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STRATIGRAPHIC, TECTONIC AND TEMPERATURE MAPPING THROUGH GEOLOGICAL WELL LOGGING: ICELANDIC EXPERIENCE

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ABSTRACT

When geothermal exploration turns from surface exploration to subsurface exploration this marks the onset of direct measurements of the properties of the geothermal reservoir through boreholes, but the objective is to gain information about the geological setting, temperature, pressure and fluid composition in the geothermal reservoir to prepare for future utilization. Geological samples in the form of drill cuttings and cores are collected during drilling of geothermal wells. Analysis of the rock samples is used both as guidance in technical aspects of drilling as well as to characterise the geological and thermal structure of the geothermal reservoir. Geothermal high temperature drilling has been carried out in Iceland for decades, but this paper will give a brief description of the types of geological investigations that performed in association with geothermal exploration in Iceland and provide examples of how they are applied to compile the volcanic and tectonic structure and thermal history of the geothermal field.

1. INTRODUCTION

The first step of exploring and developing geothermal resources is surface exploration, which typical includes geological mapping, geochemical and geophysical surveys. The objective of the surface exploration is to obtain initial estimates on: (1) the geological structure of the system (2) the fracture network that controls fluid flow within the system (3) the size of the system (4) subsurface temperatures (5) heat source and natural recharge to mention a few. The outcome of these investigations should be brought together to create a preliminary conceptual model of the geothermal area.

Provided that the results of surface exploration points towards a geothermal potential, the next step will eventually be to drill wells (exploration and production wells) into the geothermal reservoir in order to validate this initial conceptual model and confirm reservoir temperature, pressure, permeability and fluid composition.

The well gives access to the information about the subsurface. Geological samples are collected in the form of cuttings and/or cores, but these are analysed to determine the lithology and alteration of the rocks. Logging tools can be lowered into the well both during and after drilling, but they are used to measure and evaluate reservoir properties such as formation temperature, pressure, injectivity and production capacities as well as geophysical properties of the formation, while the reservoir fluid can be sampled and analysed, when the well is discharged.

This paper will address the information that is obtained through analysis of the collected geological rock samples, and how this is applied both during drilling and later to update the conceptual model. Other papers will be addressing the information obtained through logging and fluid sampling from the well.

Analysis of the cuttings and cores collected from the wells enables the well site geologist to map the stratigraphy of the geothermal reservoir, thus presenting the subsurface extension of the geological mapping at surface. Geological mapping of the subsurface through well cuttings and cores does not offer extensive surface exposures as the field geologist is privileged with. But the well site geologist can with advantage study fossil central volcanoes that have been exhumed by erosion. Examples of exposed sections through central volcanoes are found in Eastern Iceland (Figure 1), where the structure of the volcanic complex can be studied in detail such as relationships between intrusive complexes (dykes, sills, sheeted dyke complexes and plutons) and aureoles with hydrothermal alteration. Such studies enable the well site geologist to correlate observations from drilling cuttings and cores with the large scale geological structures characterising a geothermal system on which a conceptual model build upon.

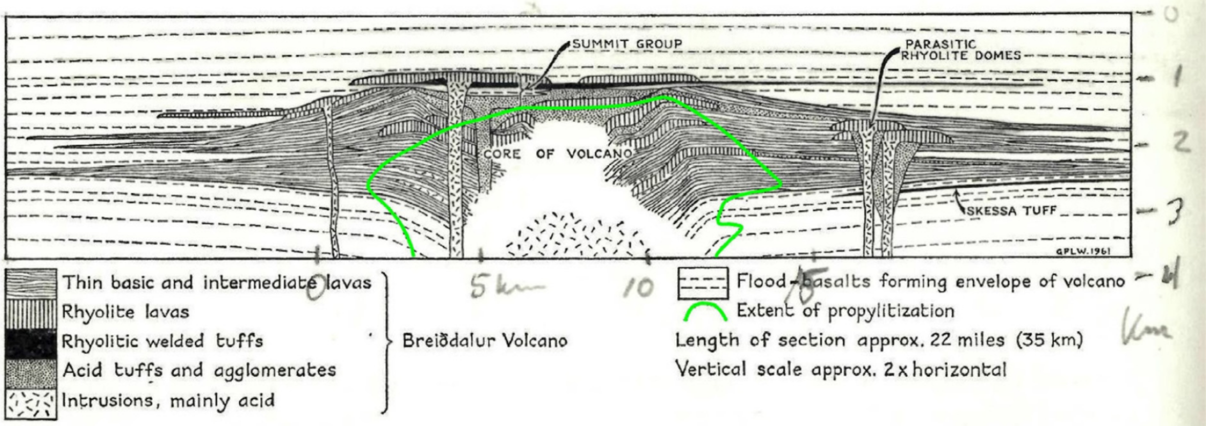

FIGURE 1: Graphic representation of Breiddalur central volcano, Eastern Iceland, but it has been exposed through erosion (Walker, 1963)

2. GEOLOGICAL WELL LOGGING – METHODS AND APPLICATIONS

During drilling into high temperature geothermal fields in Iceland drill cuttings are collected at 2 m intervals and petrographic analysis of the cuttings then forms the foundation for creating lithology and alteration logs of the well. The geologist is using a binocular microscope for the drill cuttings analysis, but first analysis is carried out in conjunction with drilling at rig site. Further and more detailed analysis is carried out when drilling is completed. In order to better characterise the hydrothermal alteration and alteration mineral sequences petrographic analysis is complemented with thin section analysis and XRD clay analysis, and this can be supplemented with fluid inclusion analysis at selected intervals.

The petrographic analyses are used to improve and refine the understanding of the geological setting within the geothermal reservoir as well as to assist with technical issues during drilling of the geothermal well.

Information gathered from drilling into the geothermal reservoir is used to extend the initial conceptual model into the geothermal reservoir, but the objective of petrographic analysis of drill cutting is to obtain information about:

1) temperature and temperature changes in the geothermal reservoir
2) geological control of permeability
3) formation porosity
4) fluid composition
5) rock type and stratigraphy e.g. characterise cap rock, reservoir rock and heat source
6) upflow, outflow and recharge zones
7) duration and thermal history of the geothermal system

During drilling petrographic cutting analysis is also used to assist with technical aspects of the well construction and drilling operation. Petrographic analysis of the cuttings is used to estimate, when the well has reached into sufficiently high temperatures in the reservoir before setting the production casing, ensure that all casings are set in solid formations as well as assisting with foreseeing or explaining drilling problems such as: a) blow outs due to over-pressured aquifers, b) stuck pipes due to swelling clays or unstable rock formation or c) drill bit performance is evaluated from cutting size, rock type, formation temperature and signs of metal fragment contaminations. In addition to analysing the drill cuttings the well site geologist is also using the drilling parameters to gain information about the reservoir conditions, e.g. circulation loss and temperature changes of the circulation fluid is monitored to identify, when the well is intersecting aquifers, while the formation hardness can be inferred from the drilling parameters. The drilling parameters are particularly valuable, when drilling with total loss of the circulation fluid, for instance are changes in parameters such as pump pressure and penetration rate used to identify whether the well has intersected new aquifers.

3. LITHOLOGY, STRATIGRAPHY AND PERMEABILITY

Analysis of lithology and hydrothermal alteration of drill cuttings are presented in logs, which are meant to give an overview of how the stratigraphy of the field is and how alteration of the rock is systematically changing with depth in the geothermal reservoir. The mud log is also showing the location of aquifers that the well has intersected, but aquifers are identified by measuring the circulation loss while drilling, through temperature measurements in the well and by observing changes in alteration in the drill cuttings, but the location of aquifers are closely compared to the lithology and alteration in the well in order identify whether the aquifers are tied to lithological contacts, intrusions or fractures and faults.

As more wells are drilled into the geothermal reservoir the lithology can be correlated between the wells in order to create a stratigraphic and structural model of the geothermal field. Correlation between wells can be difficult in volcanic terrains due to large variations in the lateral extent of the volcanic deposits and their at times rather homogeneous appearance. The geological model should depict the main rock formations of the geothermal field, what constitutes the cap rock and the reservoir rock as well as highlighting faults and fractures in the field. Surface faults can be hidden by recent volcanic deposits, so stratigraphic correlation between wells also attempt to identify hidden faults.

In Figure 2 is an example of a geological cross section through the Leirbotnar and Sudurhlídar well fields in Krafla, NE-Iceland. In correspondence with most high temperature fields in Iceland the cap rock consist of hyaloclastites interlayered with sequences of basaltic lavas. The hyaloclastites are formed by subglacial eruptions. Initially the hyaloclastite has a high porosity (20-50%). But it consists almost entirely of volcanic glass, which is highly susceptible to alteration, thus the porosity of the rock diminishes readily with alteration forming an impermeable roof zone of the geothermal reservoir. With depth pillow lavas and basaltic lavas (~10-15% porosity) become more prominent at the same time the intensity of intrusions increases, but they are dense with a porosity of 2-5%. This is particular conspicuous in the Leirbotnar and Sudurhlídar field in Krafla, but there the lower reservoir is situated in a dyke complex (Ármannsson et al., 1987) (Figure 2), which represents part of the heat source.

In Figure 2 is a schematic illustration of the geological structures permeability is tied to with depth in the geothermal reservoir in Iceland. At shallow levels where lavas and hyaloclastites are unaltered the permeability is mainly strata bound, but with depth within the geothermal reservoir the volcanics are less permeable due to alteration and permeability is mainly tied to intrusives such as dykes and sills and active faults and fractures or where these structures intersect.

In an extensional setting as in Iceland faults and fissures are almost vertical. Televiewer logging is the most powerful way to confirm the strike and dip of permeable faults and fissures to help refine the structural model of the field and for future well siting (Steingrímsson, 2013). However, as a first approximation strike and dip of faults and fissures can also be inferred through correlation between surface structures and the location of aquifers in deviated wells (Figure 3).

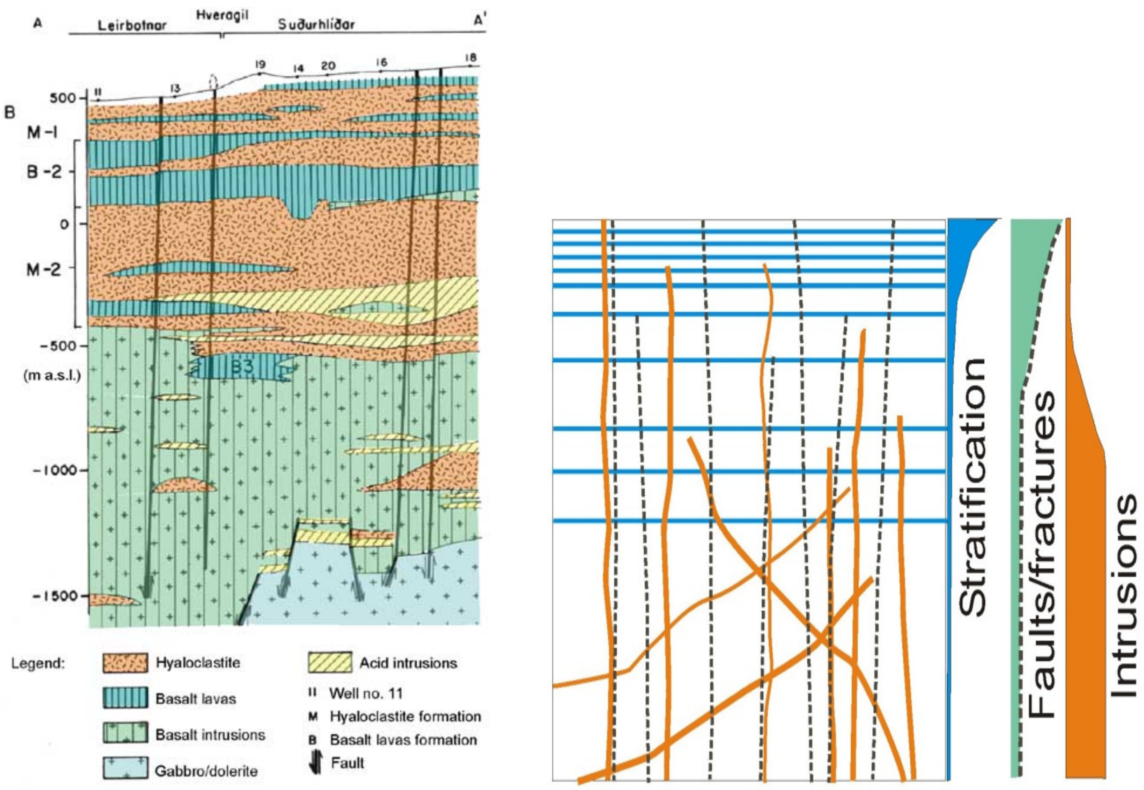

FIGURE 2: Left: Geological cross section W-E through Leirbotnar and Sudurhlídar well fields in Krafla (Ármannsson et al., 1987), the cap rock consist of sequences of hyaloclastites and basalt lavas, while the reservoir is situated in a dyke complex. Right: Schematic representation of permeability in high-T geothermal fields in Iceland, illustrating that permeability is mainly tied to faults/fractures and intrusions (dykes/sills) within the geothermal reservoir (Axelsson and Franzson, 2012)

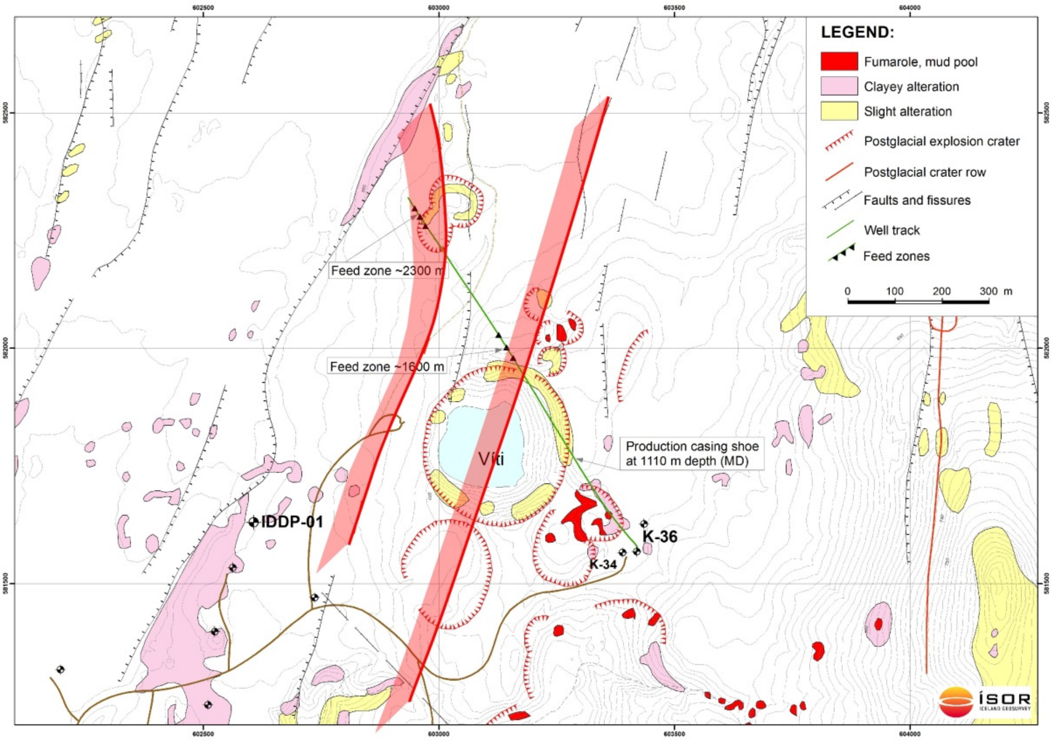

FIGURE 3: Map showing the correlation between fissure location at surface (red lines with shade pointing to the dip direction) and feed zone location in deviated well K-36 in Krafla verifying that the dip of the permeable fissures is ~3° to the west (Gudmundsson et al., 2008)

4. HYDROTHERMAL ALTERATION AND TEMPERATURE

Hydrothermal alteration in geothermal systems is a result of reaction between water and rock, but hydrothermal alteration is dependent on temperature, pressure, fluid composition, permeability, rock type and duration (Browne, 1978, 1984; Reyes, 1997). Dependent on the prevailing conditions within the geothermal reservoir hydrothermal alteration can occur either through precipitation, replacement or leaching.

Precipitation of hydrothermal alteration minerals is strongly controlled by temperature, thus systematic changes in alteration minerals assemblages with depth in the geothermal reservoir can be used as temperature indicators.

A large variety of hydrothermal alteration minerals have been identified in geothermal systems, but among the more common are carbonates (e.g. calcite), sulphides (e.g. pyrite), clays, oxides, and hydrated silicates. The most temperature sensitive alteration minerals are those, which contain OH or n.H_2O in their structure e.g. clays, zeolites, calcium silicates (e.g. epidote) and amphiboles, but in Table 1 is an overview of the temperature stability interval of the most common temperature dependent alteration minerals observed in geothermal fields Iceland.

The clay minerals are important index minerals not only due to their abundance and temperature sensibility, but also because there is a significant variation in the conductivity of the different types of clays (Flovenz *et al.*, 2005). In geothermal fields in Iceland the rocks are of basaltic composition, mainly tholeiites and olivine tholeiites, and therefore Mg- and Fe-rich clay types are prevalent such as smectite, mixed layer clays (MLC) and chlorite, while illite is scarce and only observed in association with more felsic rocks such as rhyolites.

This property of the clays to be sensitive to both temperature and conduction is of advantage to the resistivity surveys as this makes it possible to relate the resistivity structure in the ground to alteration temperature, where the conductive cap rock correlates to the presence of smectite and MLC clays, while the high resistive core of the geothermal reservoir corresponds to the presence of chlorite clays in the formation.

Table 1: Common temperature dependent alteration minerals in
high temperature areas in Iceland (Kristmannsdóttir, 1979)

Minerals	Min. temp. °C	Max. temp. °C
zeolites	40	120
*laumontite	120	180
quartz	180	>300
*wairakite	200	
smectite		<200
**MLC	200	230
chlorite	230	>300
calcite	50-100	280-300
prehnite	240	>300
epidote	230-250	>300
wollastonite	260	>300
actinolite	280	>300

*Belong to the zeolite group.
**Mixed layer clay.

The systematic change in alteration mineral assemblage with temperature in the geothermal systems is used to create isotherm maps and cross sections (Figure 4). With these maps areas of upflow (most alteration) and their structural correlation may be highlighted. In Iceland the isotherm maps and cross sections are either based on a specific index mineral or defined alteration zones as exemplified in Figure 4, but the alteration zones represent the following temperature stability interval:

1. Smectite-zeolite zone: <200°C
2. MLC zone: 200-230°C
3. Chlorite zone: 230-250°C
4. Chlorite-Epidote zone: 250-280°C
5. Epidote-Actinolite zone: >280°C

The alteration cross section in Figure 4 is showing a marked change in the alteration zoning across the Leirbotnar and Sudurhlídar well fields in Krafla. In Sudurhlídar field to the east the alteration gradient is high and alteration has reached the chlorite-epidote zone at 200-300 m a.s.l. pointing towards an area with upflow, while to the west of the Hveragil fissure in the Leirbotnar field the alteration gradient is smaller. The chlorite-epidote zone appears first at 0 m a.s.l., while the chlorite zone is relatively thick, which is indicating an interval in the reservoir with constant temperature conditions. Deeper into the reservoir the epidote-actinolite zone appears at a similar depth in both well fields, suggesting that the temperature conditions in the reservoir converge with depth.

Geothermal systems are dynamic, where changes take place through time, e.g. cooling or pulses of heating, but such changes can be revealed by petrographic analysis of alteration minerals sequences, comparison between alteration temperature and current formation temperature or through fluid inclusion analysis.

Fluid inclusion analysis comprises measurement of homogenization and melting temperature of inclusions trapped in alteration minerals. The homogenization temperature reflects at which temperature the inclusion was trapped in the crystal; it can either have formed during crystal growth or later through deformation and recrystallization of the crystal, while the melting temperatures provide an estimate of the fluid salinity. Fluid inclusion analysis is carried out in several different crystals in order to attain a statistically representative temperature distribution.

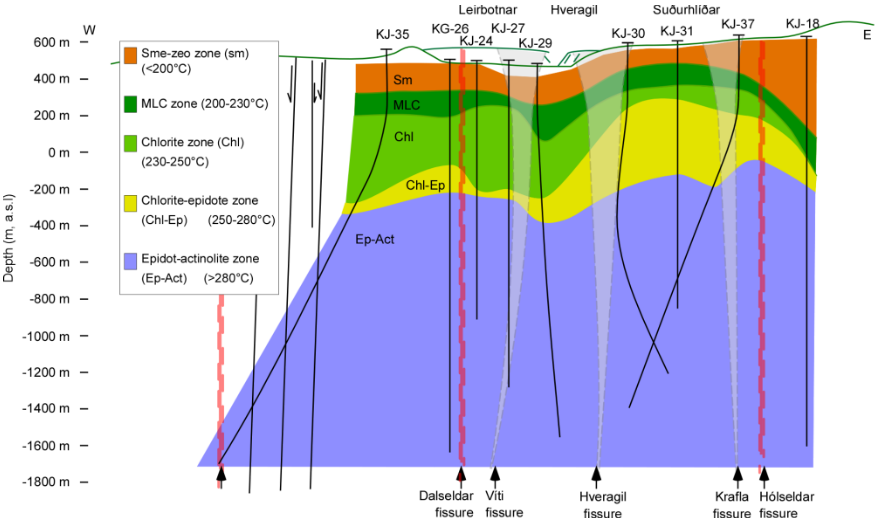

FIGURE 4: Alteration cross section W-E through Leirbotnar and Sudurhlídar well fields in Krafla (Ármannsson et al., 1987, Mortensen et al., 2009)

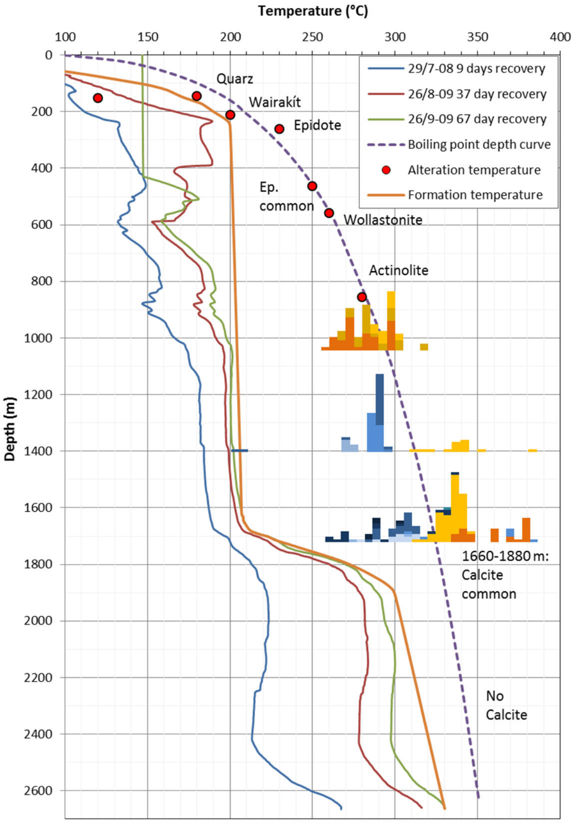

FIGURE 1: Comparison of formation temperature, boiling point curve and homogenisation temperature measured in fluid inclusions trapped in calcite (blue) and quartz (yellow) (Mortensen and Helgadóttir, 2009)

In Figure 5 results of fluid inclusion analyses from well KJ-38 in Krafla, are compared with selected temperature dependent alteration minerals, temperature logs, estimated formation temperature and the boiling point depth curve. Both fluid inclusion analyses and temperature based on first appearance of temperature dependent alteration minerals indicate that temperature has earlier stabilized near the boiling point curve with water level near surface. Temperature measurements indicate that formation temperature is 200-210°C down below 1600 m depth in the well. Indications of this cooling are scarce in the fluid inclusions, yet in calcite homogenisation temperature at 200-210°C is recorded in two inclusions, but this is pointing towards that minor changes in alteration have taken place in the reservoir since the upper part of the reservoir cooled. However, the transition between the upper and lower reservoir in Krafla (Ármannsson *et al.*, 1987) is at 1700-1800 m depth in well KJ-38 and precipitation of calcite characterise this transition zone and large temperature interval recorded in the fluid inclusion analyses points towards a zone, where heating of colder fluid from the upper reservoir results in boiling.

5. ALTERATION AND FORMATION TEMPERATURE IN CONCEPTUAL MODELLING

In geothermal fields were several wells have been drilled comparison between alteration temperature (appearance of selected temperature dependent alteration minerals) and the estimated formation temperature from temperature loggings in the well are used to highlight were the reservoir has been heating, cooling or is in equilibrium (Figure 6), but this method can be used to update the conceptual model of the geothermal system and highlight zones of upflow, outflow and recharge.

With continued reference to the geothermal field in Krafla NE-Iceland Figure 6 shows a comparison between the alteration zones and the formation temperature across the Leirbotnar and Sudurhlídar well fields in Krafla revealing that in the central part of Sudurhlídar field there is equilibrium between alteration and formation temperature. In the upper 1000 m of Leirbotnar field the reservoir has cooled, though the alteration has not been as high here as in the Sudurhlídar field e.g. due to higher permeability in upper part of the Leirbotnar reservoir. In the eastern part of the Sudurhlídar field comparison between alteration and formation temperature shows substantial cooling deep into the reservoir. Thus this relative simple comparison is highlighting an area of upflow and outflow from west into the Sudurhlídar field believed to be originating from the Hveragil fissure, which is marking the boundary between Leirbotnar and Sudurhlídar well fields. The eastern part of Sudurhlídar field is characterized by cooling and possible recharge, but the Hólseldar eruption fissure may act as an aquitard at shallow levels in the reservoir. The Leirbotnar field is characterised by an upper and a lower reservoir, but alteration and formation temperature is pointing towards sustained convection in the upper part of the reservoir.

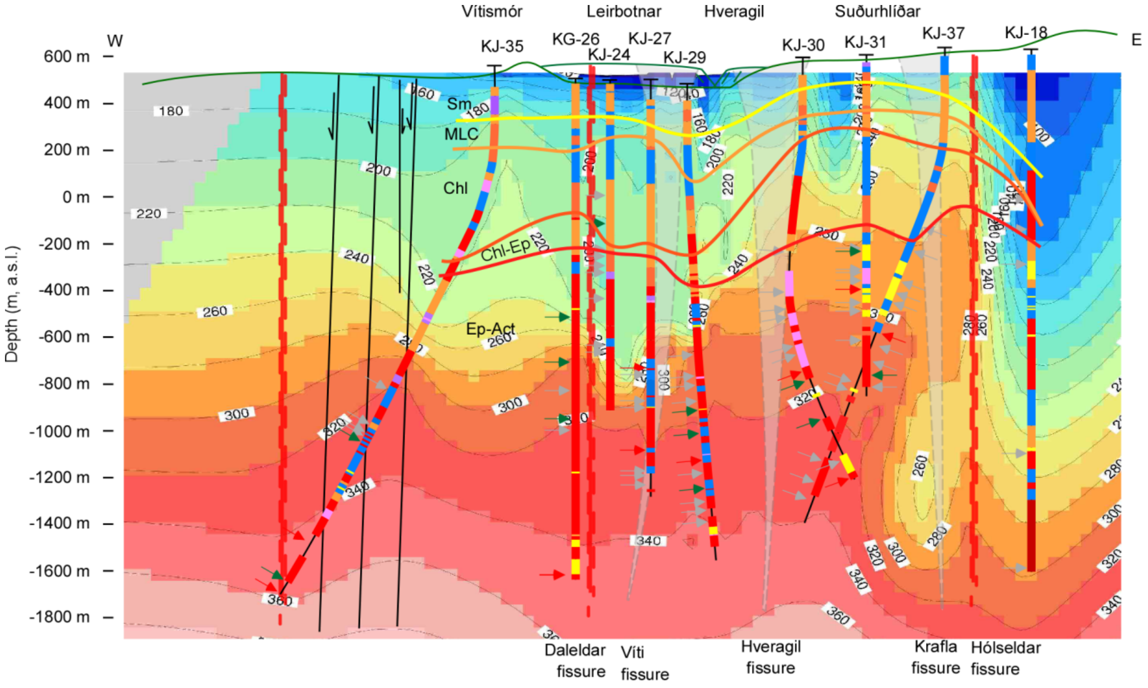

FIGURE 6: Comparison of temperature and alteration cross section W-E through Leirbotnar and Sudurhlídar well fields in Krafla. Lithology is also displayed along the well track and feed zone locations are indicated as arrows (red - major, green - medium, grey - small) (Mortensen et al., 2009)

6. SUMMARY AND CONCLUSIONS

This paper has highlighted the application geological logging in geothermal exploration, but it is not until the first wells are drilled into the geothermal reservoir that access is provided to obtaining rock samples and information about the subsurface. Geological logging of the samples collected while drilling is carried out with the objective to gather information about the geological properties of the reservoir, but petrologic analysis of the rock samples is used both to aid during the drilling process and also for further planning of the development and utilization of the geothermal field.

The main objective of petrologic analysis of the rock samples from the geothermal wells are manifold but focus on: characterising the geological formations of the reservoir, locating the stratigraphic and structural setting of aquifers with depth in the reservoir and identify temperature state and temperature changes characterising the dynamic, thermal history of the geothermal system. Petrologic information from analysis of the rock samples are merged with geochemical and geophysical data to establish a conceptual model of the field, but such a model form the basis for development of the well field and well siting in the geothermal reservoir.

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