The United Nations University

GEOTHERMAL TRAINING PROGRAMME
Orkustofnun, Grensásvegur 9,
IS-108 Reykjavík, Iceland

Reports 1998
Number 4

GEOLOGY AND HYDROTHERMAL ALTERATION IN WELLS TD-5 AND TD-6, TENDAHO GEOTHERMAL FIELD, ETHIOPIA

Zewde Gebregziabher
Geothermal Exploration Project,
Ethiopian Institute of Geological Surveys,
P.O Box 40060, Addis Ababa,
ETHIOPIA

ABSTRACT

Tendaho geothermal field is one of two geothermal prospect areas in Ethiopia which have undergone shallow and deep exploratory drilling. The prospect area is located in the Tendaho graben in the inner part of the Afar depression. This report deals with the borehole geology of shallow wells TD-5 and TD-6. The main purpose of the two wells is to obtain further information on the extent and characteristics of the shallow reservoir and to study the possibility of utilization for electric generation. The formation dissected by the drillholes consists of a sedimentary sequence (fine-medium-grained sandstone, siltstone and clay) interlayered by thin basaltic lavas in the upper part of the wells. The permeability of the system is apparently controlled by the granularity of the sediment and the boundaries of the contact zones as well as the tectonic structures in the area. The hydrothermal mineralogical assemblage consists predominantly of clays, calcite, quartz, stilbite, laumontite, wairakite, prehnite and epidote. Based on the distribution of the alteration minerals, the wells showed zones from low- to high-temperature zeolites and clay minerals concomitant with the increase of temperature down to the bottom of the wells. These appear in most cases to be in equilibrium between the measured temperature and alteration.

1. INTRODUCTION

1.1 Scope of study

This study is the result of a six months fellowship awarded to the author by the United Nations University (UNU) Geothermal Training Programme with the agreement of the Ethiopian Institute of Geological Surveys to specialize in the field of borehole geology in geothermal exploration and development.

The training programme started with six weeks of introductory lectures on various aspects of geothermal exploration and utilization. Field excursions were taken to the main high- and low-temperature geothermal fields and the main power stations in Iceland. After that the author got specialized theoretical and practical training both on a drill site and in the laboratory. The last phase of the programme was a research project which is dealt with in this report. It is the author´s belief that this training has been valuable and has helped to improve his career skills and will enhance future activity. The report was submitted to the UNU as a partial fulfilment of the training programme. It mainly describes the results obtained from analysis of drill cuttings and core samples from the Tendaho geothermal field wells, TD-5 and TD-6 in Ethiopia. The samples were examined using a binocular microscope, XRD analysis and a petrographic microscope in order to evaluate rock types and the history of hydrothermal alteration. More than150 handpicked samples of secondary minerals (selected under binocular microscope) were determined by routine XRD analysis. In addition, 35 pairs of samples were prepared and run on the XRD for clay mineral analysis for both wells.

1.2 General information

Geothermal exploration in Ethiopia dates back to 1969. The country´s high-enthalpy geothermal energy is mainly concentrated in the main Ethiopian Rift and the Afar Rift (Figure 1), which is a Tertiary-Quaternary tectonic system and a part of the great East African Rift. The Rift System extends from the Ethiopian - Kenya border to the Red Sea extending for over 1000 km within Ethiopia, in a north to northeasterly direction. It covers an area of 150,000 km^2 (Figure 1). In the last decades, geothermal exploration activities for electric power development on reconnaissance stages and detailed integrated geological, geochemical and geophysical surveys have been conducted in selected prospect areas. These studies have led to the development of the Aluto-Langano geothermal field and a pilot plant with capacity of about 7 MWe, and drilling of six geothermal exploratory wells in the Tendaho geothermal field.

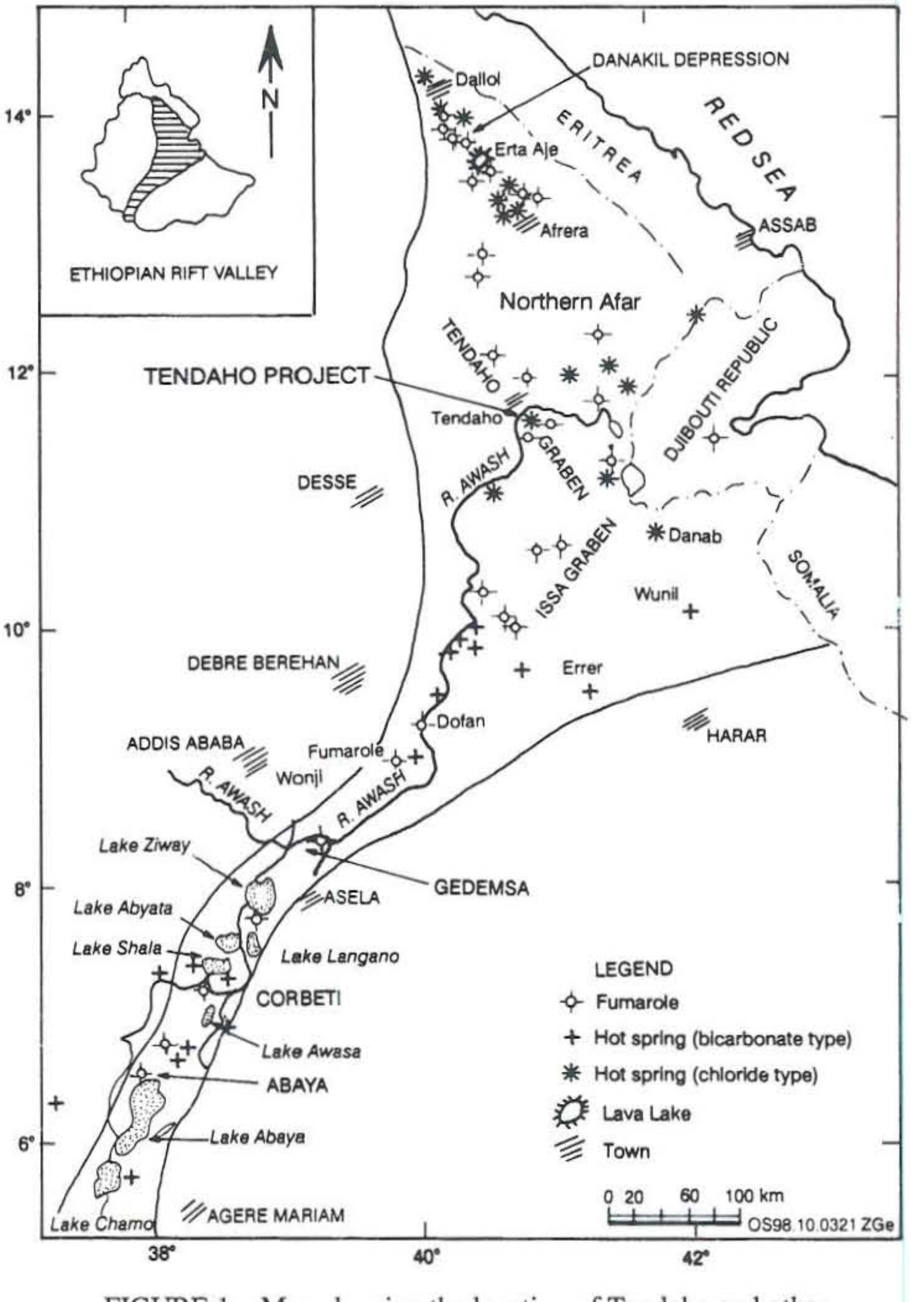

FIGURE 1: Map showing the location of Tendaho and other geothermal areas in the Ethiopian Rift Valley

Tendaho geothermal field is thus one of two geothermal prospects areas in the country exposed for intensive geothermal exploration activities which have undergone a deep geothermal exploratory drilling. The field is located in the northeastern part of the country, in the central Afar Rift depression. It is a part of an active NW-SE trending rift basin, filled with lacustrine deposits and post-stratoid basalt flows (Figure 2).

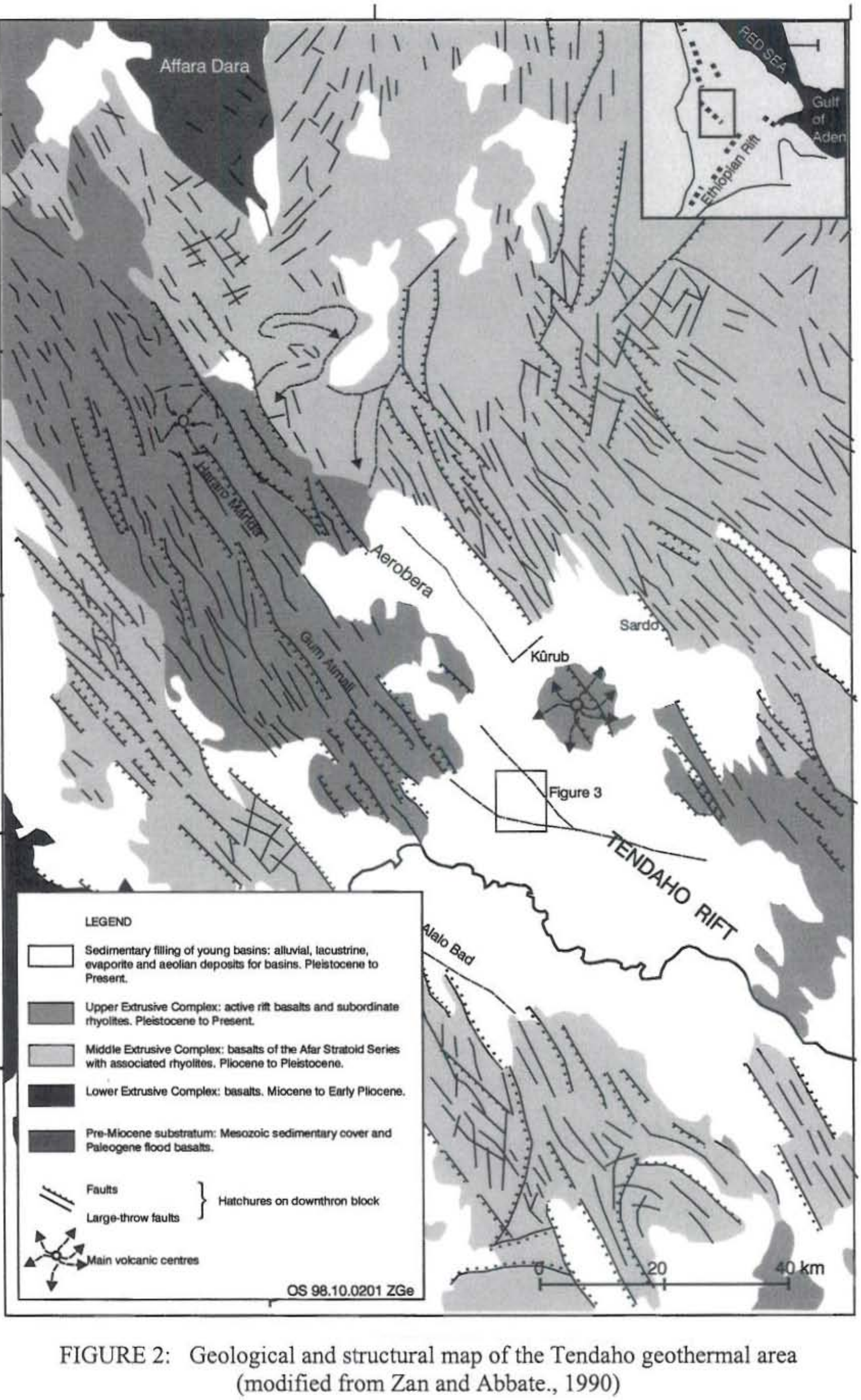

FIGURE 2: Geological and structural map of the Tendaho geothermal area (modified from Zan and Abbate., 1990)

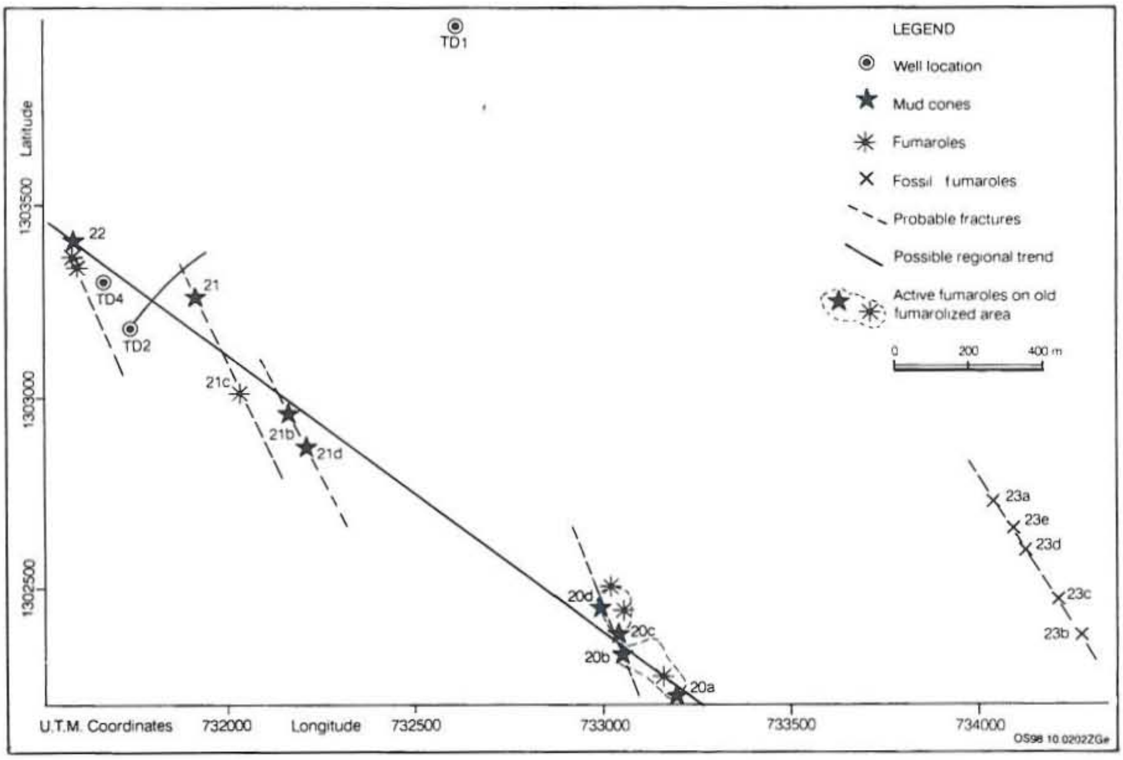

FIGURE 3: Locations of the first wells and geothermal manifestations in Tendaho

The first phase of exploration drilling in Tendaho commenced in October 1993 with the technical cooperation agreement between the Ethiopian and Italian governments. This agreement resulted in the accomplishment of three deep exploratory wells (maximum depth 2000 m), and one shallow exploratory well (466 m). These wells proved the existence of a shallow reservoir (TD-4, 466 m), and a promising deep reservoir through the productivity of a deep well TD-2 (Figure 3). This is further indicated by the existence of a large resistivity anomaly, which is isolated from the shallower reservoir (Aquater, 1996).

The proven productivity of the shallow well TD-4 (466 m) induced a second phase of drilling financed by the government of Ethiopia. Two shallow wells were planned in order to obtain further information on the extent and characteristics of the shallow reservoir, as well as to study the possibility of utilization for electric generation for the surrounding areas. The second drilling phase of two shallow wells commenced in December 1997 and was completed in February 1998.

2. GEOLOGY

2.1 Geological background

Tendaho geothermal field is located in the Tendaho graben in the inner part of the Afar depression. The Tendaho graben is considered to be a part of an active structure where 3 rift zones (Ethiopian Rift, Red Sea Rift and Gulf of Aden) converge to attenuate the crust in the Afar depression.

Rifting in Afar began during lower Miocene on a continental arch where important basaltic activity was probably in progress. The beginning of the rift formation was accompanied by a change in the magmatic product from transitional basalt, peralkaline granites and rhyolites to a more alkali and undersaturated composition (Aquater, 1979). The age of these is in the range of 25-15 million years.

The second stage is characterized by the deposition of a large volume of acid volcanics with subordinate basaltic and intermediate lavas (Mabla rhyolites) dated between 15.3 and 3.3 m.y. The third stage consists of the emplacement of the prevalently basaltic Dalha series from 8.0 to 4.9 million years (Aquater 1979). Since approximately 4 million years ago, the inner part of the depression became affected by tensional tectonics, with intense volcanic activity, mostly fissure type Afar stratoid series.

The Afar depression is believed to have reached its present geological setting during the Pleistocene period, with the determination of axial ridges. Intense tensional tectonics affect the entire depression, thus, forming a complex mosaic of horsts and grabens which are still active and contain localized sedimentary basins. From west to east the these are the Tendaho graben, the Dobi graben, the Gaggade graben and the Asal graben.

2.2 Surface geology of the Tendaho geothermal field

The Tendaho graben consists of a NW-SE elongated broad plain of about 4000 km^2, and is located in the lower part of the Awash Basin (Figure 2). The basin is filled by alluvial and lacustrine deposits. According to various researchers who have surveyed the area, the volcanic and sedimentary units of the Tendaho graben are the products from the upper Pliocene to present time. The oldest products in this area are the lava pile outcroppings on the graben edges, whereas the most recent activity, both linear and central, are concentrated within the graben.

The edges of the Tendaho graben are composed of volcanic products related to the Afar stratoid series. The Afar stratoid series is predominantly a basaltic formation extruded through fissures with a dominant NW- SE direction. The thickness of the sequence reaches up to 1200 m in the southeastern part of the graben. Thin lacustrine intercalations, probably of Pleistocenic age, were observed only on the southeastern edge of the Magenti Ale plateau. The series is affected by numerous tension tectonics (faults and fractures).

Several acidic eruptive centres are also interbedded in the upper part of the Afar Stratoid series. These centres are the Fini on the eastern border of the graben and near Serdo and Asgura on the western side of the graben, 6 km from Tendaho (Aquater, 1979). The upper extrusive complex is less than 1 Ma and with a sequence of basalt flows of fissure associated rhyolitic volcanoes, such as active Kurub (5 km from the well site) with youngest products aged 4,000-10,000 years, and Dama Ale with deposits aged 2,500 years (Abbate et al., 1995).

The oldest sediments of the area are found along the southern wall of Magnti´Ale in the marginal inlet of Erole. They consist of silts, clay and marls of Plio-Pleistocenic age (Gasse, 1975). After the Pleistocene time lakes dried up between 17,000 and 12,000 years ago and eolian sands and lava flows covered large areas of the Tendaho graben. Following the dry period, new lacustrine transgressions occurred during Holocene, alternating with regressions (Gasses, 1977). The lacustrine sediments lying on the bottom of the Tendaho graben were covered by silts and sands carried by wind or by wadis during their flood periods. Fluvio-lacustrine and continental intercalations are probably located inside the recent lava formations. The graben sedimentary formation (sedimentation) can reach several hundred metres above the top of the stratiod series and these are not interrupted by lavas flows.

Hydrothermal manifestations occur in various parts of the Tendaho rift, mainly steaming grounds in the northern part of the field (Aerobera), hot springs at Allalobeda, and mud pots and fumaroles around the drill sites and cotton plantation (Figures 2 and 3).

2.3 Analytical techniques

Cuttings and core samples recovered during the drilling of wells TD-5 and TD-6 were used to establish stratigraphic sections and to study the distribution of secondary minerals in the wells. The following are the main techniques used during the study.

Binocular microscope: Cutting samples were analysed by binocular microscope at 5 m intervals during drilling. This method assisted in determining the formation boundaries and the permeability, the fractures and secondary minerals. During the present study, selected cuttings were studied with this technique in great detail, and samples were selected for XRD and thin-section analysis.

Petrographic microscope: A total of 25 cutting samples were selected for petrographic analysis to study rock types and alteration mineralogy. Five additional thin-sections were made from the core samples.

X-ray diffractometer: The XRD was found very useful for studying the alteration minerals. In some instances, there was difficulty in differentiating between primary and secondary minerals. Samples were analysed for clay by XRD where the samples were run untreated, glycol-saturated and then heated to 550°C (see Appendix 1).

2.4 Borehole geology

During drilling, sampling of cuttings was taken at five metre intervals whenever possible. Two core samples were recovered in TD-5 at a depth of 301-310 m and 488-497 m. One core sample at a depth of 251-260 m was taken in well TD-6. The temperature of the fluid (in and out) was recorded at the same time as cutting samples were taken. Moreover, circulation losses were regularly measured during drilling.

Bentonite was used as the drilling fluid down to 220 m depth in well TD-5. The rest of the well was drilled down to 516 m using the brine of TD-4. TD-5 is at an elevation of 366 m a.s.l. having coordinates E731670.42 and N1302918.8 and drilled to a depth of 516 m. The well design includes casing of 20" to 47 m, 13 3/8" to 137 m, 9 5/8" to 220 m, and 7" liner was placed down to 508 m.

For TD-6, bentonite was used as the drilling fluid down to 217 m depth; the rest of the well down to 504 m was drilled using the brine of TD-4. TD-6 is at an elevation of 366 m a.s.l. having coordinates E731558.01 and 1302980.05 and its total drilled depth is 504 m. The well design includes casing of 20" down to 40 m, 13 3/8" to 126 m, 9 5/8" to 217 m, and 7" liner was placed down to 504 m.

2.4.1 Borehole geology of TD-5

Lithology established for TD-5, based on cutting analysis, is shown in Figure 4. Lithological descriptions are as follows:

Depth(m)	Lithological descriptions
0-15 m	Light brown fine- to medium-grained sand and silty clay (loose sediment).
15-30 m	Fine- to medium-grained sandstone. Calcite is found as a cementing material along with minor iron oxides and clay minerals.
30-35 m	Grey siltstone cemented by carbonate.
35-65 m	Fine- to medium-grained grey sandstone cemented by carbonate. Calcite and zeolites are found in cavities and veins.

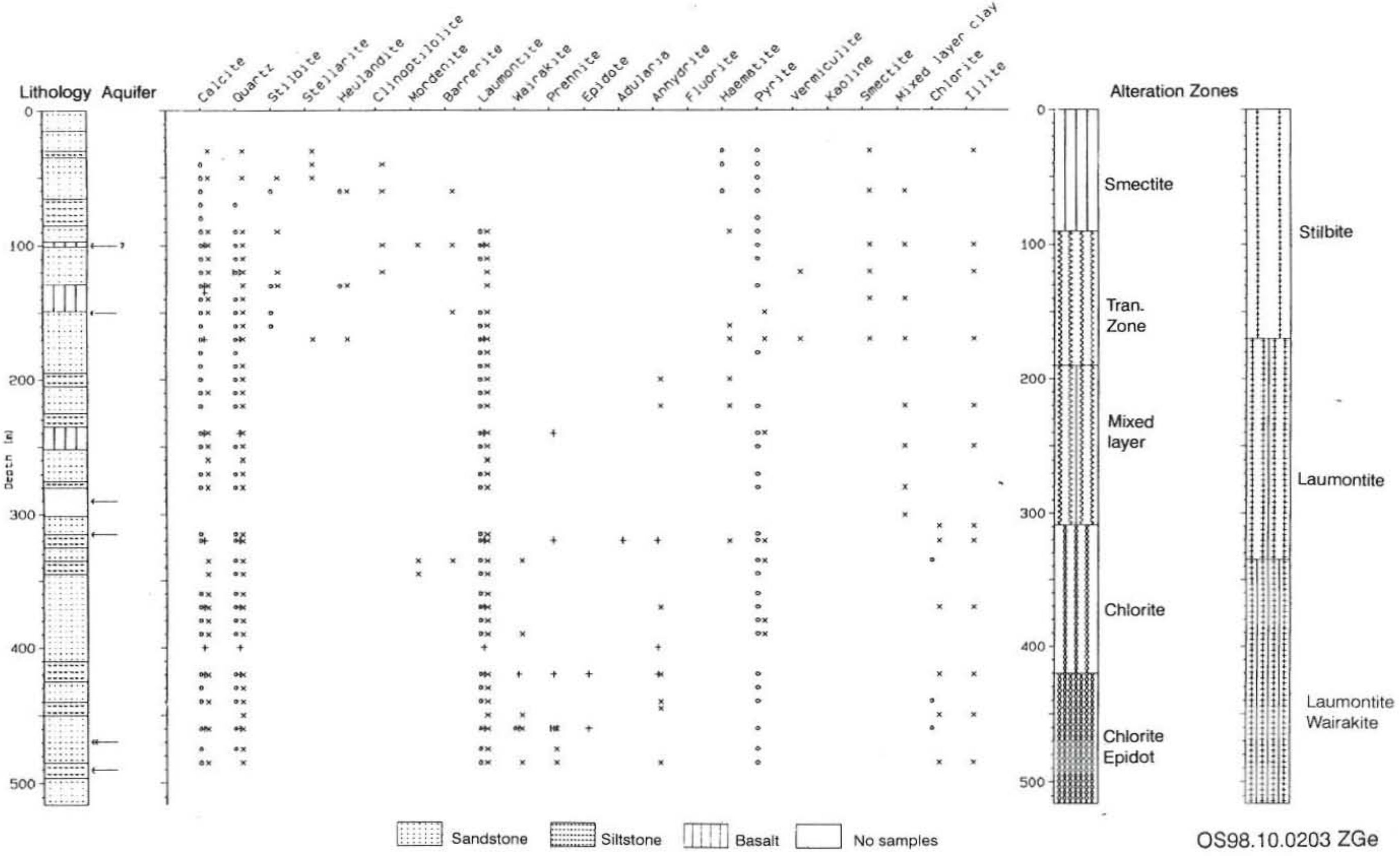

FIGURE 4: Lithology, distribution of alteration minerals and alteration zone in well TD-5
(x = XRD analyses, o = binocular and + = petrographic analyses)

65-85 m	Grey siltstone cemented by carbonate.
85-97 m	Fine- to medium-grained grey sandstone cemented by carbonate, also containing some silica deposition and zeolites.
97-101 m	Dark micro-porphyritic basalt with unaltered phenocrysts of plagioclase and clinopyroxene. It contains some unaltered olivine and glass groundmass. It has a few vesicles which have not been filled by secondary minerals. Microfractures are visible under petrographic microscope partially filled by clay and calcite.
101-129 m	Fine- to medium-grained brown sandstone cemented by carbonate. Low-medium intensity alteration with the presence of pyrite and minor zeolites.
129-149 m	Dark sub-ophitic/intergranular basalt, with unaltered phenocrysts of plagioclase and clinopyroxene. Olivine and the ground mass are completely altered to clay. Vesicles and minor fractures are partially filled with clay.
149-195 m	Fine-to medium-grained brown sandstone cemented by carbonate. Under petrographic microscope plagioclase is slightly altered to clay. Calcite and zeolites cement the sediment grains.
195-205 m	Brown siltstone with minor zeolites and calcite.
205-225 m	Fine- to medium-grained sandstone cemented by carbonate.
225-235 m	Brown siltstone cemented by carbonate.
237-245 m	Brown fine- to medium-grained sandstone. In thin-sections hydrothermal quartz occurs as the interstitial filling of the sedimentary grains. Zeolites occur as cavity fillings and, to a certain extent, replace the sedimentary grains.
245-252 m	Dark grey aphanatic basalt with calcite deposition in fractures.
252-280 m	Brownish siltstone with intercalation of light brown silty clay.
280-301 m	No sample was recovered, a partial loss of circulation.
301-309 m	Fine- to medium-grained greenish grey sandstone cemented by carbonate. Secondary minerals present are laumontite, calcite and minor quartz.
309-320 m	Greenish grey siltstone with veins filled by laumontite and calcite.
320-335 m	Fine- to medium-grained greenish grey sandstone. Groundmass and glass are altered to clay. Pores and veins are almost filled with secondary minerals.
335-345 m	Greenish grey siltstone cemented by carbonate.
345-410 m	Fine- to medium-grained greenish grey sandstone. In thin-section cavities and interstitial voids are filled by secondary minerals. Zeolites are replaced by quartz and calcite. Veins are filled by anhydrite calcite and zeolites.
410-420 m	Greenish grey siltstone.
420-440 m	Fine- to medium-grained greenish grey sandstone with cavities partially filled by calcite, clays and zeolites.
440-450 m	Greenish grey siltstone.
450-485 m	Fine- to medium-grained greenish grey sandstone with cavities and veins mainly filled by calcite, zeolites, quartz, wairakite and anhydrite.
485-496 m	Greenish grey sandstone.
496-516 m	Fine- to medium-grained greenish grey sandstone.

2.4.2 Borehole geology of TD-6

Lithology established for TD-6, based on cutting analyses, is shown in Figure 5. Lithological descriptions are as follows:

Depth(m)	Lithological descriptions
0-15 m	Light brown unconsolidated fine- to medium-grained sand and silty clay.
15-25 m	Fine- to medium-grained grey sandstone. Poorly cemented by carbonates and zeolites.

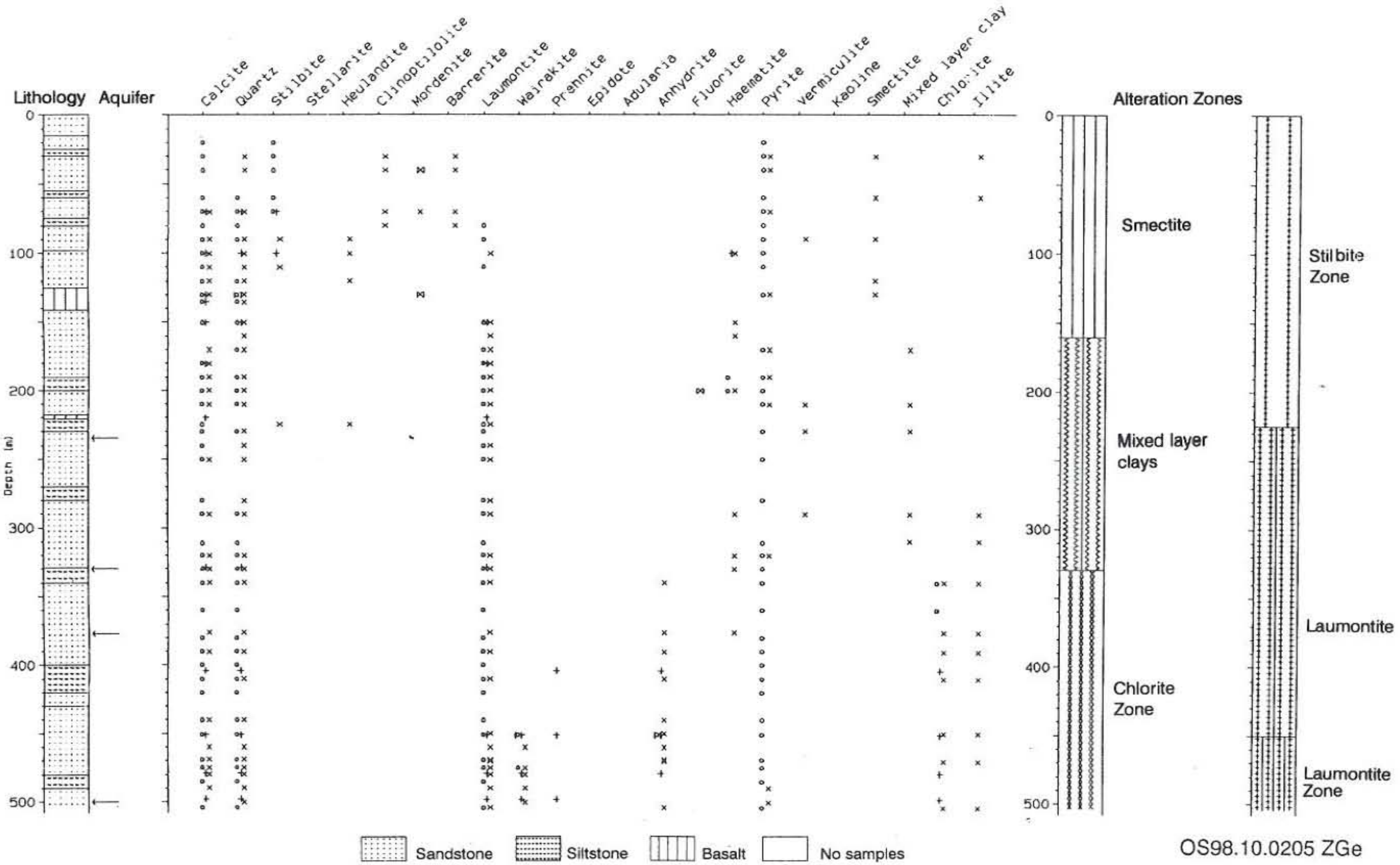

FIGURE 5: Lithology, distribution of alteration minerals and alteration zone in well TD-6 (x = XRD analyses, o = binocular and + = petrographic analyses)

25-30 m	Grey siltstone cemented by carbonate with minor zeolites.
30-55 m	Fine- to medium-grained grey sandstone cemented by carbonate.
55-60 m	Grey coloured siltstone cemented by carbonate.
60-75 m	Fine- to medium-grained grey sandstone cemented by calcite. In thin-section the glass part is altered into clay, plagioclase is not altered, cavities and fractures are partially filled by calcite and zeolites.
75-80 m	Grey coloured siltstone.
80-98 m	Fine- to medium-grained grey sandstone cemented by carbonate.
98-125 m	Fine- to medium-grained brown sandstone cemented by carbonate. Cavities and veins are partially filled by calcite and zeolites.
125-141 m	Dark grey subophitic basalt. Phenocrysts of plagioclase (labradorite) remain unaltered while clinopyroxene shows some alteration. Olivine and glass in the groundmass are altered. Vesicles and factures are also partially filled by calcite and clay minerals.
141-190 m	Brownish fine- to medium-grained sandstone cemented by carbonate. Cavities and veins partially filled by zeolites, calcite and clay.
190-200 m	Brownish siltstone cemented by carbonate.
200-218 m	Fine- to medium-grained brown sandstone containing calcite and zeolites.
218-221 m	Dark grey subophitic basalt. Labradorite plagioclase shows minor alteration with cracks filled by clays. Clinopyroxene and olivines are highly altered even though an indication of the presence of both minerals is still preserved.
221-230 m	Brown siltstone cemented by carbonate.
230-270 m	Fine- to medium-grained brown sandstone cemented by carbonate. Main secondary minerals present are calcite, zeolites and clay.
270-280 m	Brown siltstone cemented by carbonate.
280-329 m	Fine- to medium-grained brown sandstone cemented by carbonate. Major alteration minerals present are calcite, quartz and zeolites.
329–340 m	Greenish grey siltstone cemented by carbonate. Secondary minerals present are calcite quartz and laumontite.
340-400 m	Fine- to medium-grained greenish grey sandstone. Calcite and zeolites fill cavities and interstitial grains of the sediment as well as substituting the grains of the sediment.
400-415 m	Greenish grey siltstone.
415-480 m	Fine- to medium-grained greenish grey sandstone. Open spaces and veins are filled by calcite, laumontite, quartz and wairakite. Other secondary minerals present are prehnite, chlorite and anhydrite. Replacement of laumontite by quartz and wairakite is observed in thin-sections.
480-490 m	Greenish grey siltstone cemented by carbonate.
490-504 m	Fine- to medium-grained greenish grey sandstone. Has the same character as the sediment of 415-480 m.

3. HYDROTHERMAL ALTERATION

The formation of secondary minerals in geothermal system is controlled by chemical/physical conditions in the system. For instance the presence, abundance and stability of hydrothermal alteration minerals mainly depend on temperature, pressure, lithology, permeability and the fluid composition in the system. By studying hydrothermal minerals, estimates of subsurface temperature and permeability and some comments on any temporal changes can be deduced (Browne, 1984).

In the Tendaho geothermal field the occurrence of hydrothermal alteration minerals in the shallow reservoir ranges from low-temperature zeolites and clay, to high-temperature minerals like prehnite, epidote and wairakite in the deeper part of the wells.

3.1 Rock alteration

Hydrothermal alteration often produces changes in the properties of rocks by altering their density, porosity, permeability, magnetic strength and resistivity. This includes replacement, leaching deposition and causes chemical changes in the rock. Types of fluid and the duration as well as the type of rock play an important role in rock alteration (Browne, 1984).

The lithology of wells TD-5 and TD-6 consists mainly of sedimentary units with minor interlayering basaltic layers in the upper part of the wells. The primary mineral composition of sedimentary rocks includes clay, glass, quartz, calcite, pyroxene and plagioclase. The basaltic rock is composed of glass, (ground mass) olivine, plagioclase, pyroxene and iron oxide. Alteration mineral assemblage and their formation in both wells are very similar; except for the first appearance of high temperature, indicative minerals are located at different depths towards the bottom of the well.

Generally, the sediment contains quartz as a constituent of the primary mineral composition of the grains, and calcite during the process of sedimentation. Thus, the sediment contains both quartz and calcite, which are also products of hydrothermal alteration. The groundmass in the sediment has undergone alteration to clay minerals, calcite and zeolites and the clay in the lower part is completely chloritized. In the lower level zeolites are partly replaced by quartz and wairakite. Olivine is altered to clay and in some cases replaced by calcite. In the basaltic unit, which is mostly fresh, the glass is altered to clay, and olivine is also altered to serpentine and iddingssite. The plagioclase and the pyroxene remain relatively unaltered, showing only clay alteration along microfractures. The pyroxene which is present in the sediment is kept intact to a certain extent when we consider the alteration of the sedimentary grains. Some of the grains of the sediments are altered and replaced by secondary minerals keeping the former shape of the grains. This is most clearly seen when it is altered by zeolites. Opaque minerals like haematite and ilmenite in the sediments may, in some cases, be altered to pyrite in the wells.

3.2 Distribution of alteration minerals in TD-5

Types and distribution of hydrothermal minerals along with the stratigraphy of TD-5 are shown in Figure 4. They are identified with the help of XRD (Brindley and Brown, 1980), binocular and thin-section studies. The secondary minerals are: calcite, quartz, stilbite, stellarite, heulandite, clinoptilolite, mordenite, barrerite, laumontite, wairakite, prehnite, epidote, adularia, anhydrite, gypsum, iron oxide, pyrite, fluorite, vermiculite, kaoline, smectite, mixed layered smectite/chlorite, illite and chlorite. The occurrence and distribution of individual minerals is discussed below.

Calcite: Calcite is one of the most common alteration minerals in TD-5. Calcite occurs in the upper level as a cementing material of the sediment which is probably the product of lake sedimentation deposition process, and as fillings and micro fractures, which is a product of the hydrothermal process. In the lower part of the well it occurs as interstitial cavity filling as well as filling micro-fractures in the association of zeolite, quartz and in some cases with wairakite.

Quartz: Quartz is widely distributed in the well. The presence of hydrothermal quartz which is not the original constituent of the rock can only be recognized by thin-section studies. Quartz occurs embedding the grains and replacing or filling micro fractures of the rock. It occurs with calcite and zeolites and is associated with wairakite. In some of the thin-sections quartz appears to replace zeolites.

Zeolites: Zeolites are principally aluminosilicates with a three-dimensional framework structure composed of AlO_4 and SiO_4 tetrahedra linked to each other by sharing all of the oxygens to form interconnected cages and channels that contain mobile water molecules and alkali and/or alkaline earth cations (Tschernich, 1992). The zeolites show a transition of low-temperature zeolites in the upper part of the wells to high temperature zeolites near the bottom of the wells. In the sedimentary formation of this well, the glass and groundmass may be substituted by zeolites, and, in some cases, the zeolites are pseudomorphing the sedimentary grains. Individual zeolites were identified by binocular, petrographic and XRD analysis. The characteristic peaks for some zeolites in cuttings at 90 and 475 m depth in TD-5 well are shown in Figure 6.

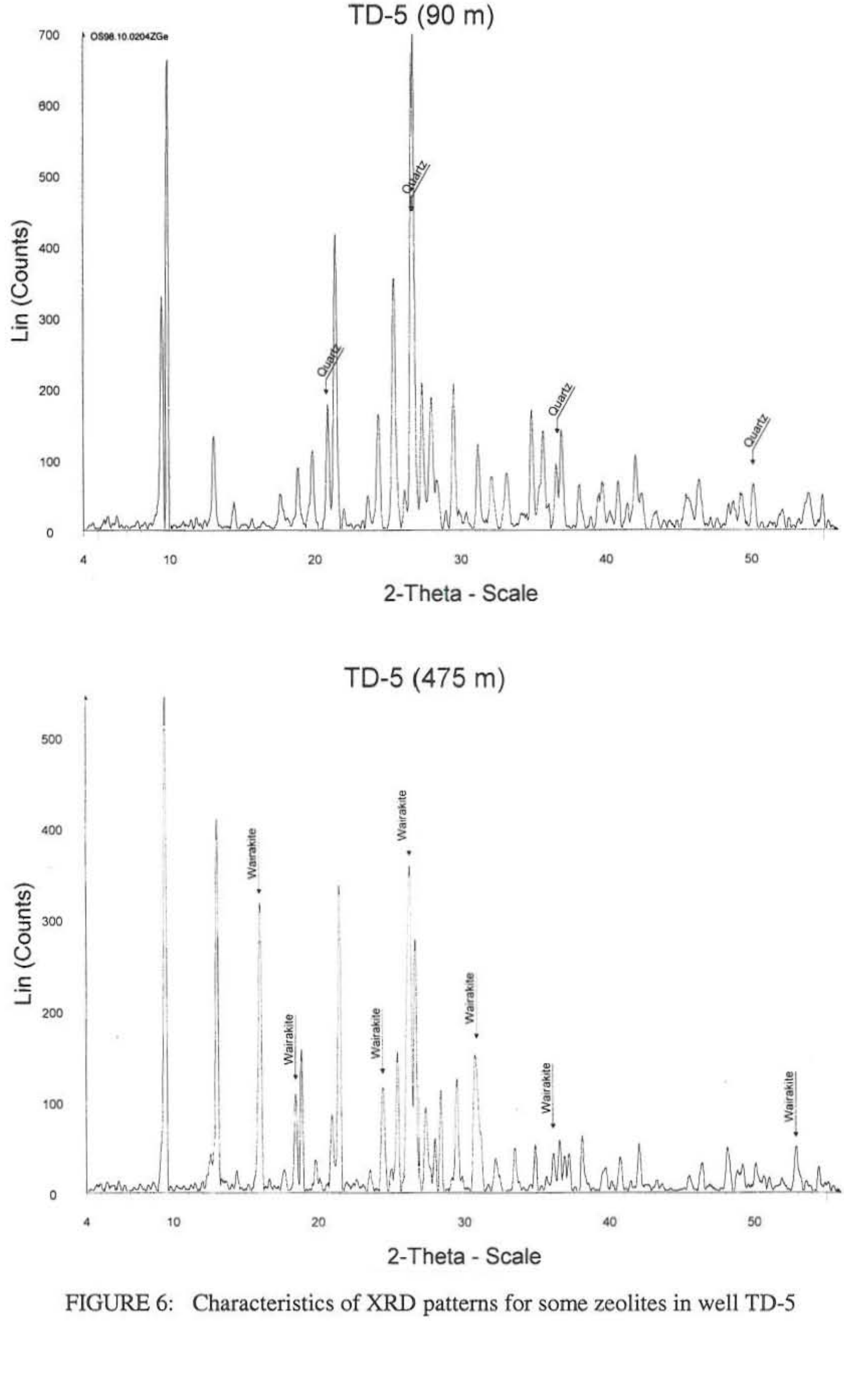

FIGURE 6: Characteristics of XRD patterns for some zeolites in well TD-5

Heulandite. This low-temperature zeolite occurs in the drill cuttings from 60 to 170 m. In XRD it has major peak values of 8.96 and 2. 97 Å.

Clinoptilolite is a silica rich variety of heulandite (Tschernich, 1992) and occurs in the drill cuttings at 30-110 m. In XRD it shows peak values of 8.94, 3.95 and 2.97Å.

Stilbite is abundant in the well at 30-160 m . It has major XRD peaks of 9.14 and 4.16 Å. This includes barrerite and stellerite, varieties of stilbite occurring in the upper level as seen in Figure 4. Barrerite is a Na-rich variety and stellerrite is a Ca-rich varities of stilbite (Tschernich, 1992).

Laumontite. Its presence is identified both on XRD and in thin-sections. It is one of the common zeolites observed at 90 m depth and continues to the bottom of the well. On XRD it shows peak values of 9.48, 4.16 and 3.51 Å.

Mordenite is the most silica rich zeolite type found (Tschernich, 1992). It was analysed by XRD at 100 m depth.

Wairakite. The first appearance of wairakite in the well is at the depth of 335 m, and it occurs to the bottom. It is seen as vein filling associated with laumontite, quartz and calcite. It also occurs in the groundmass of the sediment. Wairakite is evident in some of the thin-sections, replacing the zeolites. On XRD it shows typical peaks of 3.38 and 5.56 Å.

Prehnite: Prehnite is one of the high-temperature alteration minerals and occurs in well TD-5 at a depth of 240 m in minor amount but becomes common towards the bottom. Some show in thin-sections, a bow-tie structure or sheaf-like structures filling the cavities or altering the ground mass of the rock. As the cuttings are very fine, it was difficult to recognise and separate samples for XRD analysis. It was, however, successfully analysed by XRD at 460 m depth. Its relationship with other alteration minerals could not be established from petrographic analysis.

Epidote which is one of the high- temperature index minerals in a geothermal systems, was identified in thin-sections at 420 and 460 m depth. It occurs as very small pale yellowish crystals, with high relief and pleochroism.

Adularia's presence was identified in a thin-section at 360 m depth. It was identified by its twinning and diamond-like outline.

Anhydrite which may be an indication of deep geothermal water, was recognized below 200 m down to the bottom of the well in thin-sections and XRD analysis. On XRD it gives main peaks at 3.5 and 2.85 Å. It occurs mostly with calcite or on its own.

Pyrite: Pyrite is one of the common minerals and occurs from the top to the bottom of the well. It occurs in the form of cubic crystals. The abundance of pyrite is more common in the fine-, medium- to coarse-grained sandstone.

Clay minerals: Clay minerals are abundant throughout well TD-5. They are the alteration products of glass, olivine and, to a certain extent, pyroxene and plagioclase in the sediment. The clay minerals are smectite, vermiculite, illite, chlorite/smectite and chlorite (see Appendix 2). The clays in this well showed textures of fine- to coarse- grained character, depending mostly on the type of sediment.

Smectite occurs in the upper part of the well (25-220 m). In XRD it shows reflection peaks of 14-15 Å untreated, which swell upon glycolation up to 17 Å and collapse to 9-10 Å after being heated to 550°C.

Kaoline occurs in trace amounts in the upper part of the well. It shows a characteristic peak around 7-7.3Å, which collapses upon heating to 550°C.

Mixed-layer clays: In TD–5 mixed layer clays include chlorite/smectite and chlorite/illite, the former being more common. They occur in the well at 100-309 m. They are distinct at 14-15 Å and 28-30 Å, which may expand to higher values upon glycol saturation and collapse upon heating to 550°C.

Illite occurs in the upper part of the well in trace amounts and increases down to the bottom of the well. It occurs along with the mixed-layer clays and chlorite. Illite clays shows a distinct characteristic peak around 10 Å. The peaks do not show much change upon glycol saturation or heating.

Chlorite is distinguished by conspicuous peaks at 14-14.7 Å in the untreated, glycolated and oven-heated samples. In the petrographic study it is identified by its green colour and very weak pleochroism. It occurs from 309 m down to the bottom of the well. It gives the sediment a light greenish colour when it is abundant.

3.3 Distribution of alteration minerals in TD-6

Figure 5 shows the summarized lithology, distribution of alteration minerals and zones of well TD-6. They are identified by the help of XRD, binocular and thin-section studies, in the same manner as TD-5. The types of secondary minerals are calcite, quartz, stilbite, heulandite, clinoptilolite, mordenite, barrerite, laumontite, wairakite, prehnite, anhydrite, iron oxide, pyrite, fluorite, vermuculite, kaoline, smectite, mixed-layers (chlorite/smectite), illite and chlorite.

Calcite occurs in the cutting samples from the top down to the bottom of the well. It has a similar behaviour as found in TD-5 cutting samples. Calcite in the sedimentary units in the lower part of the well showed a replacement of plagioclase. A thin-section at 451 m also showed fractures filled by calcite and wairakite.

Quartz is one of the common minerals and is widely distributed in the well. It has a similar behaviour as found in TD-5 cutting samples. Thin-sections of the basalt showed a presence of quartz in the cuttings but these were probably derived from the sedimentary units. Quartz occurs as fillings in cavities and veins in the sediments. The presence of quartz in some layers indicates a cementing material of the sediment similar to calcite. At 150-516 m depth it occurs in association with laumontite and calcite. In places where wairakite is present (below 451 m), it occurs with wairakite in veins replacing the zeolites.

Pyrite is present in the well starting from 20 m depth. It is a common mineral and recognized by its yellow luster and cubic crystal form. It is more abundant in the fine- to medium-grained sandstone. Its abundance decreases around the middle of the well and then again towards the bottom of the well. Chalcopyrite is believed to be present at certain levels of the well but it was difficult to distinguish it clearly from pyrite through the binocular microscope.

Prehnite, which usually forms at relatively high temperatures, is found in thin-sections below the depth of 404 m. Some show a bowtie structure or sheaflike structures and are found in the groundmass and cavities of the rock.

Anhydrite occurs sporadically from 404 m to the bottom of the well. Its presence is recognized both in thin-sections and XRD analysis. In XRD the main characteristic peaks are at 3.5 and 2.85 Å.

Iron oxides and hematite. Reddish Fe-oxides and haematite are present in variable amounts being more common in the sandstone layers from 100 to 370 m.

Zeolites occur in all parts of the well and show a zoning from low to high temperatures (Figure 6).

Stilbite is abundant in the well from 20 to 225 m. Barrerite is also found in its upper part.

Heulandite is one of the low-temperature zeolites occurring in the drill cuttings from 90 m down to 225 m. In XRD it shows peak values of 8.96 Å and 2. 97Å.

Clinoptilolite is found in the cuttings at 20-80 m depth. In the XRD it shows major peak values of 8.94, and 3.97 Å.

Laumontite. Its presence is identified in binocular, XRD and thin-sections. It is identified first at 100 m and is commonly found from 150 m to the bottom of the well.

Mordenite was identified with the help of XRD in the drill cuttings at 20, 40 and 130 m depth. In XRD it has main peaks at 9.06 and 4.0 Å.

Wairakite. Its first appearance in the well is at 451 m depth and it is found to the bottom of the well. It occurs as a vein filling and replaces laumontite with the association of quartz and calcite.

Clay minerals are abundant in well TD-6. They are the products of glass, olivine and partly plagioclase and pyroxene, and are also found as alteration minerals. The clay minerals are chlorite/smectite mixed-layer, vermiculite, illite, kaoline and chlorite (Appendix 3).

Smectite occurs in the upper part of the well (30-170 m). In XRD it shows reflection peaks of 14.5- 15.5 Å untreated, which swell upon glycolation to 16 Å and collapse to 9-10 Å after being heated to 550°C.

Illite is one of the common widely spread clay minerals in TD-6. In the upper part it is found in trace amount. It occurs along with the mixed layers and chlorite. Illite clay shows a distinct characteristic peak around 10 Å. The peaks do not change upon glycol saturation or even when heated to 550°C.

Kaoline is common from 60 m down to 290 m. It shows a characterstic peak around 7-7.3 Å which collapses on heating to 550°C.

Chlorite /smectite. Mixed-layer clays occur in the well from 170 m down to 310 m. They give main peaks at 14-15 Å, which may expand to higher Å upon glycol saturation and collapse upon heating to 550°C.

Chlorite is distinguished by its main common peak 14-14.7 Å in the untreated, glycolated and oven-heated samples, and also with no change or collapse of its peak when heated to 550°C. In the binocular study it is identified by its green colour; where abundant. It occurs from 302 m down to the bottom of the well.

3.4 Hydrothermal zones

Factors affecting the formation of the hydrothermal minerals are mainly temperature, rock type and fluid composition and the duration of activity (Browne, 1984). Fluid circulating in a system for the deposition or formation of secondary minerals depends on, and is governed by, pressure and temperature. Secondary minerals such as clays and zeolites have been shown to be temperature dependent. In this study, two sets of alteration zones are presented. One is related to zeolites. The other is mainly defined by the clays. Alteration zones established for zeolites and clay minerals are shown in Figures 4 and 5.

3.4.1 TD-5

According to the presence of alteration minerals, the following zeolite zones can be established for TD-5 (Figure 4):

Heulandite-stilbite zone	20-170 m
Laumontite zone	170-335 m
Laumontite-wairakite zone	335-516 m

Heulandite-stilbite zone. Abundant stilbite and sporadic heulandite characterizes this zone and these are found together with calcite deposition, especially with sandstone and in rare cases in the intercalated siltstone. They occur interstitially as a filling of voids in the coarse sediments and in veinlets in the siltstone. The presence of pyrite and iron-oxide is associated with this zone which may be associated with sediment deposition.

Laumontite zone. This zone is delineated by the predominant appearance of laumontite and the disappearance of stilbite and heulandite. Mixed-layer clay is dominant (chlorite/smectite) and it is the zone where prehnite appears at 240 m. Aquifer 3 occurs in this zone (see Chapter 4).

Lamontite-wairakite zone is delineated by the appearance of wairakite at a depth of 330 m and below 390 m to the total depth as a common alteration mineral, mainly replacing laumontite. It is also a zone where the occurrence of epidote at 420 m and 470 m is recorded in the cutting samples. The laumontite-wairakite zone is associated with chlorite and illite clays. Aquifers 4 and 5 are located in this zone.

In spite of relatively few XRD clay analyses done on clay minerals, the following zones can be roughly delineated (see Appendix 2). These clay zones show progressive heating with depth as does the zeolite distribution.

Smectite zone	20-90 m
Transition Smectite to mixed-layers	90-190 m
Mixed-layer clay zone	190-309 m
Chlorite-epidote zone	309-516 m

3.4.2 TD-6

TD-6 shows three types of zeolite zones (Figure 5):

Stilbite zone	20-225 m
Laumontite zone	225-450 m
Lamontite-wairakite zone	450-504 m

Stilbite zone. Stilbite and heulandite are the dominant zeolites and are associated with calcite. The zeolites occur in the interstitial pore space between the sediment grains and act as a cement along with calcite. This zone is associated mainly with smectite, with subordinate amounts of possible vermuculite and illite.

Laumontite zone is characterized by the disappearance of stilbite and the appearance and abundance of laumontite. It is associated with mixed-layer clays, chlorite/smectite and illite. This zone is associated with Aquifers 2 and 3. The temperature for this zone is more than 200°C.

Laumontite -wairakite zone is characterized mainly by the first appearance of wairakite at 450 m depth. Prehnite is found sporadically below 404 m. The whole section below shows the presence of both minerals. Wairakite is associated with zeolites and shows a replacement of the laumontite which was deposited before the occurrence of wairkakite. The zone is characterized with the highest temperature >250°C measured at the bottom of the well.

The same zones of clay minerals as defined for TD-5 can be established for TD-6, with the occurrence of high- temperature clay minerals as temperature increases (Figure 5).

Smectite zone	20-160 m
Mixed-layer clays zone	160-330 m
Chlorite zone	330-504 m

4. AQUIFERS

Aquifers in the geothermal system are the main resource for geothermal utilization. They are influenced by many factors such as the nature of the rock type (porosity, permeability) and the amount of secondary deposition during fluid circulation. In the exploitation of a geothermal system, the extent, nature, and dimension of an aquifer and its productivity and recharge ability are important.

Locating aquifers in drill holes can sometimes be problematic. To reliably locate aquifers, one has to rely on a number of independent methods. The two most widely used ones are monitoring circulation losses/gains and temperature logs. Additional evidence may include variation in penetration rate and alteration. The exact location of an aquifer is very important because its relationship with the surrounding geology becomes clearer. If the connection of the aquifers and the well geology is well understood, the direction and the shape of the aquifers can be expanded far out from the well, and the siting of subsequent wells will be made easier.

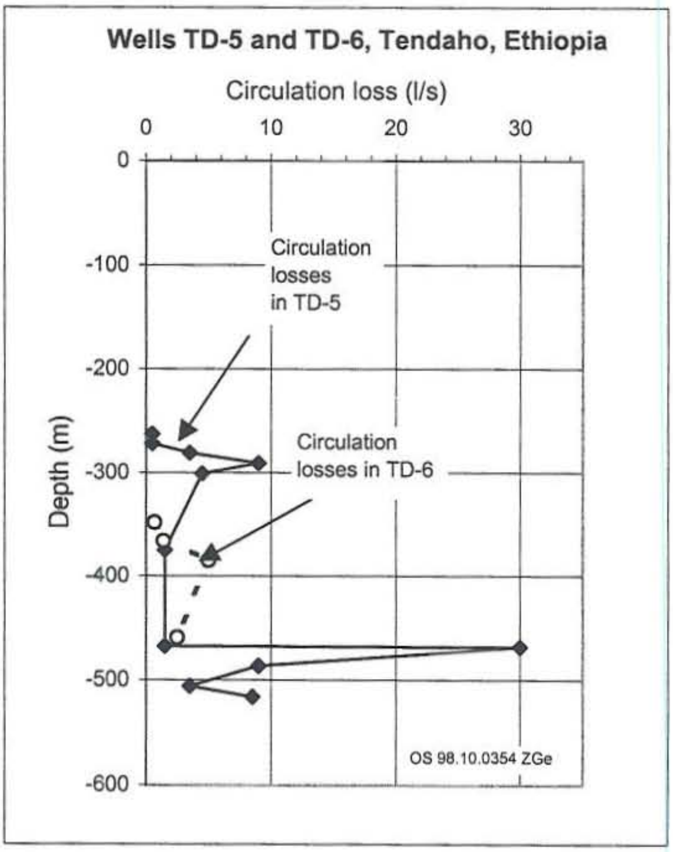

FIGURE 7: Graph showing loss of circulation during drilling of TD-5 and TD-6

4.1 Aquifers of TD-5

During drilling, the circulation loss was unfortunately not monitored down to 220 m depth because it was decided before drilling to run 9 5/8 inch casing (anchor casing) to that depth. A graph showing loss of circulation during the drilling of TD-5 and TD-6 is shown in Figure 7.

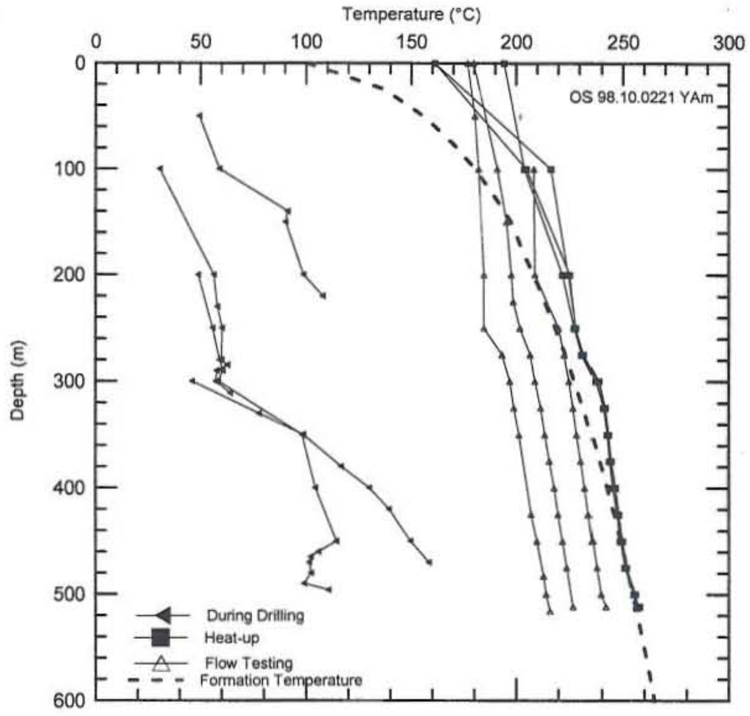

FIGURE 8: Temperature logs of well TD-5

Below the data of possible aquifers penetrated by TD-5 are described from top to bottom, as well as their relation with the formation, temperature and mineral assemblages.

Aquifer 1 is tentatively put at 100 m depth, based on temperature profile T-1 (Figure 8), in a fresh 5 m thick basalt lava. Alteration minerals present are calcite, quartz and low-temperature zeolites which are mostly associated with the sediment cuttings. These may be associated with fractures of the basalt in the other well, and/or may be assumed to be a feeding zone, due to the contact of the sediment and the basalt.

Aquifer 2 is located around 150 m as indicated by temperature profile (Figure 8). This zone is found at the boundary of a 18 m basalt lava flow and the underlying brown medium grained sediment. Alteration minerals present are calcite, quartz and low-temperature zeolites.

Aquifer 3 occurs around 290 m depth. This is the zone where around 10 l/s circulation loss was registered. Unfortunately, samples from depth 285-301 m were not recovered. However, core samples recovered at the depth of 301 m show the rock to be a medium grained sandstone. The temperature profile measured just after injection shows the presence of a feed zone in the formation. This zone is on the boundary where mixed-layer clays are replaced by chlorite and also where the first appearance of prehnite is registered.

Aquifer 4 occurs at around 469 m depth. Circulation loss recorded at this depth is 8-10 l/s. This zone is at the contact of silty clay and fine- to medium-grained sandstone. The hydrothermal mineral assemblage includes calcite, quartz, prehnite, wairakite, illite, chlorite and epidote. In the thin-section, secondary minerals are present in cavities and veins, and laumontite is replaced by wairakite and quartz. This may indicate the formation of wairakite and quartz in the second phase of alteration deposition. Temperature logging T-12 is measured on the boiling curve. Temperature measurements taken after injectivity test T-3 indicate the presence of a feed zone shown as a cooling point.

Aquifer 5 occurs at around 490 m. It occurs in a fine- medium-grained sediment where a circulation loss of 3 l/s is recorded. The mineral assemblage is the same as above where the probable replacement of zeolites by quartz and wairakite is also evident.

4.2 Aquifers of TD-6

The presence of loss zones during the drilling of TD-6 were unfortunately not monitored above the 9 5/8" casing (217 m depth), and possible aquifers based on temperature could not be traced. A graph showing loss of circulation during the drilling of TD-6 is also shown in Figure7. Below is a list of possible aquifers penetrated by TD-6.

Aquifer 1 is at 235 m, indicated by a temperature profile recorded during drilling. No major circulation loss is recorded. The formation is at the top of a fresh basaltic lava flow. This indicates that the contact zone between the basalt and the overlying sediment is the permeable structure.

Aquifer 2 occurs at 320-340 m, where a circulation loss of about 1.4 l/s on average is registered. The formation is fine- medium-grained sediment. The alteration mineral assemblage is clay, quartz, calcite, laumontite and chlorite.

Aquifer 3 occurs at 366-385 m where a circulation loss of greater than 5 l/s is registered. This unit is fine- /medium-grained sediment. It is believed to occur at a contact of two sediment zones. The mineral assemblage is calcite, quartz, clay, laumontite and chlorite. It is also also worth mentioning that it is a zone where the transition from mixed-layer clays to chlorite occurs. Even though the change of alteration minerals and circulation loss indicate an aquifer, measured temperature profiles during drilling and the warm-up period do not give clear evidence for the presence of this feeding zone.

Aquifer 4 occurs at 500 m depth. No major circulation loss is recorded. The mineral assemblage plus a higher intensity of alteration in the sediments indicate the presence of a feed zone. Alteration minerals found are calcite, quartz, laumontite, chlorite, wairakite and prehnite. The presence of abundant wairakite and prehnite and the replacement of laumontite by wairakite may further indicate the presence of a feed zone at this depth. The presence of a feed zone is also confirmed by the temperature profile. It is also in this zone where the highest temperature was registered during the last temperature log of warm-up (see T-4, Figure 9).

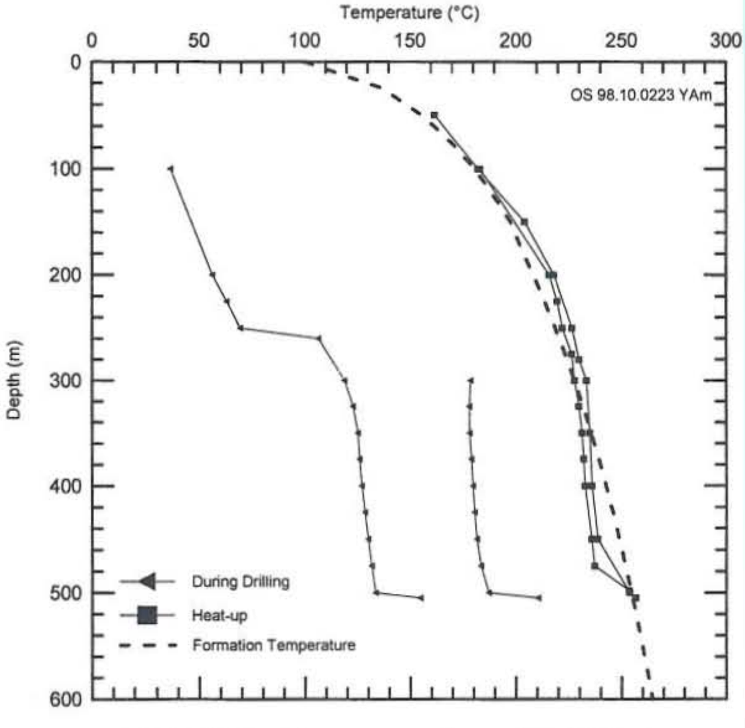

FIGURE 9: Temperature logs of well TD-6

5. CORRELATION OF TD-5 AND TD-6 WELLS WITH PREVIOUSLY DRILLED WELLS

Results of the deep wells TD-1, TD-2 and TD-3 in the Tendaho graben revealed the following:

The maximum thickness of the sediment is 1300 m in TD-1 with interlay of basalts, where the thickness of the basalt increases below 600-700 m.

A lower basaltic sequence, encountered in wells TD-1, TD-2 and TD-3 around 1400, 1180 and 1300 m, respectively, are assumed to be the Afar stratoid series (ASS). This unit is a monotonous basaltic sequence with interlayering of pyroclastic deposits (Aquater, 1995, 1996).

Correlation between the two deep wells TD-1 and TD-2 shows a displacement of the lower basaltic unit (AAS) of about 230 m, which may be due to a major fault or series of faults possibly occurring prior to the deposition of the sediment.

Four of the wells, TD-2, TD-4, TD-5 and TD-6, are located in the vicinity of mud pools and fumaroles which are aligned NW-SE and are assumed to lie en echelon to the main manifestations. Correlation of the established stratigraphy shows a similar lithological succession with minor displacement which may be inferred as a fissure/fault assumed to contribute to the manifestation of mud pots and fumaroles in the area. A NE-SW geological cross-section is shown in Figure 10.

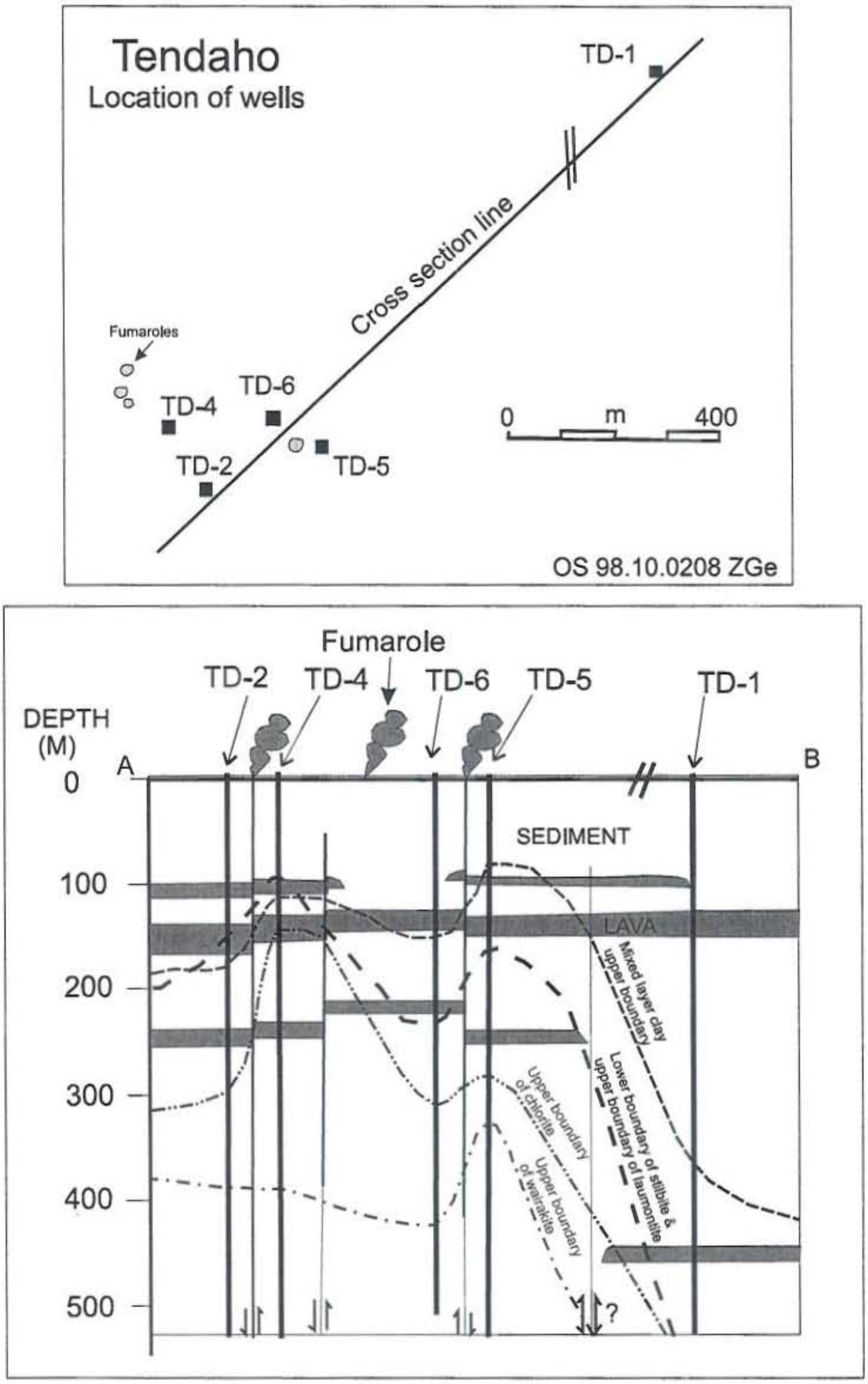

FIGURE 10: Location of shallow geothermal wells in Tendaho, and a NE-SW simplified geological cross-section through the wells and alteration minerals

The mineral assemblage in these shallow wells is mainly calcite, quartz, stilbite, laumontite, wairakite, prehnite and epidote. The occurrence of high-temperature indicative minerals is at slightly variable depths. Permeability and the abundance of secondary minerals are apparently associated with the coarse sediment and contact zones of the interlayers.

6. COMPARISON OF ALTERATION MINERALS AND MEASURED TEMPERATURE

Hydrothermal alteration in both TD-5 and TD-6 shows progressive zonation with depth and temperature, as is discussed above. Figures 11 and 12 show formation temperature and the zonation of secondary minerals for wells TD-5 and TD-6. The formation temperature is considered to follow the boiling point curve because both wells show actual measurements close to boiling temperature. The occurrence of individual minerals is compared to the temperatures of the boiling point curve. The measured temperatures are also shown in Figures 11 and 12. By comparing the presence of particular minerals in the wells with the formation temperature, a progressive change from low-temperature minerals to higher-temperature minerals is noted as the depth and temperature increase. And it also apparently shows the high-temperature indicative minerals to be stable and in equilibrium with the present temperature.

Under the present temperature and fluid conditions, the wells show a sequence of mineral assemblages influenced mainly by the progressive increment in temperature. The disappearance of smectite above 190°C, the presence of mixed-layer clays of chlorite/smectite in the range of 160-230°C and the disappearance of mixed-layer

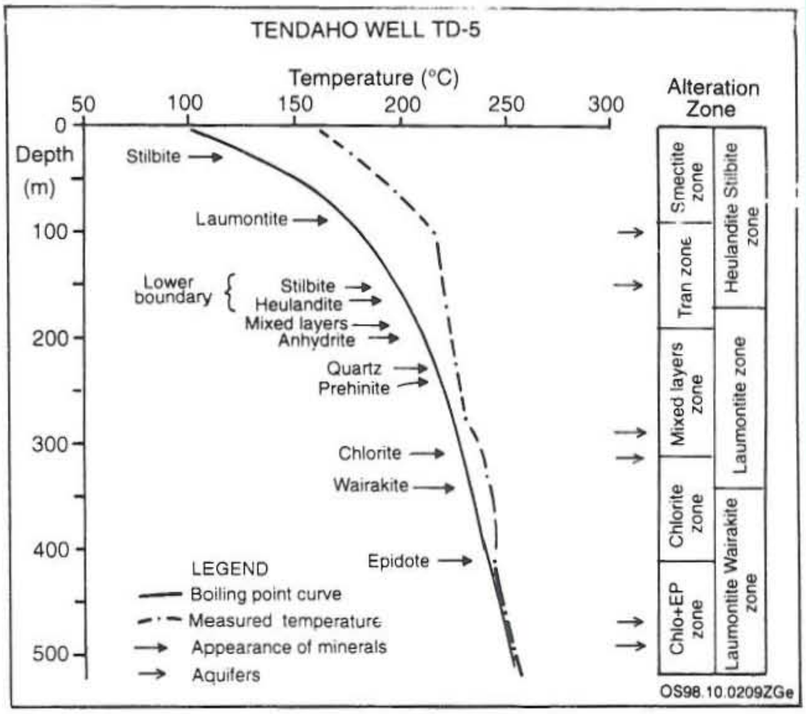

FIGURE 11: The appearance of secondary minerals, boiling point curve and measured temperature in well TD-5

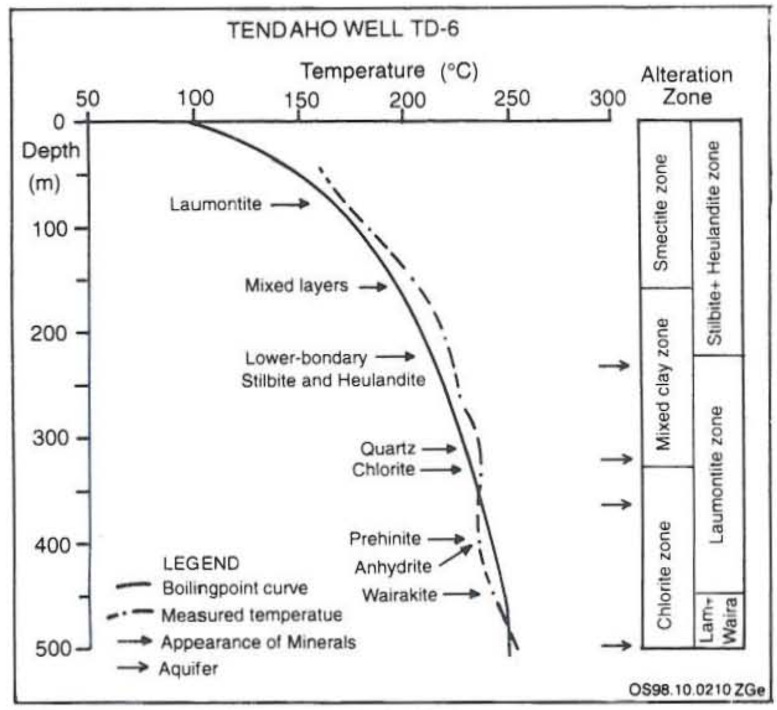

FIGURE 12: The appearance of secondary minerals, boiling point curve and measured temperature in well TD-6

clays with the appearance of chlorite at temperature greater than 230°C. Chlorite and illite are the only dominant clay minerals found above 230°C.

The presence of low-temperature zeolites like stilbites and heulandite is recorded at temperatures up to 175°C and the appearance of laumontite >170°C, as well as the existence of wairakite >230°C, as shown in Table 1. This shows that zeolites depend on temperature. Anhydrite is present at greater than 200°C. The appearance of prehnite and epidote is recorded above 220 and 240°C, whereas calcite and pyrite are common at all depths of the well, and quartz appears to be stable at >190°C and persists up to the recorded rock formation temperature at the bottom of the wells.

The appearance of different kinds of zeolites are temperature dependant. High-temperature indicative minerals occur above 230-240°C, and appear to be fairly stable and in equilibrium with the formation temperature. As is shown in Table 1, comparing the secondary mineral stability of Tendaho with other geothermal fields, the occurrence of high-temperature minerals (prehnite, wairakite and epidote) show similar dependance with a slight variation of a few tens of °C. Stilbite and heulandite disappear around 175°C in Tendaho, whereas the existence of stilbite in other fields occurs up to around 120°C. This may indicate less permeable zone in the sediment.

TABLE 1: Distribution of alteration minerals in the shallow wells at Tendaho as a function of temperature (°C) and mineral temperature stability found in other fields (Kristmannsdóttir and Tómasson, 1978; Teklemariam et al., 1996; Brown, 1978 and Reyes, 1990)

Minerals	Iceland	New Zealand	Cerro Prieto	Philippines	Langano (Ethiopia)	Tendaho
Epidote	>240	230	>225	>230	>200	>240
Prehnite	(>250)	>220	>280	>230	>250	>220
Wairakite	>200	>230	>240	210-310		>230
Laumontite	120-200	<200		>110	60-240	>170
Stilbite	70-120	<120				<175
Anhydrite				>180		>200
Quartz	>180	>110	150-330	180-340		>190
Smectite	30-200			20-180	90-200	<190
Chlorite	>230		150-325	>120	155-300	>230
Kaolinite			<160	0-160		<225
Illite	230-330	>230	150-325	220-330	>175	>130
Mixed layer clays	200-230		200-225		150-240	160-230
Vermuculite			>325		160-280	180-210
Illite+Chlorite		>220	>145			>230

Table 1 shows the established temperature scale for the hydrothermal alteration minerals. It shows that most of the minerals present are in equilibrium with the formation temperature except low-temperature zeolites which have partially been replaced by wairakite and quartz.

7. DISCUSSION

In this discussion, data will first be presented to define the structure of the geothermal system; then hydrothermal alteration will be used to evaluate the evolution of the hydrothermal system.

The stratification of the wells shows mainly three rock types:

Siltstone. This appears to be a very low-permeability rock with no intergranular porosity and to a large extend cemented by carbonates. The only visible permeability of the rock are micro fractures filled with secondary minerals. These fractures presumably are due to tectonic activity.

Sandstone, fine- to medium-grained, and it is quite obvious that it contains a high intergranular porosity. Laboratory measurements of the core taken at 300 m in TD-5 show porosity ranging up to 55%. A petrographic evaluation of porosity in the same core (point counting) showed an original porosity of about 33% and about 10% if intergranular deposition is subtracted. Though some discrepancy is evident between the two methods used, they both show high porosity values.

Lava flows show relatively high porosity, but it was perhaps a little surprising that the lavas were relatively unaltered and not heavily deposited by alteration minerals.

This stratification gives a very strong signal that permeability is preferentially lying along the horizontal sandstone layers, separated by less permeable siltstones.

The area is within a very tectonically active environment with the major fault and fracture pattern being NW-SE and with only a minor N-S component. It is quite obvious that the upflow of the geothermal system must be controlled by vertical faults/fractures. A number of geothermal manifestations near the wells (Figure 2) have been tentatively linked to a major WNW-ESE structure and associated NW-SE en echelon aligned fracture pattern, implying a fault with sinistral transcurrent features. The faults pinpointed by borehole data in an area between the wells have not, at this stage, been correlated with the surface fault pattern, and await further studies.

It can be concluded, therefore, that the geothermal reservoir near the shallow wells is controlled by vertical upflow of boiling geothermal water which is partially diverted into horizontal sandstone formations (a comparison of the aquifers and the strata gives indications that the boundaries between the siltstone and the sandstone may give relatively high permeability). The apparent lack of reverse gradients in the shallow wells may imply that the wells are drilled in close proximity to vertical upflow channel.

The hydrothermal alteration has been compared with the probable formation temperature in the wells to attain probable alteration stability limits of some of the alteration minerals. These temperature stability limits have then been compared with the alteration pattern in other areas (Table 1). These, in general, show a very good comparison, confirming that alteration minerals can effectively be used as reliable temperature indicators in future drilling in this type of geological environment.

Compared to other geothermal studies the hydrothermal minerals show a good correlation with measured temperatures, except where the zeolites stilbite and laumontites, are found at anomalously high temperatures,. The instability of the zeolites in Tendaho is also seen where laumontites are observed in places partially or totally replaced by wairakite and probably quartz. It appears thus that the alteration indicates that the Tendaho geothermal system is progressively heating up where the older zeolite assemblage is gradually giving way to higher temperature minerals (prehnite and wairakite).

8. CONCLUSIONS AND RECOMMENDATIONS

The following are the main conclusions and recommendations of this study:

The lithology of the wells studied shows a sedimentary sequence of intercalating sandstone, siltstone and rare basalt lava flows. Porosity is highest in the sandstone and lowest in the siltstone.

The aquifers encountered in the wells are generally associated with the sandstone beds, especially near the boundaries between the siltstone and sandstone. Surface manifestations indicate a geothermal relationship with vertical fractures/faults, and it is assumed that the main geothermal upflow is connected to such a feature.

The main alteration mineral assemblage consists mainly of calcite, zeolites, clays, sulphides, prehnite and wairakite. In well TD-5, epidote is found sporadically. The alteration indicates a progressively heating geothermal system, where the older zeolite assemblage is giving way to younger higher temperature alteration minerals. The higher alteration minerals show good conformity with the measured formation temperature in the wells.

The strata consists of interlayered sandstone, siltstone and lavas. In future drilling, it is recommended that samples be taken if possible at shorter intervals than 5 m, in order to map in more detail the permeable horizons. This study has shown that much more detailed information can be gained through petrographic analysis of the cuttings rather than through use of the binocular microscope. It is, therefore, recommended that the cuttings should be studied petrographically in detail in order to gain as much information on the geothermal system as possible.

Much can be learned about the boundary of the geothermal system by monitoring circulation losses and making temperature logs while drilling for the production casing. It is recommended that such measurements should be taken more vigorously in future drilling.

In order to study the temperature dependency of the alteration minerals and the temperature changes in the field, fluid inclusion studies should be initiated at some stage of the geothermal investigation of Tendaho field.

The lithology penetrated by TD-5 and TD-6 includes sedimentary units interlayered with thin layers of basalt. The sedimentary unit includes sandstone, siltstone and volcaniclastic. The primary mineral composition of the sedimentary rock is glass, quartz, pyroxene and plagioclase. It is mainly cemented with carbonates not connected to hydrothermal alteration but due to the deposition under a water environment. Quartz occurs both as a constituent of the formation as well as a hydrothermal deposition. The latter can be distinguished on grounds of its intergranular deposition.

In the fine- to medium-grained sandstone there are a lot of spaces (mainly intergranular spaces) which are not totally filled by secondary minerals. But in the siltstone, the only open space seen are the micro fractures which are relatively rare. Core samples of fine- to medium-grained sediment taken from TD-5 and TD-6 give a 55% porosity measurement maximum of the total volume (EIGS laboratory). A point counting under a microscope gives a value of up to 30% total porosity for the same rock type. Even though the two values have a large discrepancy, both measurements show the presence of significant permeability in the fine- to medium-grained sandstone. Moreover, the presence of veins and cracks in a thin-section study indicates tectonic activity which can also be inferred from the stratigraphical correlation of the wells especially between TD-2 and TD-4 as well as TD-5 and TD-6 (Figure 10). All these faults are considered responsible for the occurrence of mud pools and steaming grounds around the drill sites.

The major faults visible on the surface and buried under thick sediments are open channels for the geothermal system and serve as upflow channels to the shallow depth reservoir and dispersed into horizontal layers in the sediment. Permeability in the reservoir is mainly the porosity of the sandstone, the contact boundary between different layers of the sediment and micro fractures in the formations.

Aquifers, as indicated by the circulation, losses temperature logs and alteration are present in the fine- to medium-grained sandstone layers. Upflows in a vertical direction may indicate the presence of a high-temperature mineral assemblage at a shallower depth in well TD-5 when compared to other wells.

The temperature range shown by the alteration distribution in the Tendaho field compares in most cases with other geothermal fields. The exceptions are the existence of stilbite and laumontite at 175 and >200°C, respectively. In thin-sections, laumontite gives a clear indication of being replaced partly by wairakite and quartz. This indicates the presence of low-temperature zeolites in the first phase of deposition at lower temperature than at present and followed by the second phase of deposition such as wairakite, prehnite and epidote at a higher temperatures.

ACKNOWLEDGEMENTS

I would like to extend my gratitude to the government of Iceland and the United Nations University for the privilege accorded me to attend the Geothermal Training Programme and to the Ethiopian Institute of Geological Surveys which granted me leave.

Special thanks are due to the director, Dr. Ingvar B. Fridleifsson, to the deputy director Mr. Lúdvík S. Georgsson and Mrs. Gudrún Bjarnadóttir for their efficient help and kindness through the study period. My deepest and sincere appreciation to my supervisor, Dr. Hjalti Franzson, for his motivation and guidance in my specialization. Many thanks are due Mr. Sigurdur S. Jónsson for training and close assistance in XRD analysis. My thanks also to Ms. Helga B. Sveinbjörnsdóttir and Audur Ágústsdóttir for the drawing of figures. Finally, to all the lecturers and staff members of Orkustofnun for sharing their knowledge with us and their help.

REFERENCES

Abbate, E., Passerini, D., and Zan, L., 1995: Strike-slip faults in a rift area: a transect in the Afar Triangle, East Africa. *Tectonophysics 241*, 67-97.

Aquater, 1979: *Geothermal exploration project.* Ministry of Energy and Mines Ethiopian Institute of Geological Surveys, Ethiopia, report DROGUE A0422,, 115 pp.

Aquater, 1995: *Well TD4 - Drilling report. Tendaho geothermal project.* EIGS, report H9385.

Aquater 1996: *Tendaho geothermal project, final report.* MME, EIGS - Government of Italy, Ministry of Foreign Affairs, San Lorenzo in Campo.

Brindley, G.W., and Brown, G. (editors), 1980: *Crystal structures of clay minerals and their X-ray identification.* Mineralogical Society, London, 495 pp.

Browne, P.R.L., 1978: Hydrothermal alteration in active geothermal fields. *Annual Reviews of Earth and Planetary Science, 6,* 229-250.

Browne, P.R.L., 1984: *Lectures on geothermal geology and petrology.* UNU G.T.P., Iceland, report 2, 92 pp.

Gasse, F. 1975: *The evolution of lakes of the Central Afar region (Ethiopie and T.F.A.I.) from Plio-Pleistoscene to the present* (in French). Thesis presented at the University of Paris, France.

Gasse, F., 1977: Evolution of Lake Abbe (Ethiopia and T.F.A.I.) from 70,000 b.p. *Nature, 265,* 42.

Kristmannsdóttir, H., and Tómasson, J., 1978: Zeolite zones in geothermal areas in Iceland. In: Sand, L.B., and Mumpton (editors), *Natural zeolites, occurrence, properties, use.* Pergamon Press Ltd., Oxford, 277-284.

Reyes, A.G., 1990: Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment. *J. Volc. Geoth. Res., 43,* 279-309.

Teklemariam, M., Battaglia, S., Gianelli, G., and Ruggieri, G., 1996: Hydrothermal alteration in the Aluto-Langano geothermal field, Ethiopia. *Geothermics, 25-6,* 679-702.

Tschernich, R.W., 1992: *Zeolites of the world.* Geoscience Press Inc., Phoenix, Arizona, 563 pp.

Zan, L., and Abbate, P.P., 1990: *Map of the gelogical structure of Central Afar region.*

APPENDIX 1: Preparation of sample minerals for analysis by the XRD techniques

The preparation of samples with hydrothermal alteration and clay minerals for identification and classification is done as follows:

Procedure A:

1. Hand pick grain filling either vesicles or veins from the cuttings under the binocular microscope. This can be done continuously at specific depth ranges in order to follow the appearance and disappearance of some minerals.

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

3. Fill an appropriate sample holder for the XRD with the powder.

4. Run the sample from 3-56° θ.

This technique was used to distinguish between the different zeolites in the wells and for accurate first occurrence of minerals in the cuttings.

Procedure B: Preparation of samples for clay mineral analysis.

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

2. Allow to settle for 1-2 hours, until particles finer than approximately 4 microns are left in suspension. Pipette a few millilitres from each tube and place on labelled glass plates. Avoid having the samples thick. Make a duplicate of each sample and let them dry at room temperature overnight.

3. Place one set of samples in a desiccator containing glycol ($C_2H_6O_2$). Store at room temperature for at least 24 hours.

4. Run both sets of samples from 2-15 on the XRD.

5 Place one set of the samples on asbestos plate and heat in a preheated oven at 550°C. Oven temperature must not exceed 600 °C. Cool the samples sufficiently before further treatment.

6 Run the samples from 2-15° on the XRD.

APPENDIX 2: X-ray results for clay samples in well TD-5

Depth (m)	Untreated d(Å)	Glycolated d(Å)	Heated (Å)	Result
25	13.0, 9.96	16.36, 11.23, 9.96, 7.61	11.23, 9.92, 7.5	Smectite, illite (trace)
60	14.85, 9.18	17.9,13.36, 9.14	15.5, 13.36	Smectite, chlorite/illite (?), heulandite (?)
100	30.18, 14.42, 12.54, 10.47, 9.45, 7.15	30.18, 16.69, 14.03, 13.21, 9.92, 7.08	31.0, 16.69, 9.92, 7.08	Smectite, mixed-layer clays, illite (trace), kaoline (trace)
120	22.4, 14.17, 10.02, 7.12	16.32, 14.17, 10.02, 7.12	22.4,14, 10.02, 7.12	Smectite, vermiculite (?), illite
140	14.14, 12.5,	14.14, 8..22	9.74	Smectite, chlorite/smectite
170	31.50, 14.28, 12.50, 9.97, 7.16	29.68, 17, 14.09, 10.00, 7.08	9.90, 7.1	Chlorite/smectite, vermiculite, illite
220	30.83, 14.34, 9.96, 9.46, 7.10	30.83, 14.03, 9.96, 9.3	9.93, 9.28	Illite,chlorite/smectite, laumontite
250	29.20, 14.31, 9.93, 9.40, 7.1	29.20, 9,93, 9.4, 7.06	9.95, 9.09	Chlorite/smectite, illite
280	14.25, 11.54, 7.11	14.25, 11.36, 9.13, 7.14	8.14	Chlorite/smectite, illite
301	29.3, 14.34, 9.5, 7.19	31.09, 15.26, 7.66	21.79, 12.52, 7.99	Chlorite/smectite
309	14.26, 10.4, 7.09	14.26, 9.97, 7.09	14.07, 10.07, 7.12	Chlorite, illite
320	14.18, 10.27, 7.07	14.18, 9.98, 7.07	14.10, 9.97	Chlorite, illite
370	14.27, 9.94, 7.60, 7.09	14.18, 10.0	14.49, 9.93	Chlorite, illite
420	14.21, 10.01, 9.42, 7.6, 7.09	15.23, 14.21, 10.01, 9.42, 7.09	14.58, 10.01, 8.5	Chlorite, illite, laumontite
445	14.25, 9.43, 7.59, 7.09	14.25, 9.43, 7.09	14.45, 9.93, 8.56	Chlorite, illite, laumontite
485	14.25, 9.98, 9.42, 7.58, 7.10	14.25, 9.98, 9.42, 7.10	14.45, 9.93, 8.56	Chlorite, illite, laumontite

APPENDIX 3: XRD results for clay samples in well TD- 6

Depth	Untreated d(Ä)	Glycolated d (Ä)	Heated 550°C d (Ä)	Result
30	15.41, 10	16.85, 10	9.93	Smectite, illite (trace)
60	14.99, 10.06, 9.02, 7.22	16.06, 10.06, 9.02, 7.22	9.96, 9.02	Smectite, illite (trace), kaoline
90	14.82, 8.97, 7.18	14.84, 8.96, 7.19	Collapsed	Smectite, kaolinite, vermuculite (?)
120	14.81, 10.21	16.47,14.81, 10.21	Collapsed produced 9.7	Smectite
130	14.42, 12.72	15.89	Collapsed	Smectite
170	30.18, 14.68, 7.24	32.05, 14.62, 7.24	Collapsed	Chlorite/smectite, kaolinite (trace)
210	31.22, 14.48, 7.26	30.95, 14.59, 7.26	Collapsed	Chlorite/smectite, vermiculite, kaolinite
230	29.55, 14.45, 7.17	29.2, 14.28, 7.12	Collapsed	The same as 210 m.
282-291	29.55, 14.51, 10.03, 7.28	29.55, 14.42, 10.13, 7.25	10.01	The same as 210 m and illite (trace)
302-310	31.77, 14.45, 10.23,	30.5, 14.78, 10.27,	Collapsed	Chlorite/smectite, illite
338-348	14.39, 10.11, 7.63, 7.12	14.25, 10.14, 7.10	14.33, 9.97	Chlorite, illite
366-376	14.37, 10.04, 9.49, 7.65, 7.14	14.37, 10.06, 8.49, 7.12	14.45, 10.04, 8.64	Chlorite, illite, kaolinite
394-404	14.25, 10.07, 7.6, 7.09	14.28, 10.7, 7.10	14.39, 10.07	Chlorite, illite, kaolinite
413-423	14.33, 9.97, 9.42, 7.6, 7.12	14.31, 9.99, 9.42, 7.12	14.36, 9.97, 8.61	The same as above plus laumonite
441-450	14.25, 12.32, 10.03, 9.49, 7.62, 7.10	14.14, 9.93, 9.41 7.09	14.4, 9.9, 8.52	The same as above
470-478	14.22,10.04, 9.44 7.6, 7.11	14.19, 10.31, 9.45, 7.12	14.54, 10.0, 8.57	The same as above
498-504	14.22, 10.03, 9.45, 7.60, 7.09	14.25, 10.01, 7.10	14.48, 10.04, 7.29	The same as above