the other hand represent the present state of the reservoir. The difference of the two curves represents the mixture of the amount of cooling exemplified by the calcite, and the more recent heating up as exemplified by well 9. This type of comparison has been done for all wells, and figure 4 shows a cross-section of the alteration zones (c.f. lower left side of figure 1) where the differential shading indicates areas of heating, equilibrium and cooling. Connecting this to the spatial distribution of the aquifers shown in figure 1 indicates, that the most recent heating of the Nesjavellir system is along the eastern side of the faults and eruptive fissure at Kyrdalsbrunir, along the faults in Koldulauga- and Nesjalaugagil, and may also be confined to the aquifers lying along the relatively fresh sub-horizontal basalt intrusions. The aquifers along the diorite intrusions, though relatively big, seem to be more inert to the heating, the possible reason being that they are, due to their relatively old age, no longer in good connection to the main outflow zone.

An attempt has been made to put tentative dates on the geothermal episodes, and these are shown at the bottom of figure 2. As mentioned above the proposed maximum age of the Hengill central volcano of 300 x 10^3 years, puts an upper age limit on the Hengill geothermal system. The geology of the Hengill volcano has been mapped in detail (Arnason et al. 1986). The oldest episode of the Nesjavellir system, is associated with the diorite intrusives, and these are tentatively connected to the extrusion of acid rocks found in the NW-part of Hengill dated at about 80 x 10^3 years. It must be emphasised, however, that since Nesjavellir is situated at the margin of the Hengill system evidence of older geothermal episodes may be found nearer to the core of the Hengill geothermal anomaly. It is quite obvious, by looking at the shape of the geothermal alteration zones that they are closely associated with distinct geological structures (c.f. figure 1). Thus it is suggested that assemblage III and latter part of IV may be associated with the eruption of the Hengill table mountain dated at about 55-65 x 10^3 years. Deposition of assemblage V is tentatively associated with the postglacial fissure eruptions of 5000 and 2000 years which lie along Kyrdalsbrunir. The relatively fresh basalt intrusions found in the reservoir (figure 1) may be the intrusive equivalent of these eruptions. The cooling expressed by the calcite may therefore by younger. The even more recent heating is confined to the south part of the geothermal system, and partly along the sub-horizontal intrusions, but its western boundary is restricted by structures in Kyrdalsbrunir, indicating that the heat source driving the thermal north-eastward flowing pulse is located to the south of Nesjavellir and east of the fissure line in Kýrdalsbrunir. It is conceivable that it may be associated with a major tectonic episode in the latter part of the 18^{th} century.

Nesjavellir field is at the northern tip of a much larger Hengill high-temperature anomaly which is surrounded by a colder groundwater system. A consequence of a change of permeability at such a location may essentially be twofold. If the pressure of the geothermal system is higher than the surrounding cold groundwater system, the permeability change will result in an outflow of the former and a heating up will occur. If the pressure difference favours the surrounding groundwater system it will intrude the geothermal system and cause cooling. Such heating/cooling will be more rapid and extreme at the margin of a geothermal system than in its central part. The incomplete alteration of the zeolite assemblage by the assemblage V deposition, implies a short-lived geothermal pulse into the Nesjavellir system, and the apparent cooling shown by the calcite. Whether the heating presently experienced has reached its maxima is yet to be known.

4. CONCLUSIONS

The information gained from the study of mineral deposition in vesicles and veins in the Nesjavellir system shows that high-temperature activity may have started less than hundred thousand years ago and perhaps related to diorite intrusions. The system shows a progressive heating until a cooling occurs exemplified by calcite deposition. Presently though, Nesjavellir is undergoing a heating which is not apparent in the alteration minerals. The temperature fluctuations within the geothermal system is considered to be due to its position at the margin of the Hengill thermal anomaly.

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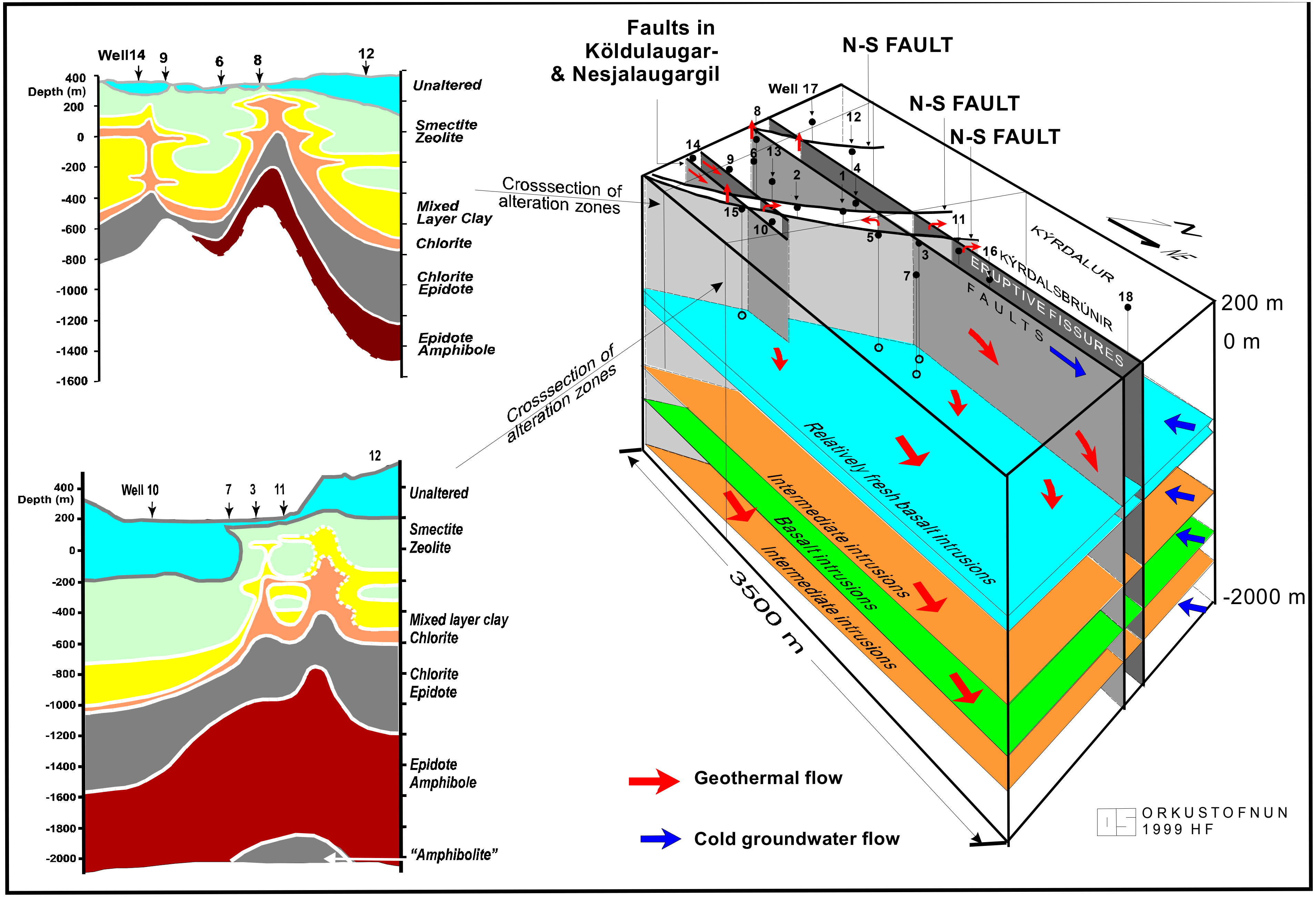

Figure 1. Main permeability structures in the Nesjavellir high-temperature system. Cross sections of alteration zones to the left. See text for further information.

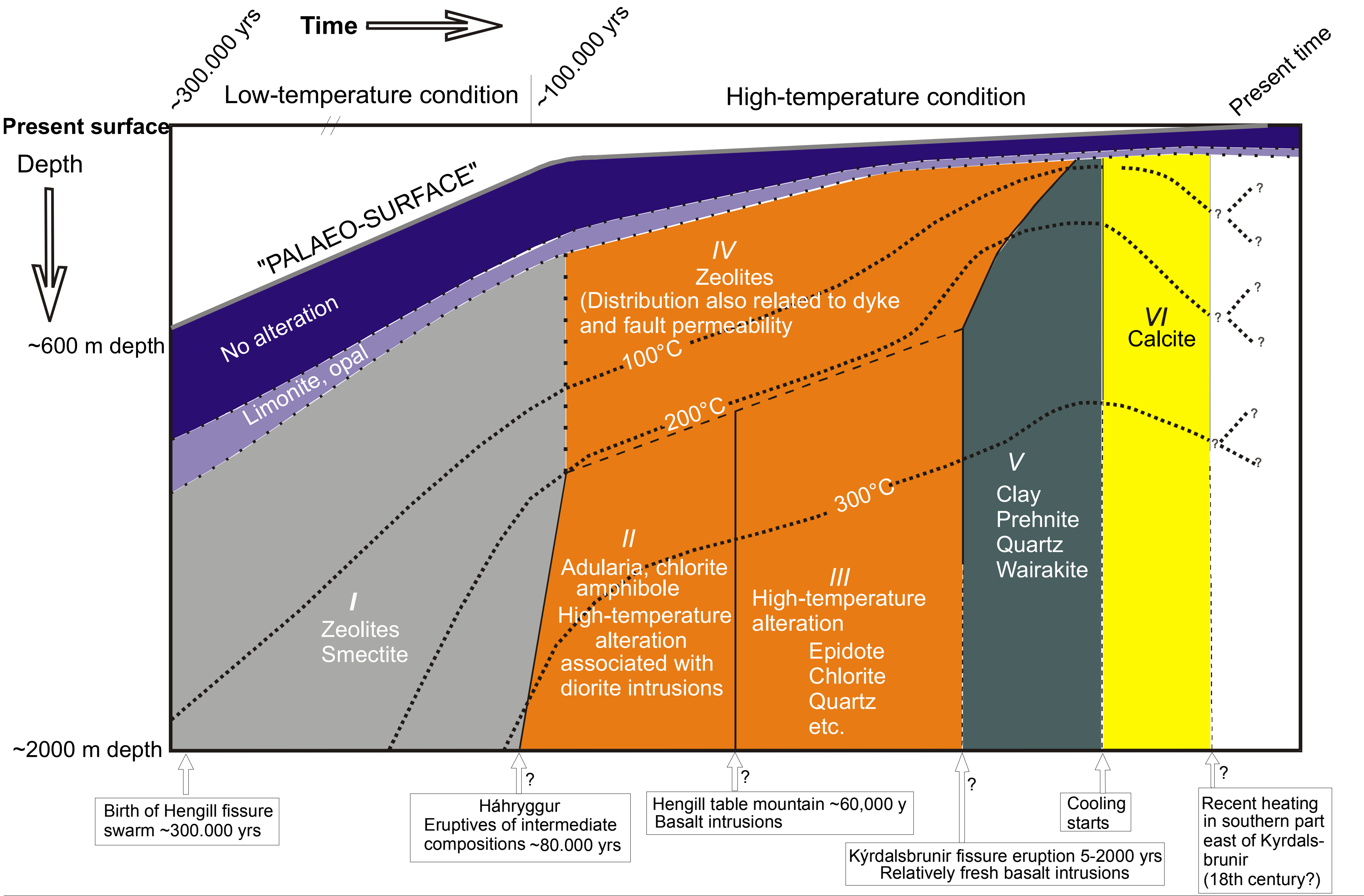

Figure 2. A schematic diagram showing time relation of deposition assemblages, temperature range, elevation changes and plausible association with volcano/tectonic events.

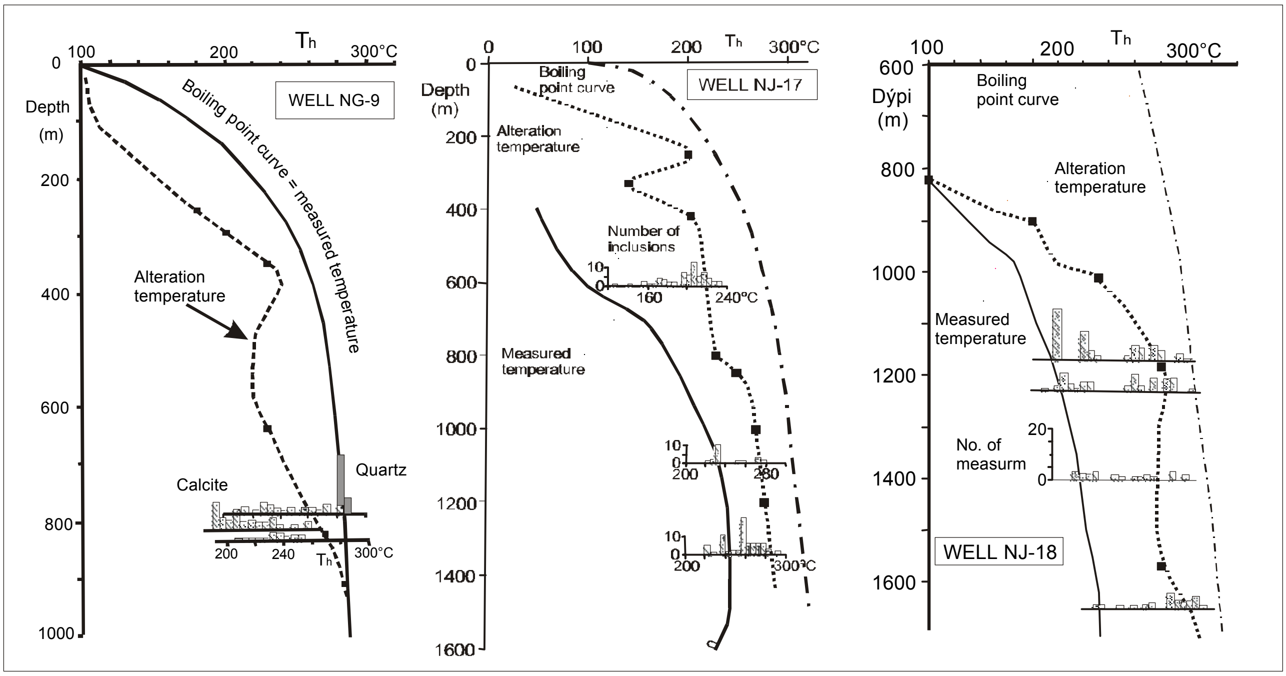

Figure 3. Th measurements in fluid inclusions mostly in calcites, and a comparison with alteration and formation temperatures.

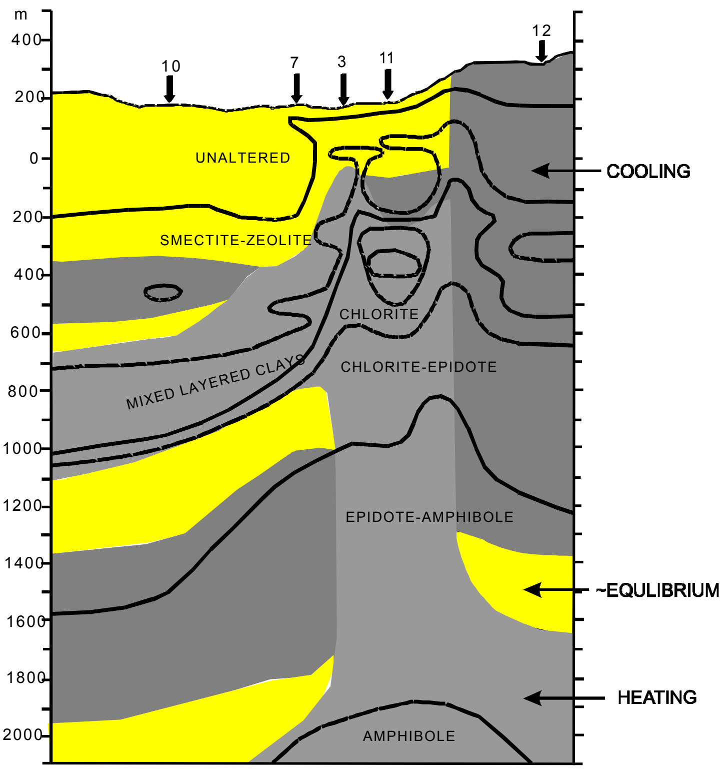

Figure 4. An E-W cross section (c.f. lower left alteration section in figure 1) showing areas of recent heating, and earlier cooling. See text for more information.

Porosity range	% rock-samples
0-10%	43
10-20%	25
20-30%	17
30-40%	9
40-50%	4
50-60%	1
60-70%	1

Table 1. Range of primary porosities found in Icelandic rocks, based on petrographic analysis (Franzson et al. 1997)

No. of minerals in void	No. of observations
1	38
2	801
3	124
4	26
5	7
6	2

Table 2. Observation on number of minerals in voids in Nesjavellir system

	Laumontite	Quartz	Wairakite	Prehnite	Clay	Calcite
Stilbite	2	6	4			
Mordenite	1	16	1			1
Mesolite		3				1
Scolecite		2	1			
Laumontite		9	7	1	9	
Analcime						1
Total	3	36	13	1	9	3

Table 3. Observations on alteration of zeolites (see text for more information).