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BOREHOLE GEOLOGY OF WELL ASAL-5, ASAL GEOTHERMAL FIELD, DJIBOUTI

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UNU Geothermal Training Programme
Reykjavík, Iceland
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ABSTRACT

This report describes the borehole geology of the well Asal-5 in the Asal geothermal field in Djibouti. This well was sunk down to 2105 m depth in the "inner rift" in order to explore there the temperature, permeability and the fluid characteristics of the area. The well penetrated a lava succession of olivine-, ferro- and trachybasalts as well as trachytes. Intrusive rocks are inferred at four depth intervals. The well showed a very low permeability and could not be discharged. Three aquifers were located above the production casing, the largest and the hottest one being at 500-550 m. Three minor aquifers were found in the production part of the well below 1600 m depth. The rocks show an extensive water/rock interaction where the intensity as well as rank of alteration increases with depth. The hydrothermal assemblage above ca. 1700 m depth indicates a much higher temperature condition than presently measured which clearly shows that the geothermal system has cooled down by as much as 200°C at 1000 m depth. A vague indication of retrograde mineralization, by the common occurrence of smectite down to 1000 m depth and laumontite presence at 600 m and 800 m depth, may indicate a lowering of temperature to below 200°C.

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1 INTRODUCTION

This report is the last stage of the six months training course conducted by the UNU Geothermal Training Programme at the National Energy Authority in Reykjavik, Iceland.

The training programme consisted of five weeks of introductory lectures dealing with various aspects of geothermal research, such as exploration and utilization; two weeks excursion to some of the geothermal fields in Iceland. Apart from these weeks the author studied borehole geology.

The report summarizes first the geology of the Asal field in the Republic of Djibouti followed by the exploration history of Asal and Hanle fields. The main topic deals with the lithology and the mineralogy of the well Asal-5. Binocular, petrographic microscopes and X-Ray diffraction (XRD) are the main techniques applied in the identification of the hydrothermal minerals using the cuttings recovered from the well Asal-5.

2 REVIEW OF PREVIOUS WORK

2.1 Geological Outline of the Asal Geothermal Field

The Asal Geothermal Field (fig. 1) lies within the Asal-Ghoubbet rift zone between Ghoubbet el Karab in the south-east and Lake Asal in the north-west. This part of the rift is characterized by active tectonism, periodic eruptions (the last volcanic eruption was Ardoukoba eruption in 1978) and continuous seismicity. The zone has also been uplifted due to magma intrusion at depth (BRGM report 1972-1973).

The tectonic features of the Asal rift are normal faults along two principal trends i.e. NW-SE and NNW-SSE. A third tectonic trend (E-W) has been recognized in some parts of the rift zone. The NNW-SSE and E-W tectonic features are older than the current NW-SE tectonic feature of the rift and they can be associated with an older geological formation (stratoide series) that outcrop at the margins of the active part of the rift.

The geological formations that outcrop within the Asal Geothermal Field are lava flows, pyroclastics (mostly hyaloclastites) and lake sediments (diatomite and limestone). The lava flows and pyroclastics have been produced by fissures trending NW-SE.

Several geological units were distinguished on surface by Stieljes et al. (1976). These are in decreasing age towards the centre of the rift:

-Hyaloclastites at the southern external rift
-Lava flows (Asal series)
-Phreatic tuffs of the "inner rift"
-Lake sediments
-Recent lava flows
All these formations are less than 1 my.

2.2 The Exploration History of Asal and Hanle Geothermal Fields

The geothermal surface exploration in the Asal rift zone (fig.1) was carried out by BRGM since 1970. Among the various reseach techniques and methods applied were:
-Geological mapping
-Geochemical analyses of hotsprings and fumaroles
-Geophysical methods such as resistivity, magnetic and gravimetric surveys
-Shallow gradient wells

The results of the above methods led to the siting of two deep exploratory wells, Asal-1 and Asal-2 (fig. 2) at the external edge of the rift. Asal-1 and Asal-2 were drilled to 1146 m and 1554 m depth respectively. Asal-2 was dry, but hotter(280°C) than Asal-1 (258°C), while Asal-1 was productive. Asal-1 confirmed, during well testing in 1975, the existence of a water dominated high-enthalpy geothermal reservoir. Unfortunately the salinity of the geothermal fluids was very high, which might create problems during the exploitation of the resource.

Due mainly to the high salinity of the geothermal fluids of Asal-1, the strategy of the geothermal development shifted to Hanle area (fig. 1), which was assumed to contain geothermal fluids of lower salinity. After several years of surface exploration and the drilling of three gradient wells in the Hanle area, two deep exploratory wells were sunk in 1987; Hanle-1 (1600 m deep) and Hanle-2 (2000 m deep). Both wells were dry and the measured temperatures were only 70°C and 120°C respectively. The results of these two exploratory wells confirmed that the Hanle Geothermal Field is a low temperature field and not suitable in terms of economic production of electric power. Further exploration of the Hanle Field was thus abandoned and the attention redirected to the Asal Field in 1987.

In June 1987, Asal-3 was sited 4 m east of Asal-1 and drilled to a depth of 1316 m in order to verify the potential and the extention of the reservior already intersected by Asal-1 in 1975. The well was productive and the geothermal fluids had the same chemical characteristics as those produced by Asal-1. However, during three months of well discharge, a decline in mass flow occurred due to scaling within the casing.

It became therefore evident that scaling, as observed in Asal-1 and 3 would impose serious problems in the utilization of the field. The exploration emphasis was put on locating a less saline part of the reservoir. The managers of the Asal Geothermal Project believed that the densely fissured "inner rift" would be more permeable than the "external rift" and would thus increase the probability of finding those lower salinity geothermal fluids.

According to the above hypothesis, Asal-4 was sited 1250 m north of Asal-3 and drilled to a depth of 2013 m. Asal-5 on the other hand was sited 4750 m north of Asal-3 at the edge of the axis of the rift and drilled to a depth of 2105 m. Unfortunately, both wells were dry and did not give any information about the chemical characteristics of the geothermal fluids. They, however, indicated the high temperature characteristics of the area ($T<350°C$).

On the basis of the negative results of Asal-4 and Asal-5, further exploration was again directed to the area around Asal-3 and Asal-1. Asal-6 was sited about 300 m NW of Asal-3 and drilled to a depth of 1761 m. It was productive and the geothermal fluid had the same chemical characteristics as Asal-3, but is less productive.

2.3 Well Asal-5

The present work discusses Asal-5 (see fig. 2), which is the deepest well (2105 m) drilled in the Asal Geothermal Field. A shallow hot reservoir (160°C) occurs at about 500-550 m depth, then the well intersected a cold zone (about 60°C) to 1200 m depth. Below that depth the temperature increased and the bottom temperature at 2105 m was about 333°C. The well has never been discharged.

After the well became unsuccessful, Icelandic scientists, being familiar in the strategic research of geothermal fields of similar geological settings joined the exploration of Asal Geothermal Field. In March 1988, Kristjan Sæmundsson made a geological survey in the Asal Field, where he indicated that Asal-5 was not correctly sited as it would be about 700-1000 m from the geothermal uplow zone (Sæmundsson, 1988). In June 1988, resistivity survey using the TEM method (Transient Electromagnetics) was done in the "inner rift" (Árnasson et al., 1988). The survey indicated the existence of an upflow zone of geothermal fluid under the Lava Lake, as had been mentioned before by Kristjan Sæmundsson. These results show this area to be most promising for siting future exploratory wells.

3 BOREHOLE GEOLOGY

3.1 Classification of the Rocks

The rocks intersected by the exploratory wells in Asal geothermal field have been classified into the following units:

Olivine basalt is medium to coarse grained, it contains big phenocrysts of plagioclase (andesine/labradorite), olivine, pyroxene (augite) and opaques. The texture varies from porphyric to sub-ophitic. Sometimes it can be divided into two units according to texture; i.e. porphyric olivine basalt and olivine basalt.

Ferrobasalt is iron-rich, fine grained, with aphyric and rarely sub-aphyric texture. The rock contains acidic plagioclase (oligoclase) arranged in a sub-parallel manner. This character indicates that the rock is a little bit evolved.

Dark trachyte is dark in colour, very fine grained and has a trachytic texture. It consist of sub-parallel k-feldspar microlites and sodic plagioclase, with minor pyroxene (augite) and abundant opaques.

Trachybasalt is an intermediate between basalt and trachyte. It consists of randomly arranged k-feldspar microlites and acidic plagioclase, pyroxene (augite) and opaques. The texture varies from aphyric to sub-aphyric according to grain size (fine to medium).

Rhyolite is very fine grained, silicified and light grey in colour. The rock is made up of sodic plagioclase, k-feldspar and quartz. Devitrification and recrystallization occur mostly in the ground mass.

Hyaloclastite is an sub-aquatic volcanic product that has cooled rapidly to form glass. The rock is yellow-brownish in colour and the glass has been palagonitized due to the reaction with water. At some levels, **tuffs** and **clays** are found interlayering the above rocks. The tuffs are either of lithic or crystal type.

3.2 Overview of Well Asal-5

During the drilling operations of well Asal-5, cuttings were collected at every five meters interval and thin sections were prepared every ten meters at the well site. Both the cutting samples and the thin sections were studied at the same time by binocular and petrographic microscopes, thus gradually building up the current subsurface conditions of the well.

Detailed stratigraphic log of Asal-5 has already been done by the Italian Consultant Company (Aquater, 1988). However, for the present report a review of the stratigraphy (see fig. 3) was made using binocular microscope; the same lithological units were concluded to be present, but the porphyric olivine basalt and the olivine basalt used as two separate formations in the previous stratigraphy of the well have been combined into one type, as the author considered the porphyric olivine basalt is an olivine basalt with porphyric texture. Due to this the formation boundaries have been modified. Four intrusions are also suggested here due to their coarse grained and doleritic texture (fig. 3).

The well Asal-5 penetrated mainly basaltic lava flows, dark trachytes and trachybasalts. Some thin tuffs and alluvial gravel layers are also present. The geological formations intersected by Asal-5 are not in all respect the same as those formations encountered by the other wells drilled in the area, as the hyaloclastites of the Asal series (<1 my), the pleistocene shale which occurs in the upper limit of the stratoide series (6 to 1 my) and the dalha basalts are all absent in Asal-5.

Dalha basalt is the oldest formation (8 to 6 my) encountered by the other wells. It is the most permeable unit of the area and the geothermal reservoir met by Asal-1 and 3 is located in it.

4 HYDROTHERMAL ALTERATION

4.1 Definition

The primary minerals, of magmatic origin, become unstable in contact with the geothermal fluids as a result of differences between magmatic conditions and the new environment created by the invading geothermal fluids. Chemical reactions initiated by instability of the primary minerals in the changed environment tend towards a new equilibrium between the minerals and the geothermal fluid by altering the primary minerals into new mineral phases named "hydrothermal minerals" (Steiner, 1977).

Hydrothermal alteration minerals present in active geothermal fields are important to evaluate/or estimate fossil and prevailing reservoir temperature, permeability and fluid composition. Different factors such as temperature, pressure, permeability, original rock type, fluid composition and duration of activity control the formation and stability of the hydrothermal minerals, (Browne, 1978).

4.2 Analytical Techniques

The cutting samples were analysed using binocular microscope, thin sections and XRD. A total of 32 samples were run on XRD for the determination of clay minerals. 21 cutting samles and 6 amygdale filling samples were prepared for thin sections to determine the rock type, the hydrothermal minerals and their relative time sequences.

The method practised in Iceland for the preparation of the clay minerals on XRD analysis is as follows:

1. Approximately 2 teaspoons of drill cuttings were placed into a

glass tubes and washed with distilled water. The glass tubes were filled up to 3/4 with distilled water and then plugged with a rubber stopper. The glass tubes were put horizontally into a shaker for 4 to 5 hours.

2. The glass tubes were left standing for approximately 1 to 2 hours to allow the largest particles to deposit. Then the solution was pipetted on a numbered glass plates and dried in air.

3. The glass plates were stored in a dessicator containing $CaCl_2$ solution with a humidity of 35% for 24 hours, and then run on the XRD from 2°- 14° angle.

4. Dublicate glass plates were stored in a dessicator containing glycol solution ($C_2H_6O_2$) for 48 hours and then run on XRD from 2°- 14° angle.

5. The glass plates treated with CaCl2 solution were then heated to 550°- 600°C for 2 hours and run on XRD from 2°- 14° angle.

The clay minerals were identified from their basal reflections by referring a standard table which describes the intensity and the various peaks related to the basal reflections of the various minerals. The calculated peak values were compared with the data by G.W.Brindley and G.Brown (1980), Steiner (1977). Figures 5(a), 5(b) and 5(c) show the characteristic peaks for smectite, mixed layered clays and chlorite.

The clay minerals are highly sensitive to temperature variations and they are used as thermometers to asses the prevailing temperatures of geothermal systems.

4.3 The Alteration of the Primary Minerals

The primary minerals are susceptible to hydrothermal alteration, but the degree of susceptibility varies from one mineral to another. The order of decreasing susceptibility of the primary minerals to hydrothermal alteration is: volcanic glass, magnetite, olivine, pyroxene, plagioclase, anorthoclase and quartz, (Browne, 1978).

The primary rock forming minerals present in the analysed cutting samples are ferromagnesian minerals (olivine, pyroxene), plagioclase, k-feldspar and magnetite/ilmenite. The ferromagnesian minerals associate mostly with basaltic rocks, k-feldspar associates with the intermediate rocks (dark trachyte and trachybasalt), but the plagioclase and the opaques (magnetite/ilmenite) are present in both intermediate and basaltic rocks.

In the rocks intersected by Asal-5, volcanic glass and olivine are the first constituents to become unstable and to be altered. **Volcanic glass** started to alter to clay minerals in the first meters of the well and no fresh glass is observed in thin sections below 380 m. Glass has been altered to chalcedony, calcite, quartz and below 860 m depth it has been totally replaced by clay minerals. **Olivine** is unaltered down to 200 m depth, where it starts to show oxidation along crystal fractures. It is totally altered below about 380 m depth. It has altered mainly to clay minerals but also to calcite and quartz. **Magnetite/ilmenite** show a strong oxidation in the upper 500 m of the well, probably related to an oxidation zone around a basaltic intrusion which the well disects at 380-400 m. Below 500 m depth it is seen altering to sphene and pyrite. **Plagioclase** is unaltered down to 400 m - 500 m depth, where it starts to alter to albite, clay minerals and calcite. At 680 m depth it is seen altering to k-feldspar and at 860 m depth to epidote. At 1300 m alteration to amphibole is observed and at 2060 m depth to chlorite. **Pyroxene** has altered to calcite at 860 m depth. At 1300 m depth, pyroxene altered to epidote and wollastonite (or tremolite) and at 1550 m depth to prehnite.

4.4 Distribution of Hydrothermal Alteration Minerals

The distribution of the hydrothermal alteration minerals discussed below is shown in fig. 4.

Calcite is one of the most abundant hydrothermal mineral in the well. It occurs throughout the well, but below about 1380 m depth its abundance decreases down to the bottom of the well. It is formed as a replacement of primary Na-Ca plagioclase, volcanic glass and ferromagnesian minerals (olivine and pyroxene). It occurs also as a vein and amygdale infilling or as a direct deposition from the hydrothermal solution. It associates with chlorite, quartz, smectite, epidote, laumontite and mixed layered clays.

Opal is very rare, it is found sporadically as an amygdale filling in the upper part of the well from 80 m to 260 m.

Chalcedony is most common at 400 m to 600 m depth, but occurs sporadically down to 1180 m. It formed as replacement of silicic glass and as a direct deposition in association with quartz occupying mostly the outer edge of the cavity. It was identified by binocular microscope as well as in thin section.

Quartz appears first at 440 m, becomes most common at 500 - 550 m, below that depth it occurs sporadically down to the bottom of the well except at about 1030 m - 1250 m which is locally abundant. It formed as a precipitation from the geothermal fluids as well as the recrystallization of the glassy matrix of the intermediate rocks. It commonly occurs in veins and vugs. Quartz often associates with calcite, epidote, chlorite, smectite and prehnite.

Scolecite/Mesolite was only found at one location at 500 m.

Heulandite occurs sporadically from 200 m to 400 m depth. The mineral was identified both in thin section and XRD. It occurs as euhedral crystals in cavities. Heulandite is associated with smectite occupying the center of the cavity i.e. it is formed later.

Laumontite appears first at 570 m, but occurs also at 770 m together with **Wairakite.** Both minerals formed as a precipitation from the geothermal fluids, filling cavities and vesicles.

Prehnite was identified in thin section at 550 m and then again only below 1500 m where it is common. It is the alteration product of the ferromagnesian minerals and calcic plagioclase. It associates in vein and vesicle fillings with epidote, quartz and chlorite.

Epidote appears first at about 800 m and occurs sporadically down to about 1250 m, below which it becomes common and abundant. There it occurs as massive aggregates as well as radiating prismatic crystals. It is found as amygdale fillings but is also observed as the alteration product of pyroxene and plagioclase. It associates with quartz, calcite, chlorite actinolite, wollastonite (tremolite) and prehnite.

Actinolite appears first at 1300 m, where it becomes common. It forms as a replacement of pyroxene and associates with epidote and garnet. It has a green colour in thin section, is pleochroic and occurs in a long prismatic crystals.

Tremolite or Wollastonite appears first at 1300 m, where it occurs sporadically down to 1550 m, but becomes common below that depth. It forms as a replacement of pyroxene and associates with epidote and chlorite. It is colourless in thin section and occurs in a long prismatic columnar crystals to fibrous aggregates.

In the XRD analysis a persistent peak at 8.97Å is considered to be a possible indication of a tremolite.

Garnet was observed first at 990 m and becomes common in thin sections below 1180 m down to the bottom of the well. It is associated with epidote, calcite and chlorite. It occurs as euhedral or subhedral crystals with high relief.

Albite occurs sporadically from 500 m to 1180 m below which it becomes common. It formed as a replacement of plagioclase and possibly also primary k-feldspar.

K-feldspar (adularia) occurs only at about 680 m depth, below the presently active hot water zone. It is there as an alteration product of plagioclase and also as a precipitation from the geothermal fluids in association with quartz.

Anhydrite is very rare and occurs sporadically from 500 m to 990 m as vein and vesicle fillings.

Sphene appears first at 500 m and becomes common down to the bottom of the well. It is mainly the alteration product of ferromagnesian minerals and magnetite. It occurs as high relief crystals.

Hematite is abundant in the upper 600 m of the well, below that depth it occurs sporadically. It formed as alteration product of primary magnetite/ilmenite and olivine along the crystal margins and fractures. It occurs also as a vein and amygdale infilling.

Pyrite appears first at 260 m, becomes common below 400 m and abundant below 500 m down to about 1700 m depth, where it decreases slightly down to the bottom of the well. It occurs as minute grains and as well formed cubic crystals. It is the alteration product of the ferromagnesian minerals and magnetite. It occurs also as veinlets and amygdale infillings. It is found associated with chlorite, calcite, quartz and epidote. Pyrite is easily identified by its cubic form and metallic lustre.

Smectite is mostly absent above 200 m depth, becomes common and abundant from 200 m to 1000 m. Below that depth it was analysed by XRD at 1250 m and 1800 m. It is the alteration product of ferromagnesian minerals, plagioclase and volcanic glass as well as a direct deposition from the geothermal fluids to form veins and amygdale minerals. It associates with quartz, calcite, zeolite, chlorite and hematite.

Traces of **mixed layered clays** are found from 350 m down to the bottom of the well, identified both by XRD and thin section (see fig. 4). They are formed both as alteration product of the primary minerals and volcanic glass as well as a precipitation from the geothermal fluids.

Swelling-chlorite occurs from 510 m to about 1250 m, below which it disappears. It was identified by XRD (d/Å: 30.44, 32.7, 29.43).

Chlorite is a very common alteration mineral, it appears first at 500 m and becomes common below that depth. It is the alteration product of the ferromagnesian minerals, plagioclase and the glassy matrix of the rocks as well as precipitating from the geothermal fluids to form vein and amygdale fillings. It associates with calcite, epidote, prehnite and quartz. It was identified both by XRD and thin section.

Traces of **illite** are found at 350 m, 400 m and 700 m depth, identified by XRD. The formation of illite depends on the composition of the rocks i.e. it tends to form in silicic rocks, but less in basic rocks. Chlorite, on the other hand is more common in basic rocks than silicic rocks.

5 DISCUSSION

Hydrothermal minerals can be used to comment upon present and the past conditions in geothermal systems as their occurrences are strongly dependent on temperature, permeability, rock type and the fluid composition of the system. Mineralogically deduced temperatures provide information on the thermal stability of a geothermal system.

In geothermal fields the minerals mostly used for the estimation of subsurface temperatures are smectite, zeolites, mixed layer clays, chlorite, epidote, actinolite and garnet. Kristmannsdóttir (1978) established the stability temperature range found for these minerals in the Icelandic geothermal fields. Smectite and zeolites are formed at rock temperatures below 200°C. Mixed layered clay minerals of smectite and chlorite are dominant at 200 - 230°C, while chlorite has become the dominant sheet silicate at rock temperature of 230 - 250°C. Epidote occurs sporadically at 230 - 250°C, but becomes common at 260°C, while actinolite occurs at temperature 280°C. Wollastonite and garnet are stable at temperatures >300°C.

In the Asal geothermal field the common hydrothermal minerals are found in drillholes in a definite sequence as temperature increases towards deeper zones. The systematic vertical ditribution of alteration minerals indicates a zonation. Each of these zones are characterized by a definite assemblage of hydrothermal minerals which in many respects is similar to Icelandic high temperature fields.

Referring to the established alteration zones in the high temperature geothermal fields of Iceland, six hydrothermal alteration zones have been established based on the progressive alteration of the rocks. These zones are shown in fig.4, and are as follows:

1) Unaltered zone: This zone extends from the surface to about 200 m depth. The rocks are hardly affected by any hydrothermal alteration and are considered fresh. This is confirmed both by thin sections and XRD analyses.

2) Smectite zone: The upper boundary of the zone is defined by the appearence of smectite at about 200 m depth. Smectite is the most dominant clay minerals in this zone. The inferred stability temperature is less than 200°C.

3) Mixed layer clay zone: Mixed layer clays were analysed (XRD) at 350 m depth and it is proposed that, similar to Icelandic experience, this boundary indicates a temperature of about 200°C.

4) Chlorite zone: The upper boundary of this zone is at about 500 m depth, where chlorite becomes common and that boundary probably represents a temperature of about 230°C.

5) Chlorite-epidote zone: The upper boundary of the zone is at about 800 m depth, where epidote first appears. Chlorite and epidote assemblage indicate a temperature >240°C.

6) Chlorite-actinolite: The upper boundary of the zone is defined by the appearence of actinolite at about 1300 m depth and is found at all levels below that down to the bottom of the well. The stability temperature of actinolite as mentioned above is higher than 280°C.

A comparison of the measured temperature and the inferred stability temperature of the minerals is shown in fig. 6. It seems quite clear that the alteration minerals above ca. 1700 m depth from a temperature curve much higher than the presently measured temperatures. The mixed layered clays and chlorite temperatures lie on the boiling point curve (200 m water

table assumed) which might indicates that the system at that depth was in a boiling condition. Although epidote forms at about 800 m depth it does not become common until below 1200 m depth and this may indicate that temperature did not surpass much over 250°C down to that depth. Below that temperatures of 280°C are indicated by the appearences of amphiboles and garnet. Calcite is abundant in the well, but its abundance decreased below ca. 1380 m depth. A decreasing abundance of calcite at about 290°C is often observed in the Icelandic high-temperature reservoirs (e.g. Kristmannsdóttir, 1978), and is also likely to be the case in Asal-5.
The abundance of calcite usually indicates a high partial pressure of CO_2 in the geothermal fluids, but according to geochemical analyses, the geothermal fluids met by Asal-1 and Asal-3, indicated a high salinity water with low gas content. Due to this fact, it may be related to brine characteristics of the Asal geothermal fluids.

It is quite evident from fig. 6, that a drastic cooling has occurred in the geothermal system. At 500 m depth, where a hot permeable zone was intersected a temperature drop of up to 50°C can be postulated. A maximum temperature difference of just less than 200°C is observed around 1000 m and below that depth the difference becomes gradually less and at about 1700 m depth these two curves merge.

Indication of cooling of the geothermal system is only vaguely seen in the alteration assemblage:
The common occurrence of smectite down to 1000 m depth and an isolated occurrence at 1200 m may imply a temperature below 200°C. Similarly the laumontite occurrences at 600 m and 800 m depth may also indicate temperatures below 200°C. Thirdly heulandite, which becomes unstable at temperatures above 150°C. is found down to 400 m depth, some 50 m below the upper boundary of the mixed layered clay minerals.

The temperature inversion of the zone between 600 m to about 1700 m depth, has been interpreted as being due to an intrusion of a cold sea water which effectively cooled this part of the well (Aquater report, 1988). According to Tómasson and Kristmannsdóttir (1972), one would expect a high concentration of anhydrites in rocks where cold saline water is heated up during its downward percolation as was distinctly observed in the saline Reykjanes high-temperature field in Iceland. However, due to the scarcity of anhydrites in the rocks where maximum cooling is taking place, it seems probable that the well has intersected the outer perimeter of this influx zone where cooling is taking place by conduction.

The TEM-survey done by Orkustofnun (The National Energy Authority of Iceland, 1988) in the central part of Asal rift located a probable geothermal upflow zone in the Lava Lake about 700-1000 m ENE of well Asal-5 (Arnasson et al., 1988). They also pointed out the existence of an impermeable zone (a hydrological barrier) between well Asal-5 and Lava Lake below which the main geothermal upflow zone is now postulated. This confirms that the two zones are not hydrologically related and Asal-5 is located outside of the presently active geothermal system. It is possible though that the hot aquifer at 500 m depth is an outflow from that geothermal system.

The relative abundance of pyrite as veinlets and amygdale infillings can in some cases be correlated with zones of high permeability or aquifers (Franzson, 1983). This may apply to Asal-5, where pyrite is more concentrated in some horizons than others. These horizons occur from 460 m to about 1700 m depth which might be correlated to the present and the previous permeable zones when the system was active.

6 CONCLUSION

The hyaloclastite, dalha basalt, the pleistocene shale which occurs at the base of the quaternary formations or the top of the stratoide series were encountred by all the wells except in Asal-5.

A reduction of calcite abundance occurred below about 1400 m depth which implies temperatures >290°C. Hematite is most abundant in the upper 600 m of the well below which it becomes rare. This may be related to an intrusion occurring at around 380 m to 400 m depth. Quartz is most common at 500-550 m and ca. 1050 m - 1260 m depth, but at all other levels it occurs sporadically. The XRD analyses confirms the very poor presence of illite, similar to what is found in the Icelandic environment.

The hydrothermal mineral assemblages present in the Asal-5, indicate a high temperature geothermal activity. Six hydrothermal alteration zones were established based on the progressive alteration of the rock. These zones are as follows:

1) **Unaltered zone**
2) **Smectite zone:** This zone indicates a temperature range up to 200°C.
3) **Mixed layer clay zone:** This zone is found at a temperature range of about 200-230°C
4) **Chlorite zone:** The zone measures a temperature range of about 230-240°C
5) **Chlorite-epidote zone:** This zone falls in the temperature range of 230-280°C
6) **Chlorite-actinolite zone:** This zone is correlated with a temperatures exceeding 280°C.

A comparison between the temperature profiles indicated by the alteration and the presently measured temperature shows that the geothermal reservoir around Asal-5 has drastically cooled down to 1700 m depth, especially at around 1000 m depth where a difference of about 200°C is observed. Only vague indications are seen of a retrograde alteration (smectite and zeolites).

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Republique de Djibouti

GEOTHERMAL RESOURCE AND THE CENTRE OF CONSUMPTION

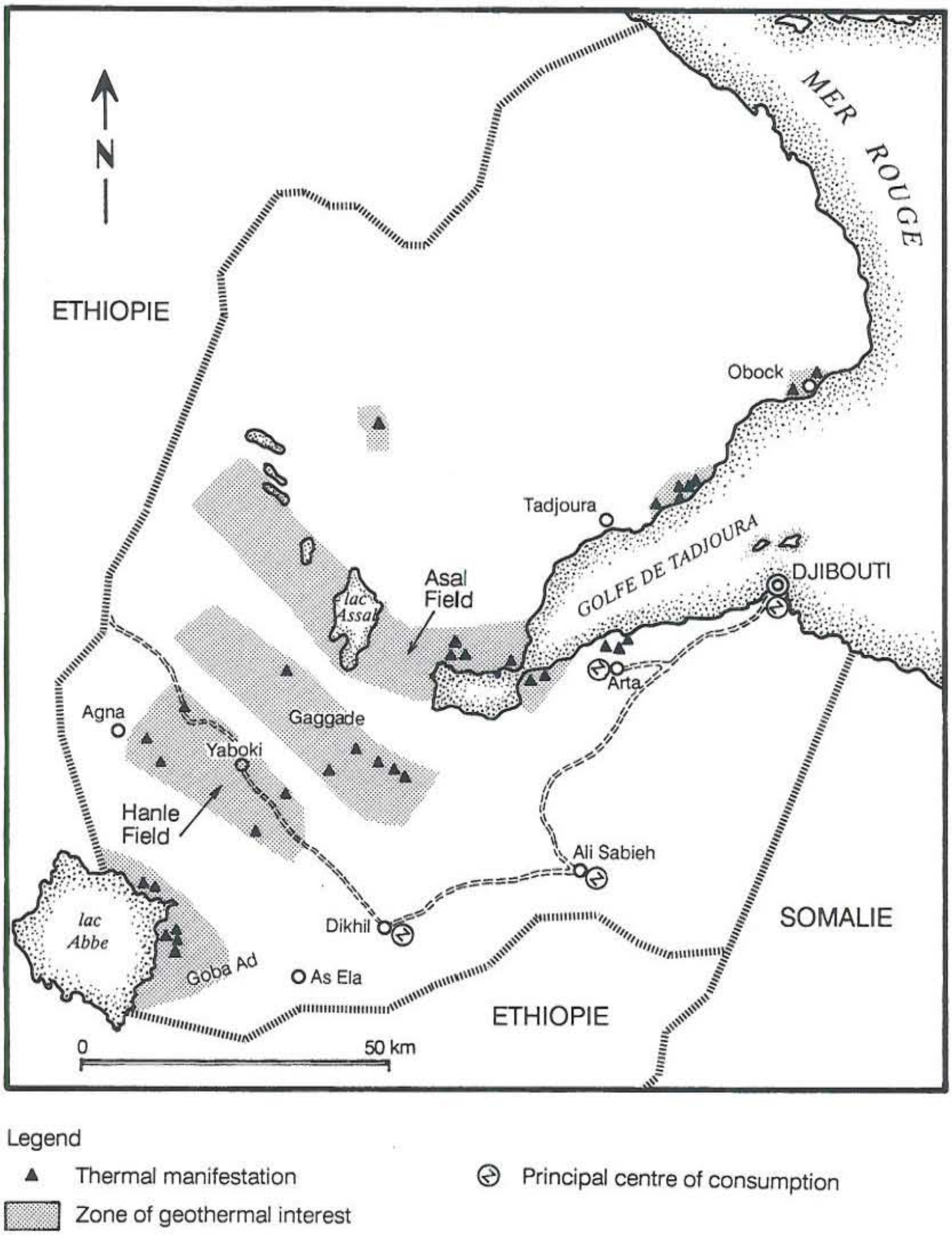

Fig. 1.

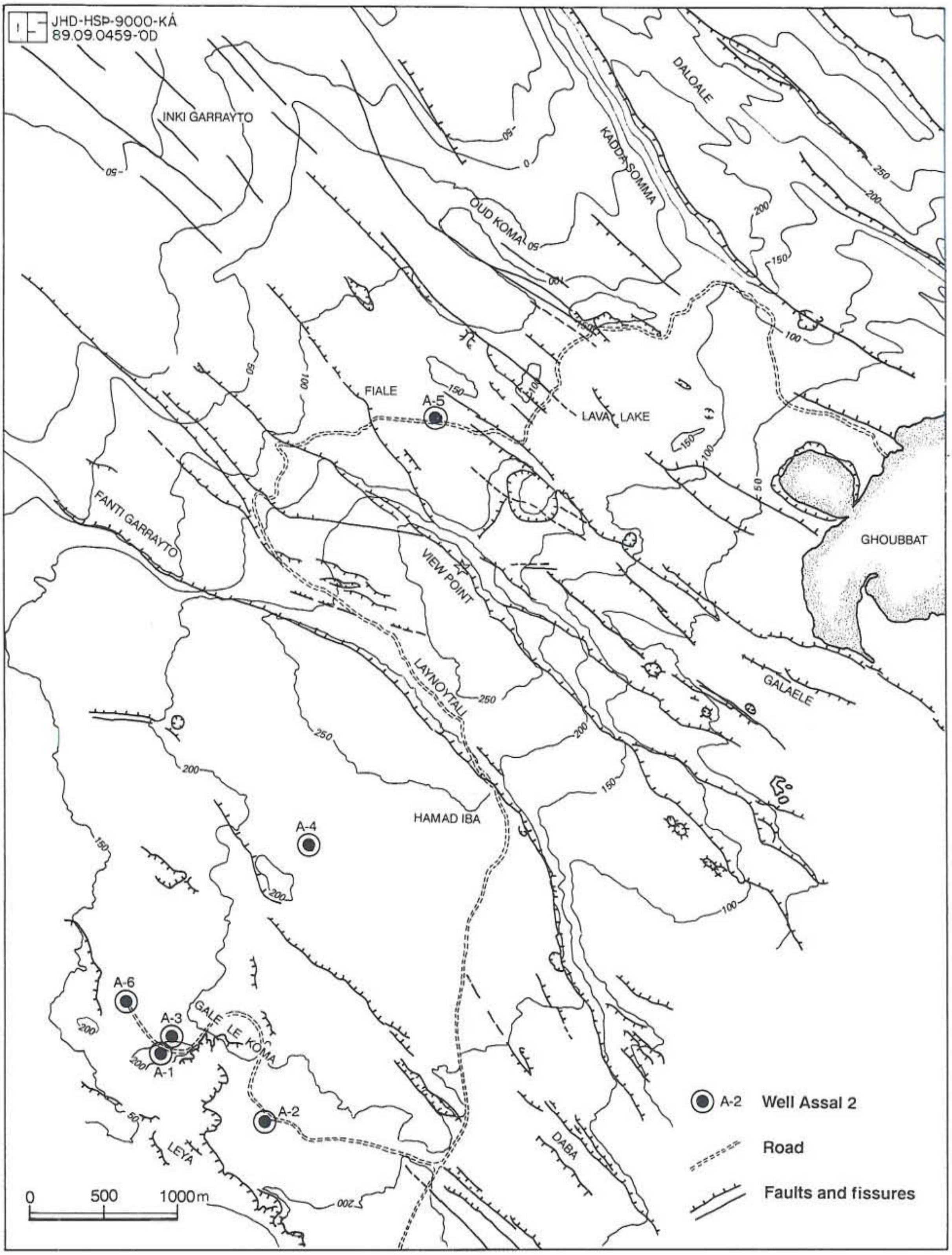

Fig. 2: Location of exploratory wells in Asal geothermal field

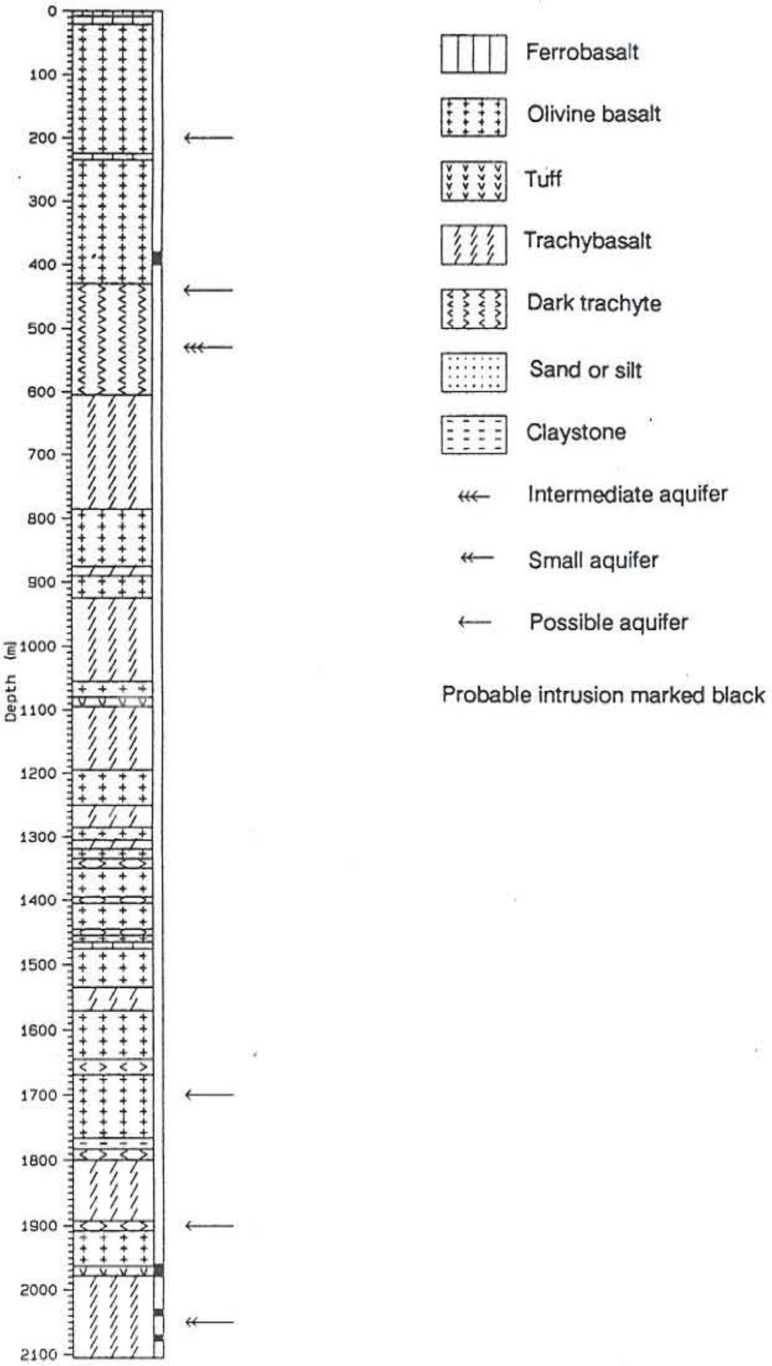

Fig. 3: Lithological log of well Asal-5

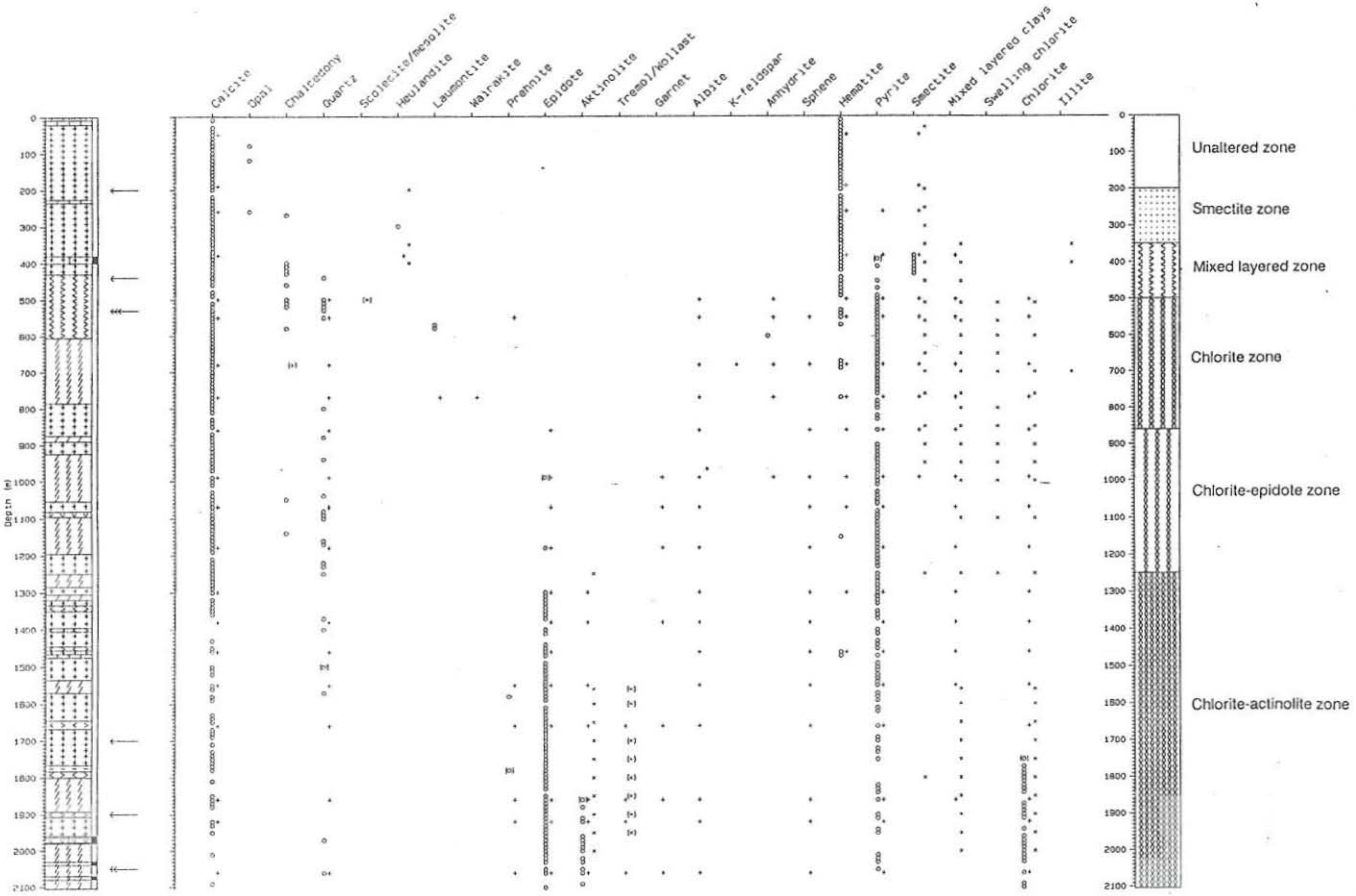

Figure 4. The distribution of alteration minerals and alteration zones of Asal-5.

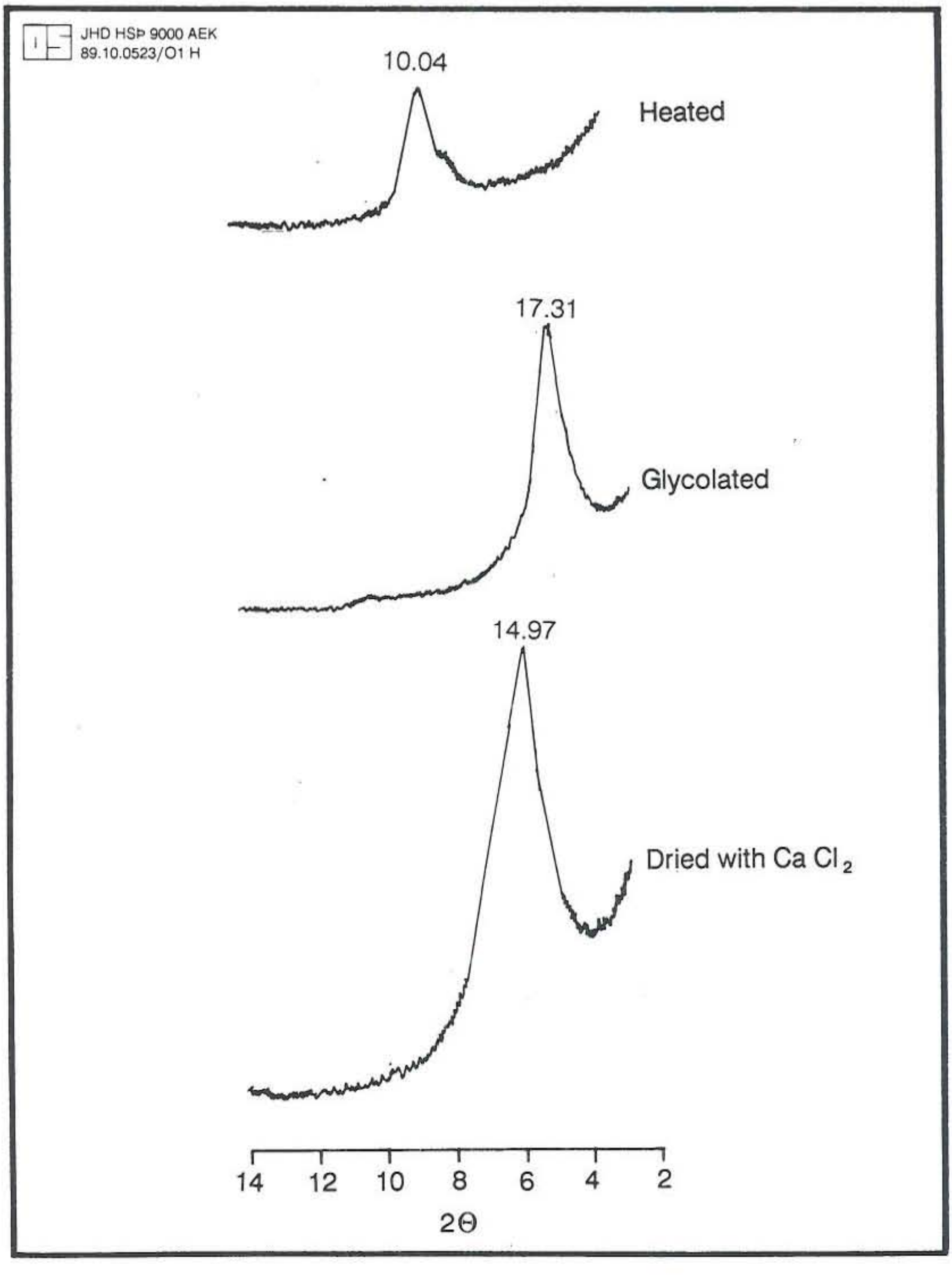

Fig. 5(a): X-ray diffraction pattern of smectite

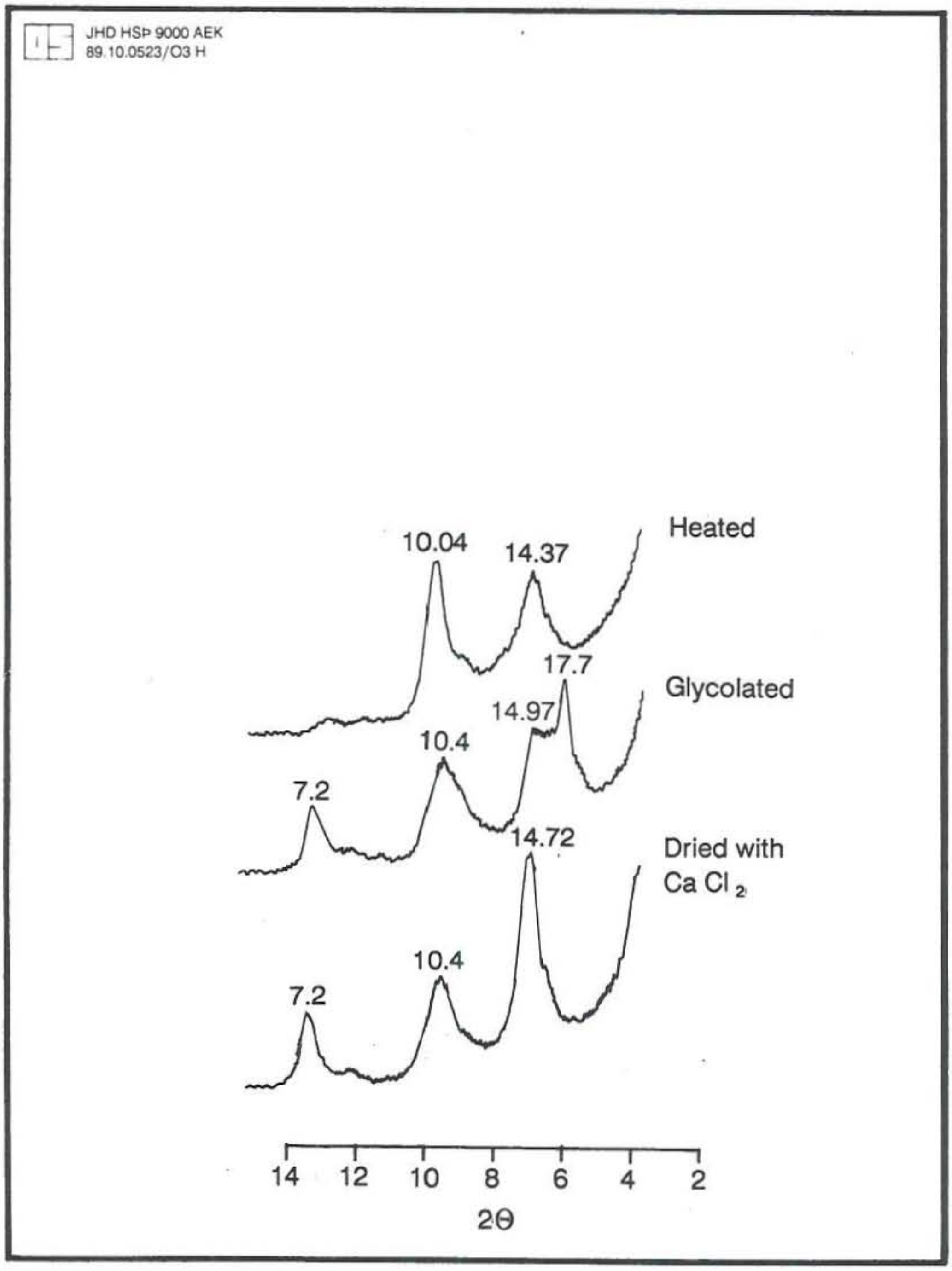

Fig. 5(b): X-ray diffraction pattern of mixed layered clays and illite

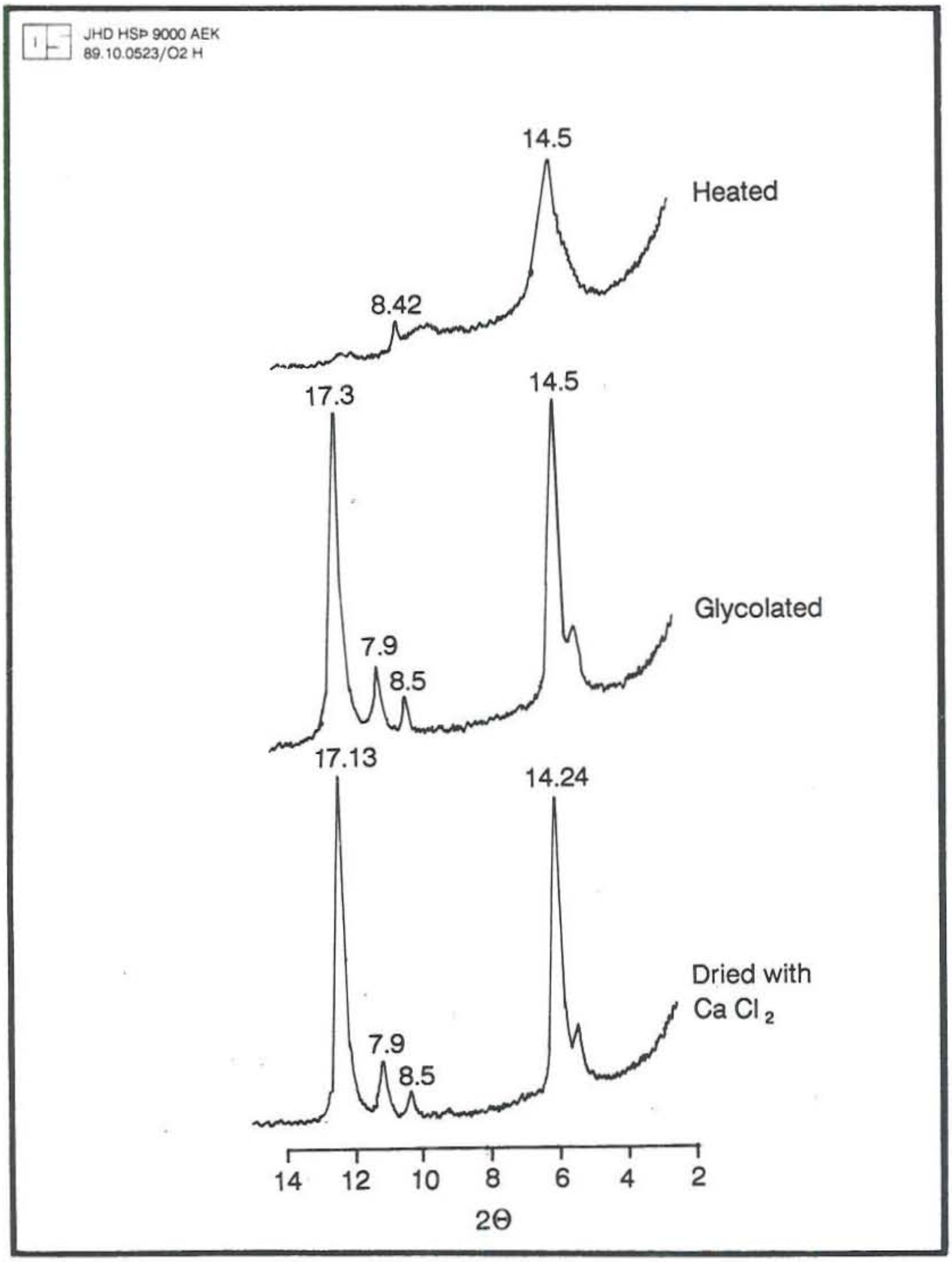

Fig. 5(c): X-ray diffraction pattern of chlorite and actinolite

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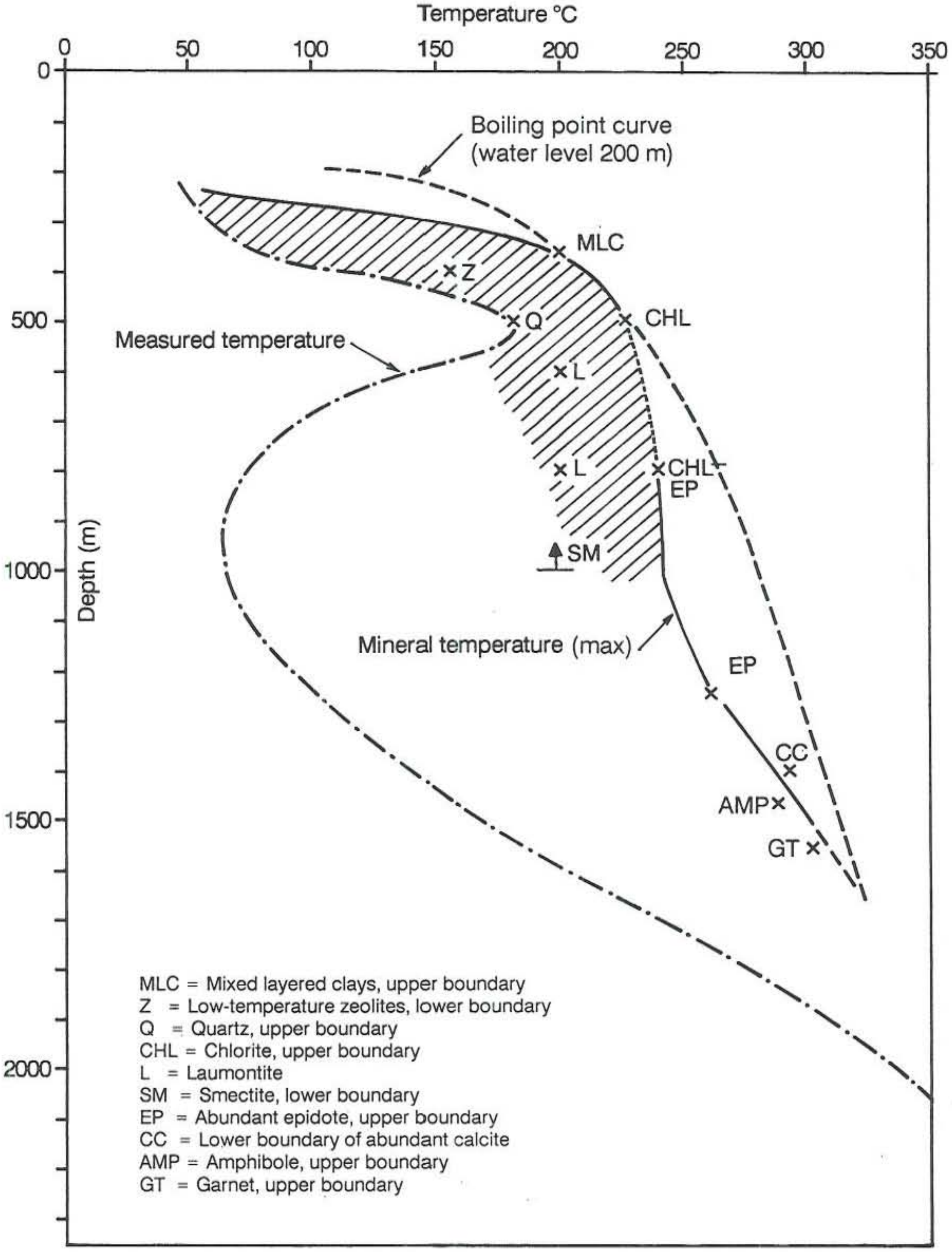

Fig. 6: Measured temperature of the well, mineral temperature and the boiling point curve profiles