HYDROTHERMAL ALTERATION IN BOREHOLES LA-3, LA-4 AND LA-6 LANGANO-ALUTO, ETHIOPIA

Meseret Teklemariam,*
UNU Geothermal Training Programme
National Energy Authority
Grensasvegur 9, 108 Reykjavik
Iceland

*Permanent address:
Geothermal Energy Exploration Project
Ethiopian Inst. of Geological Surveys
Ministry of Mines and Energy
P.O.Box 2302, Addis Ababa
Ethiopia

ABSTRACT

Correlations of the stratigraphy of the wells in the Langano-Aluto geothermal field in Ethiopia suggest the existence of a tectonic episode that step faulted the rock sequences encountered in the holes. The hydrothermal alteration mineralogy in wells LA-3, LA-4 and LA-6 show that the clay mineral assemblages are arranged in four distinct zones in order of increasing rock temperatures as follows: 1) Mixed layer clays (Illite-Montmorillonite), 2) Illite-Chlorite, 3) Illite and 4) Chlorite. At deeper levels, the hydrothermal minerals seem to reflect the present temperature in the system and confirm the production zones. The presence of adularia at the bottom of the wells coincides with the permeable zones determined by injection test and temperature log. The calc silicate mineral assemblages defined by prehnite, garnet, actinolite associated with epidote and biotite and mainly confined to well LA-3, suggest that the well is situated in the main upflow zone. Age relationships between different alteration minerals observed in veins and vugs were studied and two hydrothermal episodes were recognized. Based on the alteration minerals, the altering fluid is near neutral alkali-chloride bicarbonate type with high partial pressure of CO_2 and Ca^{+2}, K^+ as well as Na^+ ions in the solutions.

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1 INTRODUCTION

1.1 Scope of study

This study is the result of six months Fellowship awarded to the author by the United Nations University to study Borehole Geology. The course was held from April to October 1985 at the UNU Geothermal Training Programme, National Energy Authority in Reykjavik Iceland. The training started with a five weeks introductory lecture course dealing with various aspects of geothermal research, as well as practicals. Visits were made to several of the geothermal sites in Iceland where geothermal energy is being developed and utilized.

The specialized training that the author received included:

A) A field excursion to a fossil and deeply eroded high temperature area in the Geitafell central volcano, SE-Iceland.

B) Cutting analyses from well NJ-11 in the Nesjavellir high temperature area in SW-Iceland using stereoscopic binocular microscope.

C) An XRD study and thin section analyses on rocks from NJ-11 as well as from the wells LA-3, LA-4 and LA-6 in the Aluto high temperature area in Ethiopia.

The work in the latter area included in particular a study on core samples from Langano wells no. 3, 4 and 6 with respect to petrography, clay mineralogy and hydrothermal history of the area. The report describes a study on the alteration mineralogy of wells LA-3, 4 and 6 in the Aluto high temperature area in Ethiopia. XRD analyses, thin section examinations as well as binocular microscopic inspection were carried out in order to determine the rock type, texture of the rock, alteration minerals present and to observe the cross-cutting relationships of veins and infilling sequences in amygdales which are important to unravel the hydrothermal history of the area.

2 GEOTHERMAL AREAS IN ETHIOPIA

2.1 Introduction

The geothermal areas of Ethiopia are located within the Ethiopian rift system, a region of a high regional heat flow beneath a relatively thin crust. Exploration work of the geothermal field in Ethiopia started in 1970-71 by the United Nations Development Programme (UNDP) including geochemical, geological and hydrogeological surveys of the entire Ethiopian rift system. The following factors were used as criteria for the selection of an exploitable area (UNDP, 1984):

A) A magmatic heat source located at a relatively shallow depth.
B) The presence of a permeable zone acting as a reservoir at a shallow depth.
C) The presence of an impermeable formation acting as a cap rock above the reservoir.
D)The possibility of enough recharge of meteoric water to the reservoir during exploitation of the geothermal fluids.

Based on these factors the following geothermal prospecting areas were selected: Dallol, Southern Afar rift and the central southern part of the Ethiopian rift referred to as the Lakes District area (Langano-Aluto, Corbetti, Abaya).

The area of the Lakes district (Langano-Aluto) was given priority for the geothermal exploration and development for the following reasons (UNDP,1984):

A) Availability of water for drilling operations (Lake Ziway).
B) Close proximity to the high voltage interconnected national network.
C) Easy accessibility to the area.

The Langano-Aluto geothermal area is a part of the Main Ethiopian rift system about 200 km south of Addis Ababa. Deep drilling commenced in this area in 1981 and at present there are eight deep drillholes of which five are productive.

2.2 Regional geology and tectonic setting

In Ethiopia, an undifferentiated group known as the Basement complex was formed during the Precambrian. It is an extremely foliated and folded schists, granites and gneisses. In the Paleozoic, there was an unconformity or an era of denudation and peneplanation. Therefore, the Precambrian rocks are overlain unconformably by the Mesozoic sediments. In that time, subsidence of the land led to the transgression of the sea from SW to NE followed by the deposition of sediments such as Adigrat sandstone, Antalo limestone and Upper sandstone which were later affected by the rift faults. Uplifting took place in Upper Eocene which resulted in the formation of the Arabo-Ethiopian dome and followed by extensive basaltic volcanism known as the Trap series basalts. This again was followed by the occurrence of large scale faulting due to the relative movement of the Arabian and West Indian ocean plates forming the present Ethiopian Rift system which is the surface expression of diverging lithospheric plate boundaries (Tertiary times) (Mohr, 1967).

The Ethiopian rift extends in a general NNE direction for over 1000 km from the Kenyan boarder. It can be divided into the main Ethiopian rift and the Afar depression (Fig. 1). The Main Ethiopian rift extends some 400 km NNE from just south of latitude 6°N near Lake Chamo to latitude 9°N where it meets the complex Afar triple junction. The part of the rift that rises from 1230m a.s.l at Lake Chamo in the south to approximately 1800 m a.s.l at the Awash river watershed is known as the "Lakes district" (UNDP, 1973). Tectonic fragmentation of the rift floor formed the Wonji Fault Belt (WFB) which is considered to be a recent crustal extension, active since early Quaternary and is normal to the rift axis but ceases where it abuts directly against the rift margin (Mohr, 1967). Many pantelleritic volcanoes are alligned along the western boarder of the WFB and Aluto is supposed to be one of these central rift volcanoes.

2.3 Geology of the Langano-Aluto area

Aluto is sited on the northern termination of the Wonji Fault Belt (Mohr, 1967) and most of the vents are linear in NNE and sometimes in E-W directions clearly showing that they are controlled by regional faults. Aluto volcano is a complex rhyolite massif extruded on the WFB between lakes Langano and Zwai (Fig. 2).

Fig. 2 shows a simplified geological map of the Aluto area (Lloyd, 1977; Tsegaye 1985). The early rift Tertiary ignimbrites mapped on the main eastern escarpment are the oldest rocks and inferred by Lloyd (1977) to be the reservoir in the geothermal system at Langano. The Tertiary ignimbrite comprises predominantly crystal ignimbrites, waterlain ashes and older rhyolites. These are overlain by the Bofa basalts which are mapped east, north east and in the southern part of Aluto. Both Tertiary ignimbrite and Bofa basalts were encountered in the deep drilled wells of Aluto. These were followed by lake sediments indicating the presence of higher lake levels at about 1850 m a.s.l in the past (Lloyd, 1977).Then voluminous amount of ashflow, tuffs, silicic lithic breccias and pumice flows erupted which led to the formation of a caldera as a result of isostatic imbalance and to attain lithostatic equilibrium. Since the caldera collapse rhyolite lavas, pumice breccias and obsidian flows have erupted through vents which are controlled by NNE trending faults of WFB and/or fractures created by the caldera collapse. Most of these younger volcanic products have been encountered in the deep drilled wells of Aluto.

Hydrothermal activity in the area has continued throughout the history of the volcanic centre. It occurs in the form of hot springs located south and south east of the Aluto volcano, and low pressure steam vents as well as warm grounds within the volcano itself. These are mainly controlled by the fault structures and volcanic craters.

3 BOREHOLE GEOLOGY

3.1 Overview of wells LA-3, LA-4 and LA-6

The general information about wells LA-3, LA-4 and LA-6 is shown in Table 1. These wells are deep exploratory wells drilled on top of Aluto, with high temperature as well as sufficient permeability to produce two phase flow. The first two wells (LA-1 and LA-2) were on the other hand located on the southern and western base of Aluto and drilled only to a depth of 1313 m and 1600 m respectively. Insufficient permeability was encountered and the measured downhole temperatures were 88°C and 100°C respectively.

3.2 General stratigraphy of wells LA-3, LA-4 and LA-6

Detailed stratigraphic descriptions of these three wells has already been performed (Marishet, 1983; Solomon, 1985). It was based on analyses of cuttings which were collected every 5 m and core samples taken at every 100-300 m intervals. Both binocular and petrographic microscopes were used for the analyses. The earlier work on the stratigraphyis summarized iin Table 2.

3.3 Correlations of the deep drilled wells of Aluto

The SW-NE and E-W stratigraphic cross sections of the Langano-Aluto area is shown in Fig 3 to correlate the lithological units encountered in the drillholes.

The general geological sequence encountered in these wells is similar. This and the presence of marker beds, make correlation between wells possible.

Tertiary ignimbrites have been encountered in all the wells except in LA-2. These ignimbrites have a thickness of 448, 674 and 617 m in LA-3, LA-4 and LA-6 respectively. In LA-4 the ignimbrites are mainly interlayered with rhyolite lavas while in LA-3 and LA-6 they are dominately crystalline ignimbrites with some intercalations of rhyolite and ash fragments.

The Bofa basalts found in all the drillholes are similar and vary in texture from aphyric to porphyritic. The basalts in LA-1 are mainly well crystallized and coarsely porphyritic, and an intrusive origin has been suggested (Kifle, 1982). The basalts encountered in these drillholes vary in thickness from 1000 m (LA-3), 903 m (LA-6) to 700 m (LA-4).

The older lake sediments are thicker in the western direction (LA-2) while thinning towards east as indicated by their absence in wells LA-4 and LA-5. It is suggested that after the period of sedimentation a tectonic episode step faulted both the sediments and older units to deeper levels.

Quaternary Aluto pyroclastics and Aluto rhyolites (the younger volcanic products) have been encountered in all the wells. They become thinner towards the east as a result of the rift faults.

TABLE 1 Overview of the wells LA-3, LA-4 and LA-6

Well no.	Location grid reference	Elevation m	Time of drilling	Proudction casing	Total depth (m)	Aquifers (m)	Maximum temp. (°C)
LA-3	E77401;N60723	1921.2	Jan21st-May23rd 1983	9 5/8" to 747m	2143.9	2117	300
LA-4	E78300;N60800	1956.46	July6th-Oct23rd 1983	9 5/8" to 745m	2062	1445	262
LA-6	E7768;N6102	1964.9	Mar24th-July2nd 1984	9 3/8" to 754m	2203	2000-2100	317

TABLE 2 A simplified general stratigraphic description of the the wells LA-3, LA-4 and LA-6

Unit	Lithological description	LA-3 Thickness (m)	LA-4 Thickness (m)	LA-6 Thickness (m)	Probable age
Quaternary Aluto pyroclastics	Pumice breccias with abundant pumice fragments, rhyolites, obsidians and alluvium	29	32	43	Recent
Quaternary Aluto rhyolite	Flow banded crystalline rhyolite lava with some obsidian and ash beds	249	266	297.4	Recent
Quaternary silicic tuffs and breccias	Silicic breccia, lithic vitric to crystalline tuff with some rhyolite and ash beds	347	312	321.2	Late Pleistocene
Older lake sediments	Muddy siltstones with some rhyolites and ash beds	76.5	-	29	Late Pleistocene
Bofa basalts	Basaltic lavas, basaltic breccias and some intercalations of rhyolite and ash beds	993.5	777	903.1	Pliocene-Pleistocene
Tertiary ignimbrite	Welded crystalline tuff, fine grained tuff with some intercalations of rhyolites, basalts and ash beds	448.9	675.2	596.1	Miocene-Pliocene

4 HYDROTHERMAL ALTERATION

4.1 Introduction

Hydrothermal alteration minerals present in active geothermal fields are important to evaluate and/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 alteration minerals (Browne, 1978). Temperature, original rock type and the fluid composition are thought to be the main controlling factors for the formation of different types of alteration minerals in the Aluto wells.

4.2 Analytical techniques

Since no cuttings were brought to Iceland for this study, only the core samples taken every 100-300 m interval were used for petrographic as well as XRD analyses of the primary and secondary constituents of the rocks. The core samples were studied macroscopically to see the cross-cutting relationships of veins and infilling sequences which are important to know the alteration evolution history. These core samples were crushed using a hammer, then washed to remove the dust and examined with a binocular stereoscopic microscope. During this examination, secondary mineral grains occurring as vesicle (amygdales) as well as vein and/or cavity fillings were selected for the XRD analyses.

XRD analyses were runusing CuK adiation with scanning speed 2°/minute at different time scale and range. Two methods of sample preparation were used for XRD analyses. These were:

1) Bulk powder non-oriented samples; each sample was grinded and powdered to about 5-10 µm. During grinding acetone was used as a binder in order to prevent the powder being blown off. The powdered sample was put in an aluminium window (sample holder) and run from 3-45°(2θ).

2) For clays, the crushed samples were washed, put in a tube with distilled water and put in a shaker for about 48 hours in order to release the clays from the cuttings. The tubes were allowed to stay for a while until the coarsest particles had settled. The clays, still in suspension, were collected with a pipette, put on a glass slide and allowed to dry in the air. Then the samples were put in a dessicator ($CaCl_2$) for 24 hrs, followed by glycolation (48 hrs) and heating 450-550°C for one hour. After each treatment the samples were run from 2-15 (2θ). Clay minerals were identified solely by examinations of basal X-ray reflections. These reflections were recognized by referring to a standard table which describes the intensity and type of the peaks belonging to various minerals. After recognizing the reflections, thin sections from similar depths were examined and correlated with XRD results.

4.3 Alteration of primary minerals

The primary rock forming minerals present in the analysed rock samples are mainly ferromagnesian minerals (olivine and pyroxene), plagioclase, quartz and magnetite/ilmenite. The ferromagnesian minerals are mostly associated with the basaltic rocks while plagioclase and magnetite are common in both silicic as well as basic rocks. Quartz is present as a primary mineralin the silicic rocks. The degree of alteration of the primary minerals is quite variable which may reflect:- a) susceptibility of the primary minerals to alteration, b) difference in rock permeabilities and c) intensity and rank of alteration.

The order of decreasing susceptibility of rock forming minerals to hydrothermal alteration is volcanic glass, magnetite, olivine, pyroxene and plagioclase (Steiner 1968, Browne and Ellis, 1970). In the wells the ferromagnesian minerals and the silicic volcanic glass are the first to be altered and replaced by clays, chlorite, calcite and hematite while most of the plagioclases remain unaltered. With increasing intensity of alteration the ferromagnesian minerals are found to be completely altered and to remain with pseudomorphs of calcite, chlorite, pyrite and hematite while plagioclase is altered to albite, calcite, epidote, clays as well as K-feldspars (adularia). The primary magnetite/ilmenite are also altered to hematite, leucoxene and sphene.

The secondary minerals reflect different types of hydrothermal alteration processes, which take place as a result of the water/rock interaction. The processes and some of the possible reactions can be described as follows:

A) Hydration and carbonation, where pyroxene and plagioclase are altered to calcite, epidote, prehnite, actinolite, illite-mica and chlorite.

$$3CaAl_2Si_2O_8 + 2K^+ + 4H^+ = 2KAl_3Si_3O_{10}(OH)_2 + 3Ca^{+2}$$

Anorthite K-mica

$$3CaAl_2Si_2O + Ca^{+2} + 2H_2O = 2Ca_2(Al)_3Si_3O_{12}(OH) + 2H^+$$

Anorthite Epidote

$$3CaAl_2Si_2O_8 + 2Ca^{+2} + CO_2 + 3H_2O = CaCO_2 + 2Ca_2Al_3Si_3O_{12}(OH) + 4H^+$$

Anorthite Calcite

$$3(Mg,Fe)Si_2O_6 + 3/4O_2 + 2Ca^{+2} + 2H = Ca_2(Fe)_3Si_3O_{12}(OH) + 3SiO_2 + 3Mg^{+2}$$

Pyroxene Epidote

B) Sulfide formation, where iron oxides and hydroxides are replaced by pyrite.

$$Fe_3O_4 + O_2 + 6H_2S = 3FeS + 6H_2O$$

Magnetite Pyrite

C) Oxidation, where magnetite changes to hematite

$$4Fe_3O_4 + O_2 = 6Fe_2O_3$$

Magnetite Hematite

D) Solid-solid reaction, where the calcic plagioclase changes to albite and K-feldspars.

$$CaAl_2Si_2O_8 + 4SiO_2 + 2Na^+ = 2NaAlSi_3O_8 + Ca^{+2}$$

Anorthite Albite

$CaAl_2Si_2O_8 + 4SiO_2 + 2K^+ = 2KAlSi_3O_8 + Ca^{+2}$
Anorthite K-feldspar

4.4 Distribution of alteration minerals present in wells LA-3, LA-4 and LA-6

The general distribution of the alteration minerals found in boreholes LA-3, LA-4 and LA-6 are shown in Fig. 4 a,b and c respectively. The temperature profiles plotted in these figures are based on measurments taken after discharge and are assumed to represent the stabilized temperature of the rock formations.

In addition to the alteration processes described above direct deposition from the hydrothermal fluids is an important process as is evident from the abundance of vein/cavity and vesicle fillings. The alteration minerals present in the three wells studied are discussed below.

Calcite is the most widely distributed alteration mineral found in these wells. It is formed as a replacement of primary Na-Ca plagioclase, silicic glass and ferromagnesian minerals in association with chlorite, quartz, illite and epidote. It is also formed by precipitation as vein/-cavity and vesicle fillings in which precipitation of calcite depends on concentration of CO_2 and Ca^{+2} ions in the solution.

$$Ca^{+2} + 2HCO_3^- = CaCO_3 + CO_2 + H_2O$$

It was identified in the stereoscopic binocular microscope (confirmed by the use of HCl), thin section and by XRD analyses, recognized by itsstrongestpeak at d/°A = 3.03.

Siderite is not a common alteration mineral in these wells and is only found in cores 200-201 m, 402-404 m of LA-3 and 450-451.8 m of LA-6. It occurs mostly as vesicle fillings in the moderately altered vitric to crystalline vesicular tuff. It is mainly identified in thin sections and distinguished from the other carbonates by its brown staining around the boarder of the grain as well as good cleavage and higher index of refraction than the balsam. Like the other carbonates, its formation is favoured by the prescence of free HCO_3^- in the solutions.

$$Fe^{+2} + 2HCO_3^- = FeCO_3 + CO_3 + H_2O$$

Opal/Chalcedony occurs sporadically in all three wells and seems to be stable at a very wide range of temperature (Fig. 5). This alteration mineral characterizes supergene alteration occurring as vesicle and vein/cavity fillings which appear to be formed in association with quartz but earlier. It is also formed as a replacement of primary Na-Ca plagioclase and silicic volcanic glass. It was recognized through the stereo-scopic binocular microscope as well as in thin sections.

Hydrothermal quartz is widely distributed alteration mineral in all three wells, and seems to be stable at a wide range of temperature (Fig. 5). It is observed to have formed by precipitation from the geothermal fluid and crystallization of SiO_2 released during alteration of silicic glass, plagioclase and ferromagnesian minerals. Subhedral to euhedral crystals of quartz are abundant at the bottom of the holes associated with K-feldspars (adularia), calcite and illite as vein and/or cavity fillings. It is identified both by XRD technique (d/°A: 4.28, 3.35, 2.16, 1.82) and in thin sections. In some cases due to the evolved composition of the rock it was difficult to distinguish whether it is of primary or secondary origin.

Zeolites are rare in these wells. The zeolites identified are natrolite (thin section) and heulandite (XRD analysis d/A 8.85-7.8). They are only found in core samples from LA-3 (47-49 m, 149.4-149.8 m) and LA-6 (450-451.8 m). These zeolites occur mainly as vein and/or cavity fillings which could be formed by precipitation from the hydrothermal fluid.

Epidote is a significant hydrothermal mineral present in all the wells mainly associated with the highly altered basaltic rocks. The first appearance of epidote in wells LA-3, LA-4 and LA-6 is found to be 1050, 1000 and 950 m

(Solomon, 1985) respectively, where the measured temperature is >220°C. (Fig. 5). It mostly occurs as an alteration product of pyroxene as well as plagioclase and as vein/-cavity, and vesicle fillings associated with calcite, illite, chlorite and quartz. It is easily identified in the stereoscopic-microscope due to its yellowish green color, acicular form and in thin section by its pleochroism and high interference color.

Prehnite is a rare mineral in these wells in contrast to epidote and restricted to core samples of LA-3 (850, 1050, 1150 m) in the highly altered basaltic breccia where the measured temperature is >270°C. It is formed as a replacement of ferromagnesian minerals associated with chlorite, albite, epidote, illite and quartz, and occurs as vein/-cavity fillings. It is recognized in thin sections by its sheaf like (bow-tie) structure, good cleavage in one direction and strong birefringence.

Amphibole (actinolite) is only found in the core samples of LA-3 (1449.1-1450.6 m) in slightly altered porphyritic olivine basalt (intrusive?) where the measured temperature was about 307°C. It is formed as a replacement of ferromagnesian minerals associated with calcite, chlorite, biotite and illite. It is identified in thin section forming yellowish green radiated aggregates on the groundmass and by its relatively low birefringence compared to biotite.

Biotite is only present in the core samples of LA-3 (1449.1-1450.6 m) in slightly altered porphyritic olivine basalt (intrusive?). Since the rock is slightly altered with minor calcite, chlorite, actinolite and is presumably of an intrusive origin, the biotite could be a xenolith brought from below by the intrusive basaltic rock. The presence of biotite as a hydrothermal mineral in LA-6 cuttings from 1950 m depth has however been reported (Zewdie, 1984). As the measured temperature at that depth is about 307°C the biotite in LA-3could also possiblybe an alteration product of the primary ferromagnesianminerals.

Albite is common in all three deep drillholes from about 500 m depth and occurs mostly in the highly altered rocks. It forms as a replacement of calcic-plagioclase and K-feldspars as can be seen from the perthitic texture observed in some of the thin sections due to the replacement of Na^+ and K^+ ions. It is mainly associated with calcite, chlorite, illite and adularia. The occurrence of albite with adularia at the lower section can be correlated with the permeable zones encountered at the bottom of the deep drillholes. It is identified in thin sections and by an XRD run of bulk powder sample (d/°A 3.19-4.03) as low albite.

Garnet is only found in well LA-3 in the propyllitized basaltic breccia cored at 1150-1153 m where it is associated with calcite, albite, prehnite, illite and chlorite. The presence of garnet in well LA-6 at the core samples of 1505.8-1508.5 m depth has also been reported (Zewdie, 1984). The appearance of garnet in well LA-3 coincides with a measured temperature of about 290°C.

K-feldspars (adularia) is present in all the wells mainly in highly altered rocks. It is particularly abundant within the inferred production zone associated with albite, illite and subhedral to euhedral crystals of quartz while rare in the uppermost section of the wells. It is formed as a replacement of plagioclase as well as primary K-feldspars evident from the perthitic texture of the minerals. It was only detected in thin sections.

Iron oxide (hematite) is the most abundant hydrothermal mineral which is pervasive through the wells. It is mainly formed as alteration product of primary magnetite/ilmenite and ferromagnesian minerals (olivine) occurring around the old crystal margins and along what were probably fractures in the olivine crystals. It is also found as vein/cavity and vesicle fillings associated with calcite, chlorite, quartz and pyrite.

Iron sulfide (pyrite) is abundant throughout well LA-4, whereas it occurs sporadically in LA-6, and in well LA-3 it is restricted to the uppermost section of the well. It occurs as fine disseminations and large cubic crystals in the groundmass. It is formed as an alteration product of ferromagnesian minerals, magnetite and as vein/cavity fillings as well as vesicle fillings associated with calcite, chlorite and illite. It is easily identified in the stereoscopic microscope by its bright yellow reflection and cubic form.

Titanium oxides: Leucoxene and sphene occur sporadically in all the wells. They are formed as alteration products of the primary iron oxides (magnetite/ilmenite) and the ferromagnesian minerals associated with hematite, pyrite and calcite. Leucoxene was identified in thin section visible on the groundmass and around the borders of magnetite/ilmenite, whereas sphene was recognized by its euhedral crystal form and high relief.

Celadonite occurs sporadically in the middle and lower section of well LA-3 while it is rare in wells LA-4 and LA-6. It is formed as a replacement of plagioclase in the altered basaltic rocks and is associated with calcite, chlorite, illite and sericite. It was mainly identified by XRD analyses of the bulk powder sample with basal reflections at d/°A: 10.0, 4.53, 2.58.

Fluorite occurs only in well LA-3 restricted to core samples of 400.4 -402.4 m and 500.2-502.4 m in the highly altered vitric to crystalline tuff where the measured temperature was <150°C. It has precipitated from the hydrothermal fluids and is found as vein/cavity fillings. It was identified in thin section by its well recognized two directional cleavage, lack of birefringence and relatively high relief.

Sericite occurrs sporadically in well LA-3 from 500 m to the bottom of the hole, mainly within the altered basaltic rocks. It is formed as an alteration product of primary calcic plagioclase associated with calcite, albite, quartz and chlorite. It was identified in thin sections and observed mainly as fine aggregates surrounding quartz.

Mixed layered clays (Illite-Montmorillonite) occur in all the wells at theuppermost sections within the weakly altered rhyolitic lava formations where the measured temperature is < 150°C. They are formed as alteration products of the glassy matrix and the primary plagioclase present in the silicic rocks. They were mainly detected by XRD analyses (see Appendix A).

Illite occurs in all the wells as mixed layer in the form of a) interstratified illite-montmorillonite and as pure illite in the upper most section of the rhyolitic lava formation, and b) illite-chlorite in the middle section of altered tuffaceous rock and basaltic lavas and persists to the bottom of the well as pure illites (LA-3 and LA-6). It is formed as alteration product of the silicic glass and primary plagioclase mainly associated with calcite, albite, quartz, chlorite, hematite and pyrite. Illite was mainly recognized by XRD analyses (see Appendix A).

Chlorite is the most widely distributed mineral in all the wells. It is mostly formed as a replacement of ferromagnesian minerals, primary plagioclase and the glassy matrix. It has also formed by precipitation and is found as vein/cavity and vesicle fillings associated with calcite, illite, Fe-oxides and epidote. It is more common in the basaltic lavas than the illitic clay minerals, whereas illite is more abundant in the silicic rocks. The abundance of chlorite in these basic lavas might be due to the presence of ferromagnesian minerals which contribute Fe and Mg for the formation of chlorite. It is also found in the core samples 2200-2203 m of well LA-6 in the poorly altered volcanic sediments associated with minor calcite where the measured temperature was > 300°C. Chlorite was identified in thin section as light brownish green or dark green pleochroic mineral and as minute radiating aggregates with low birefringence. It was also recognized by XRD analyses (see Appendix A).

4.5 Clay mineral zones

Clay minerals of less than 2 µm were analysed by XRD technique in 33 samples from cores of LA-3, LA-4 and LA-6. This group of minerals is highly sensitive to variations in temperature and chemical environment and is therefore highly informative of conditions in the thermal system at the time of deposition. The results of XRD analyses for the clay minerals are compiled in Appendix A and diffraction patterns for mixed layer clay, illite and chlorite are shown in Figs. 6, 7 and 8 respectively.

Clay minerals have been found to be useful to classify the alteration mineral zones in geothermal fields (see for example Kristmanndottir, 1977 and Reyes and Tolentino, 1981). Earlier studies have also demonstrated that the clay minerals are effective geothermometers (Reyes and Tolentino, 1981). Clay mineral assemblages in Langano-Aluto geothermal field of wells LA-3, LA-4 and LA-6 have been classified into four distinct temperature dependent zones as follows:

ZONE I:	Mixed layer clay (Illite-Montmorillonite)
ZONE II:	Illite-Chlorite
ZONE III:	Illite
ZONE IV:	Chlorite

These zones are shown in (Fig. 9) which indicates the cross section of isothermal lines and boundaries of the clay mineral zones correlated to the measured temperature of the well. Since the samples used were cores selected at 100-300 m intervals the boundaries between these zones should only be regarded as tentative.

ZONE I: Mixed layer clay

Steiner (1977) proposed that mixed layer illite- montmorillonite minerals are most commonly products of hydrothermal alteration of silicate rocks. In the Aluto wells these minerals occur in the rhyolitic lava formation in the uppermost sections and are formed as alteration products of the matrix and the primary plagioclase present in the silicic rock. The temperature measured at the lower boundary of this zone in LA-3 and LA-4 is <150°C whereas in LA-6 it is about 205°C. These temperatures agree quite well with stability temperatures inferred from other geothermal fields (Ellis and Mahon, 1977 and Reyes and Tolentino, 1981). In addition pure illite is found associated with the mixed layer clays (see Appendix A).

ZONE II: Illite-Chlorite zone

The upper boundary of this zone is defined by the appearance of chlorite and disappearance of montmorillonite (Fig. 9). The zone occurs in the silicic tuffaceous rocks and in the altered basaltic rocks which mostly favour the formation of chlorite as an alteration product of ferromagnesian minerals. According to Browne (1984) illite and chlorite is the typical mineral assemblage found at temperatures of >220°C. Similarly, Reyes and Tolentino (1981) reported the formation of illite and chlorite at a temperature of 210-318°C in the Southern Negros geothermal field. These temperatures are comparable with those measured within the Illite-Chlorite zone in the Aluto wells (Fig. 9).

ZONE III: Illite zone

The upper boundary of this zone is at 1764 m and 1768 m depth in LA-3 and LA-6 respectively while absent in well LA-4. It is characterized by pure illite, occurring in the silicic welded tuffaceous rocks where it occurs as an alteration product of both plagioclase as well as the matrix and is associated with albite, calcite, adularia and quartz. The temperature measured at the boundary of this zone is about 300°C (Fig. 9) which is somewhat higher than previously reported for the occurrence of illite in other geothermal fields (Browne, 1978; Reyes and Tolentino, 1981; Hoagland and Elders, 1980).

ZONE IV: Chlorite zone

The upper boundary of this zone is only found in well LA-6 in core samples from 2200-2203.3 m depth, but both LA-3 and LA-4 are shallower. The temperature measured in this zone is >312°C (Fig. 9) which is in an agreement with observations made on the chlorite stability in Philippines as well as Icelandic geothermal fields (Kristmandottir, 1977; Reyes and Tolentino, 1981).

5 MINERAL EVOLUTION

The fractured and vesicular nature of rocks allow passage of hot fluid through the rocks which leads to water/rock interaction and precipitation of secondary minerals. They form the hydrothermal vein systems and mineral infillings in vesicles. As they are deposited at different evolutionary episodes, they can reflect different conditions existing in the hydrothermal systems at the time of their deposition.

Cross-cutting relationships of hydrothermal veins and amygdale infilling sequences were used to recognize the hydrothermal history of the area. Since the samples used for the analyses were cores, it was possible to see veins and amygdale textures visually as well as using a stereoscopic microscope. In addition, thin sections were also used for this analyses.

Fig. 11 shows examples of the material used to unravel the hydrothermal history of the area observed in some of the core samples of the wells. Fig. 11A is a sketch of a thin section from 950-951 m depth in well LA-3. It shows an amorphous silica vein which is cross-cut by younger calcite and a latter quartz vein. Fig. 11B shows mineral infilling sequence from a thin section of 1505.8-1508.5 m depth in well LA-6. The earliest deposition is Fe-oxide at the border of the vesicle followed by younger epidote and calcite towards the core of the vesicle. Fig. 11C shows a deposition in a fracture in a thin section from a core sample taken at 759.48-760.3 m depth in LA-4. Fe-oxide is the earliest to be deposited and is followed by quartz and calcite in order of decreasing age. The results obtained from this analysis are given in Fig. 12.

The mineral formation sequences obtained from these cross-cutting relations and infilling sequences can be grouped into two periods (Fig. 12). The first one represents a period of an earlier low temperature geothermal system characterized by deposition of amorphous silica, calcite, Fe-oxide and low temperature clay minerals. The second period represents the present active high temperature geothermal system characterized by deposition of chlorite, epidote, quartz, Fe-oxide, calcite and pyrite. Two generations of calcite and Fe-oxide were recognized as is evident from occurrences in both the earlier low temperature (period 1) and the present active high temperature geothermal systems (period 2).

Studies of the occurrences of alteration minerals at various levels and their correlation with the present measured temperature can also give information on whether the geothermal system has changed since their formations. Pure illite has for example been reported stable where temperature is >220°C (Browne, 1984). Its occurrence at shallow depths in the Aluto wells where present temperatures are 150°C could therefore be indicative of higher temperatures at earlier times.

Since the samples used for this analyses were only a few core samples it was difficult to reach a general conclusion of the mineral evolution. Hence, further studies to interprete this preliminary data are recommended.

6 DISCUSSION

The degree of alteration is quite variable in the three wells studied, and can probably be related to permeability and porosity of the rocks in the way that the more altered rocks had greater permeability and porosity.

Propylitic or potassium silicate mineral assemblages characterize alteration at depths in high temperature areas according to the classification of Meyer and Hemley (1967) while in cooler shallower zones zeolites and montmorillonite clays are common (Ellis and Mahon, 1977). The present results indicate that the rank of alteration increases with depth and temperature. This is evident from the propylitization or presence of calcite, illite, chlorite, albite, epidote, prehnite, amphibole, biotite, adularia and possibly garnet at deeper levels while amorphous silica, traces of zeolites and mixed layer clays (I-M) are present at shallower levels.

Comparisons of the present data with previous work and information from geothermal areas Philippines, Mexico , Iceland and Japan indicate that most of the mineral assemblages found in the three wells are in equilibrium with the present conditions of the thermal system. However, the presence of pure illite at shallower levels may indicate higher temperature in the past.

The first appearance of epidote occurs at measured temperatures of about 280°C in wells LA-3 and LA-6, whereas in LA-4 it first appears at 230°C. This is in close agreement with data from other geothermal fields like in New Zealand where epidote forms at temperatures >250°C (Browne,1978) and in the Philippines where it occurs at temperatures >230°C (Reyes and Tolentino,1981). Prehnite occurs in well LA-3 where the measured temperature is > 270°C which is comparable to the Cierro Prieto geothermal field where prehnite occurs at a temperatures of >300°C (Hoagland and Elders,1980). Earlier studies have shown that biotite and actinolite exist at the temperature range of 240 to >370°C, and correlate with contact metamorphic rocks (Reyes and Tolentino, 1981). The appearance of biotite and actinolite in well LA-3 within a slightly altered porphyritic olivine basalt (intrusive?) at the measured temperature of>300°Cis therefore comparative with the Philippine geothermal fields and accordingly suggests that these minerals originate from the present activity of the system. The presence of garnet in well LA-3 at the measured temperature of 292°C can also be compared with the Tongonan and Southern Negros (Philippine) geothermal fields where it occurs at temperatures as low as 280°C (Reyes and Tolentio, 1981). The upper boundary of calc silicate is defined by the appearance of epidote in LA-4 and LA-6, whereas in LA-3 it is defined by the appearance of prehnite (Fig. 10). The calc silicate mineral assemblages of prehnite, garnet and actinolite associated with epidote and biotite are only confined to well LA-3. This could indicate that LA-3 is located within the main upflow zone of the system (Fig. 10).

The abundance and early appearance of calcite at depths where measured temperature is <150°C and persistent to the bottom of the hole where the temperature exceeds 250°C suggests that calcite forms at widely varying temperatures and pressures (Fig. 5). The abundance of calcite as vein/cavity and vesicle fillings indicates high partial pressure of CO_2 in the geothermal fluid. According to Kristmanndottir (1982) the formation of zeolites is strongly dependent on PCO_2, permeability as well as temperature. The rare occurrence of zeolites in the Aluto wells (unlike Iceland and Japan) could therefore be due to the high partial pressure of CO_2 in the hydrothermal fluid.

The same reason can be given for the scarcity of calc silicate minerals in the wells compared to other geothermal fields for example in Iceland and the Phillipines. The predominance of Na zeolites (heulandite) agrees with alkali and pantelleritic nature of the rock (Molla, 1983).

The occurrence of albite at a very wide range of temperature (see Fig. 5) is in agreement with earlier observations in the Phillipine geothermal areas (Reyes and Tolentino, 1981). The presence of low albite can be used to estimate the partial pressure of CO_2 in the geothermal fluid at a certain temperature. This can be made by using the low albite-paragonite stability line from Giggenbach (1981)

(Fig. 13). This method was attempted for well LA-3 prior to production and the maximum log PCO_2 was found to be about 1.2 (Molla, 1983). The partial pressure of CO_2 of the geothermal fluid in LA-6 at a temperature of 300°C is according to the curve 1.6.

Four distinct alteration zones based on clay mineral assemblages were recognized with increasing temperature. The presence of illite at shallower levels within the mixed layer clay zone may indicate the existence of hot fluids circulating in the past. The pure illite zone in well LA-3 and LA-6 within the crystalline tuff occurs at temperatures >300°C which is slightly higher than observed in other geothermal fields. This is probably due to the composition of the original rock type, since illite is a common alteration mineral in silicic rocks.

Prominent mineral veins and amygdales are present mainly within the Bofa basalts indicating the existence of permeability in the past, which have been sealed by deposition of secondary minerals such as calcite, chlorite, quartz etc. Browne (1978) has shown that the feldspar mineralogy can be related to increasing permeability in the following way: primary Andesine - Albite - Albite + Adularia - Adularia. Table 3 shows that for different geothermal fields, mineral precipitates in fractures are in general quartz, adularia and illite. Accordingly the presence of adularia with subhedral to euhedral quartz at the bottom of the Aluto wells may indicate permeable zones (aquifers). This is in accordance with aquifers determined by injection test as well as temperature log. On the other hand, the rare occurrence of adularia in the upper section of the wells could be indicative of past permeability that have been sealed by secondary minerals.

The occurrences of pyrite may in some cases be correlated with zones of high permeabilities where high PH_2S/H_2 occurs (Browne, 1970; Steiner, 1977). This interpretation agrees with the abundance of pyrite in well LA-4 where better permeability was encountered than in the other two wells. High PH_2S/H_2 ratio in the geothermal fluid are associated with low CO_2 values and this in turn complies with the abundance of calcite in LA-3 and LA-6 compared to that of LA-4.

The existence of hematite with some pyrite implies relatively high oxygen fugacity of the altering fluid. This could be true for wells LA-3 and LA-6 where hematite is more abundant than pyrite. The high oxygen fugacity implies potential casing corrosion problems in this geothermal field, unlike for example Wairakei and Broadlands of New Zealand geothermal fields (Browne, 1984).

The study of alteration minerals is useful in defining the composition of the altering fluid. According to the mineralogy the altering fluid is of near neutral alkali-chloride bicarbonate type, which is mainly inferred from the abundance of calcite and has a high partial pressure of Ca^{+2}, Na, K^{+}, CO_2 and O_2 as is demonastrated by the reaction given in section 4.3.

TABLE 3 Common hydrothermal minerals found in permeable zones of different geothermal fields

Selected geothermal areas	Lithology of permeability	Alteration mineral found in permeable zones	References
Wairakei (NZ)	Lapilli tuff and ignimbrite	Quartz, adularia, illite, calcite	Steiner, 1977
Daklan Benguet (Philippines)	Volcanics and calcareous sediments	Quartz,adularia illite,calcite	Reyes and Tolentino, 1981
Langano-Aluto (Ethiopia)	Crystalline welded tuff	Quartz, albite illite,adularia	Present study

7 CONCLUSIONS

1. The younger Aluto volcanic products were encountered in all the drilled wells and they become thinner towards the east. The older lake sediments are thicker in the western direction (LA-2) while thinned out to the east (absent in LA-4 and LA-5). The Bofa basalts are drilled in all the wells and their thickness is more in LA-3 than in LA-4 and LA-6. Tertiary ignimbrites with intercalations of rhyolite and ash fragments were encountered in all the wells except in LA-2.

2. The hydrothermal mineral assemblage identified in the Aluto wells indicates a high temperature activity in accordance with the present measured temperature. No retrograde mineralization was observed in the wells suggesting equilibrium in the present geothermal system.

3. Four major clay mineral zones were recognized with increasing depth and temperature. These are:

   Zone I: Mixed layer (Illite-Montmorillonite) found where the measured temperature is <150°C.

   Zone II: Illite-Chlorite occur in the temperature range of 170-310°C.

   Zone III: Illite zone occurs where the measured temperature is 310-312°C in wells LA-3 and LA-6.

   Zone IV: Chlorite zone persists only in well LA-6 where the measured temperature is >310°C.

4. The occurrence of adularia coincides with permeable zones found from temperature logs. The appearance of adularia at shallower depths could indicate a fossil permeable zone.

5. The study of age relationships suggests the occurrence of two hydrothermal events. However, since these are only preliminary data further studies are recommended.

6. Some of the alteration minerals present indicate that problems can arise in the future development of the geothermal field. For example the abundance of calcite in the wells suggests a high PCO_2 in the geothermal fluid which can cause a scaling problem during exploitation of the field. The abundance of pyrite in well LA-4 shows high H_2S content in the fluid which may cause environmental problems in the future. Prominent Fe-oxides (hematite) in all wells indicate high oxygen fugacity which may create corrosion problems in the development of the geothermal field. Pronounced deposition of quartz as well as amorphous silica can indicate the possibility of silica deposition during reinjection of the geothermal fluid at lower temperatures.

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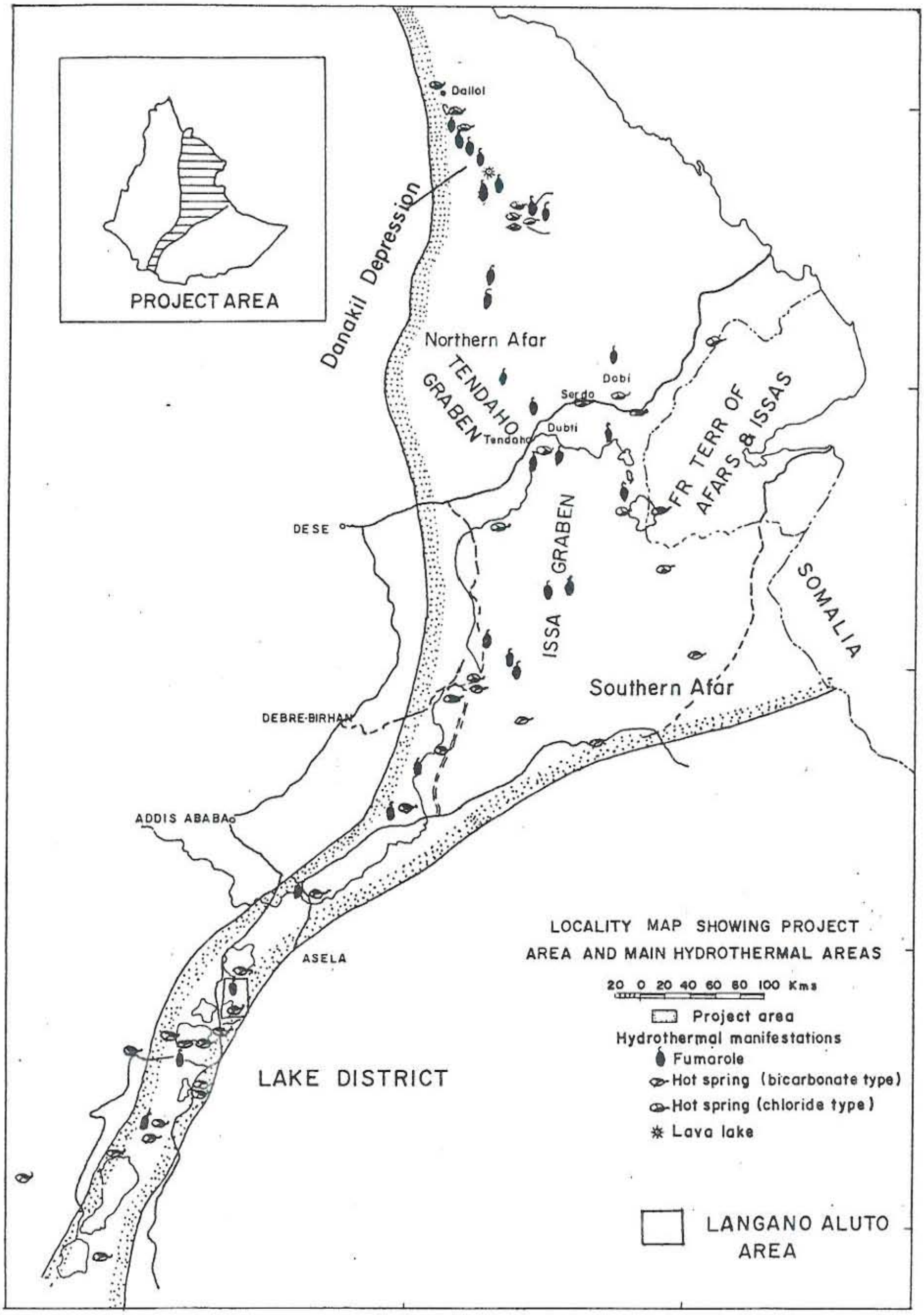
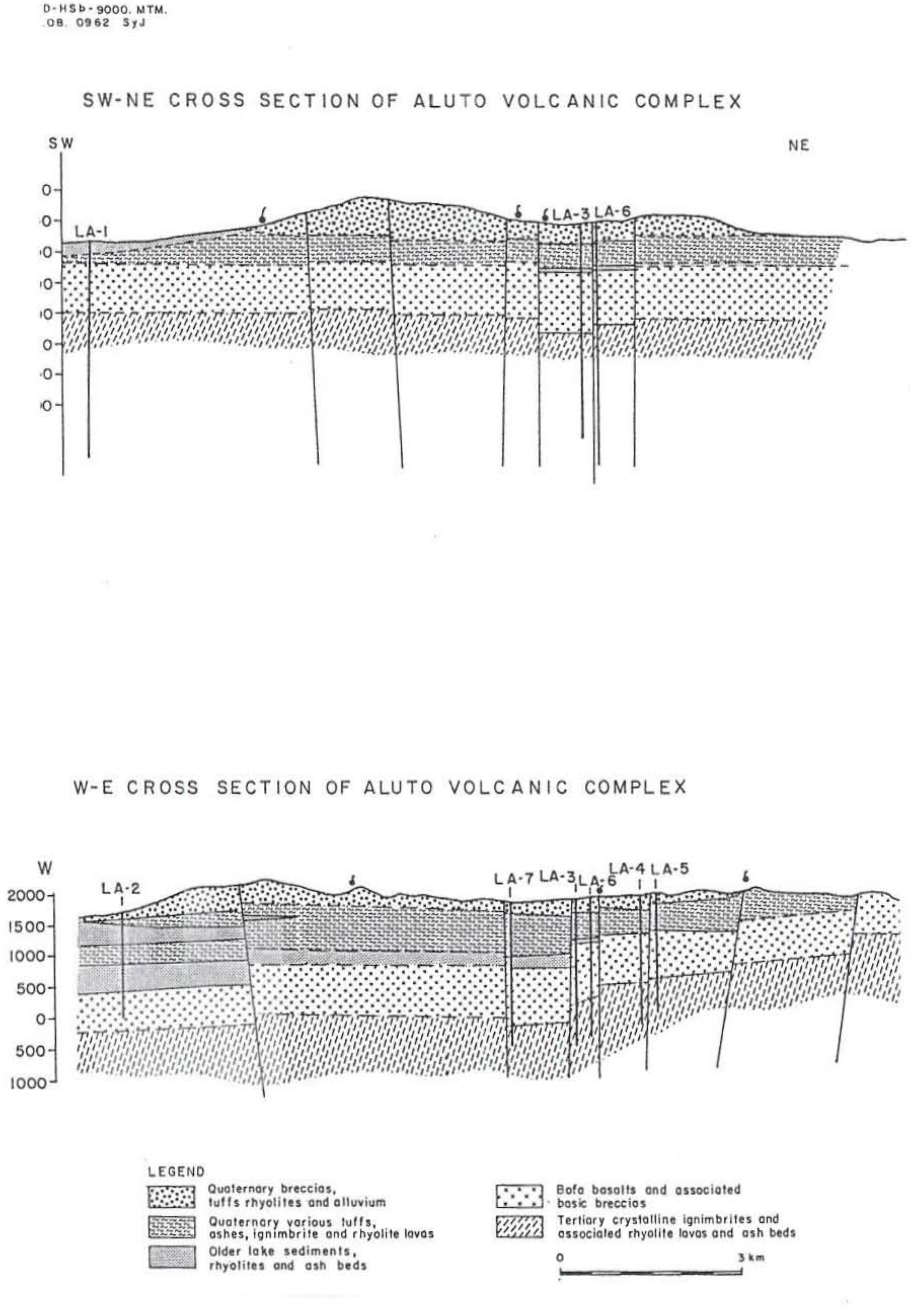


Fig. 1 Location map of the Ethiopian Rift showing the project area and main hydrothermal areas.



SW-NE CROSS SECTION OF ALUTO VOLCANIC COMPLEX

W-E CROSS SECTION OF ALUTO VOLCANIC COMPLEX

Fig. 2 A simplified geological map of Langano-Aluto area.

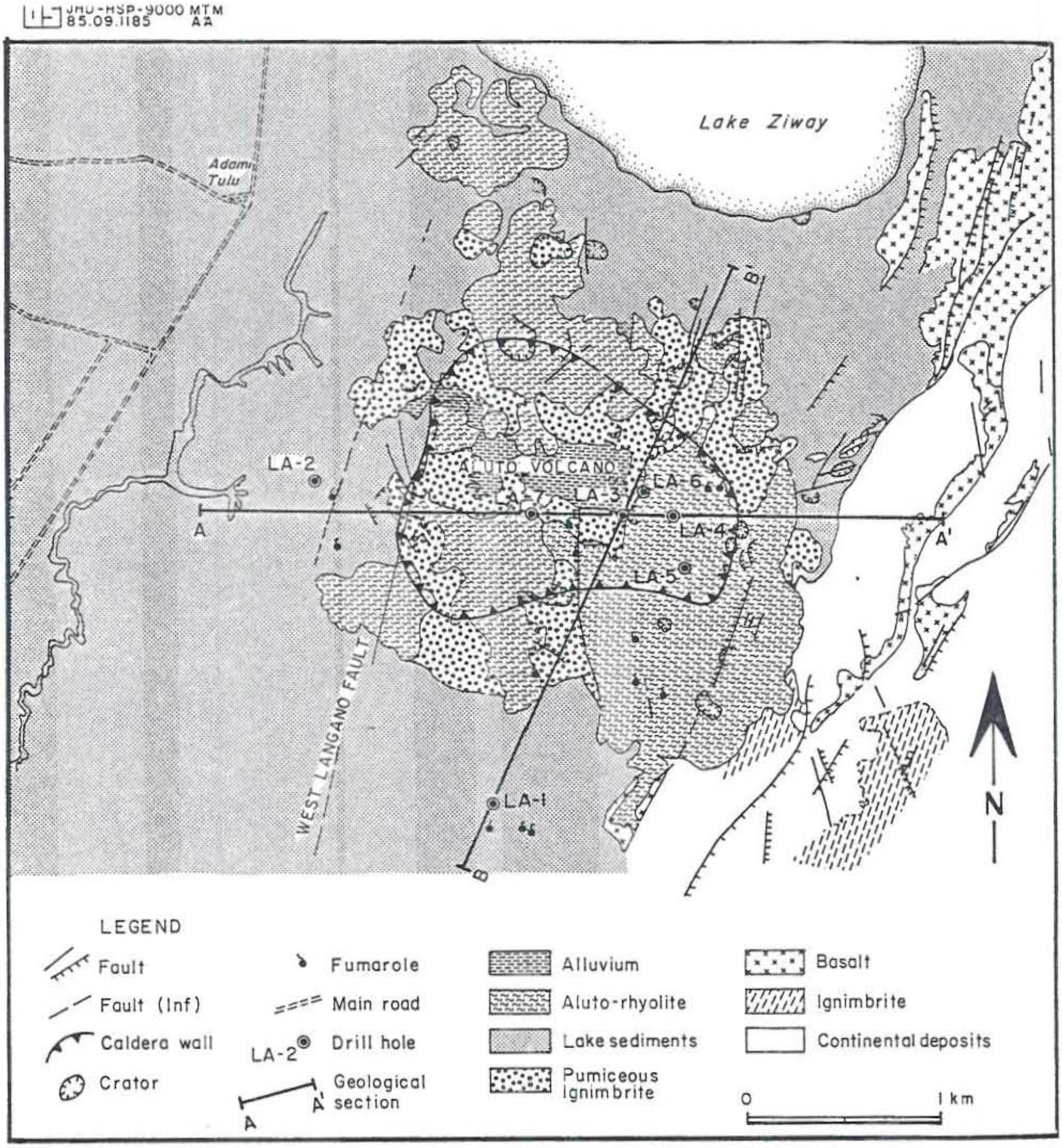


Fig. 3 SW-NE and W-E cross sections across the drilled area in the Aluto volcanic complex.

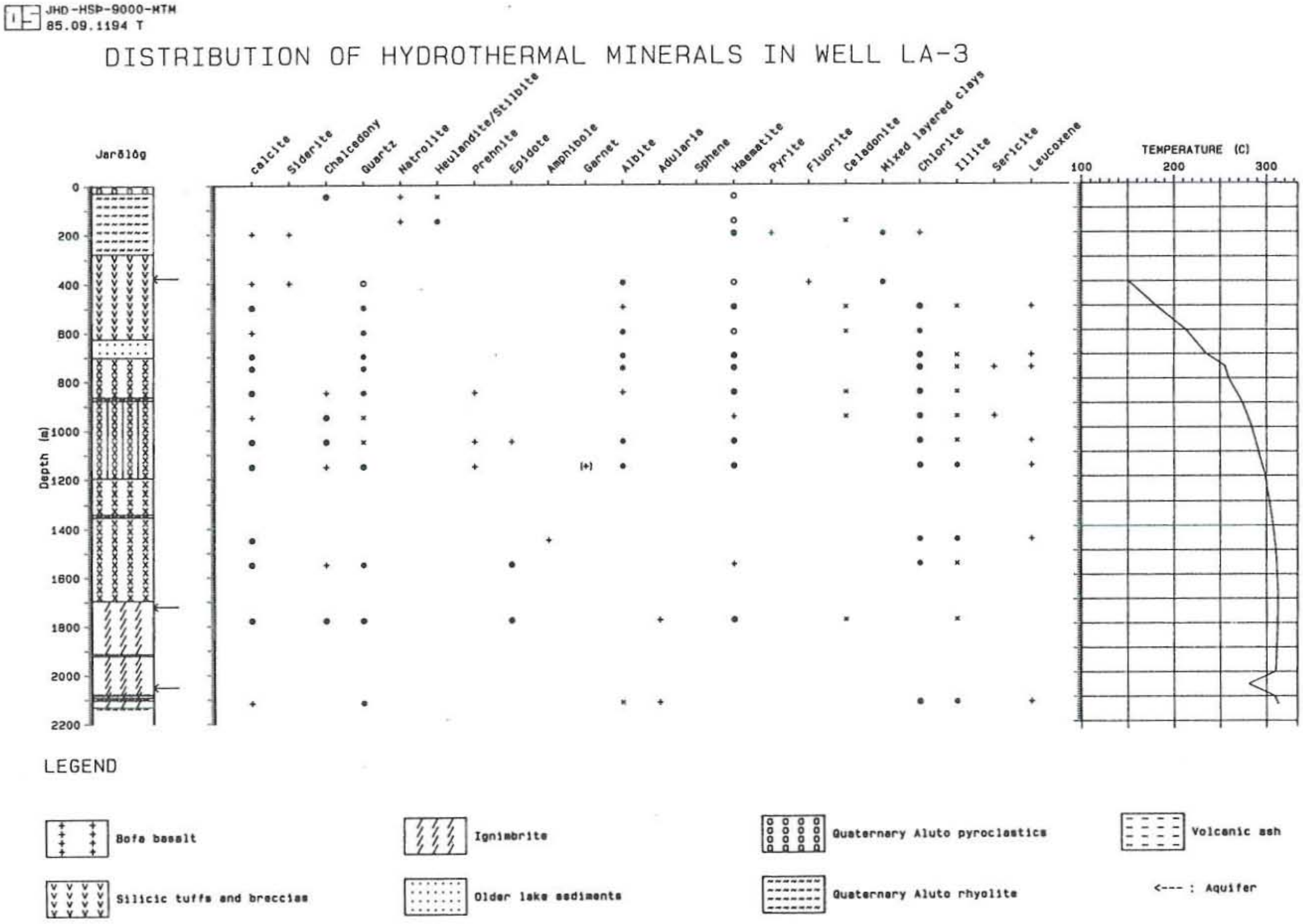


Fig. 4a Distribution of alteration minerals, temperature profile and stratigraphy of well LA-3.

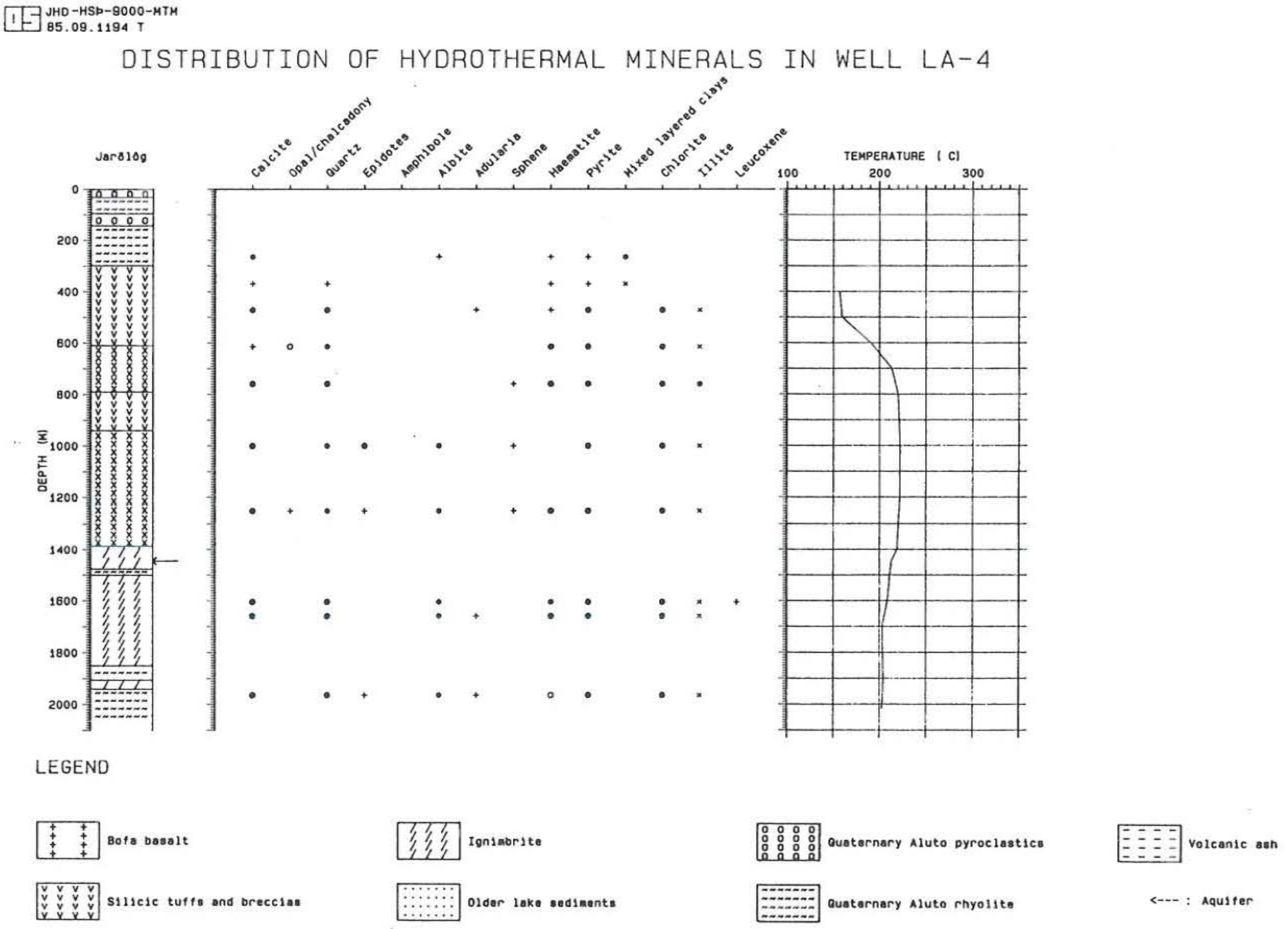


Fig. 4b Distribution of alteration minerals, temperature profile and stratigraphy of well LA-4.

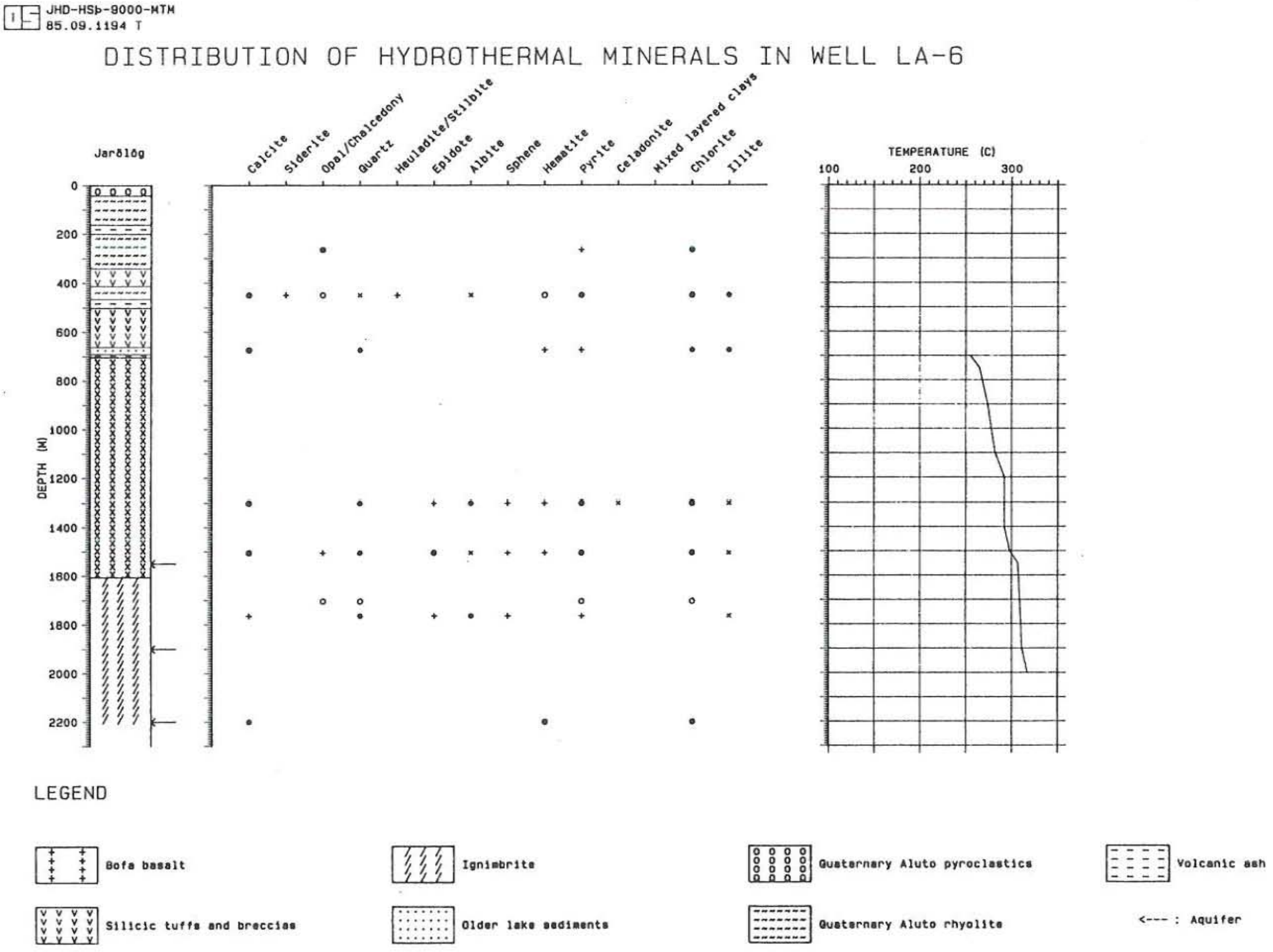


Fig. 4c Distribution of alteration minerals, temperature profile and stratigraphy of well LA-6.

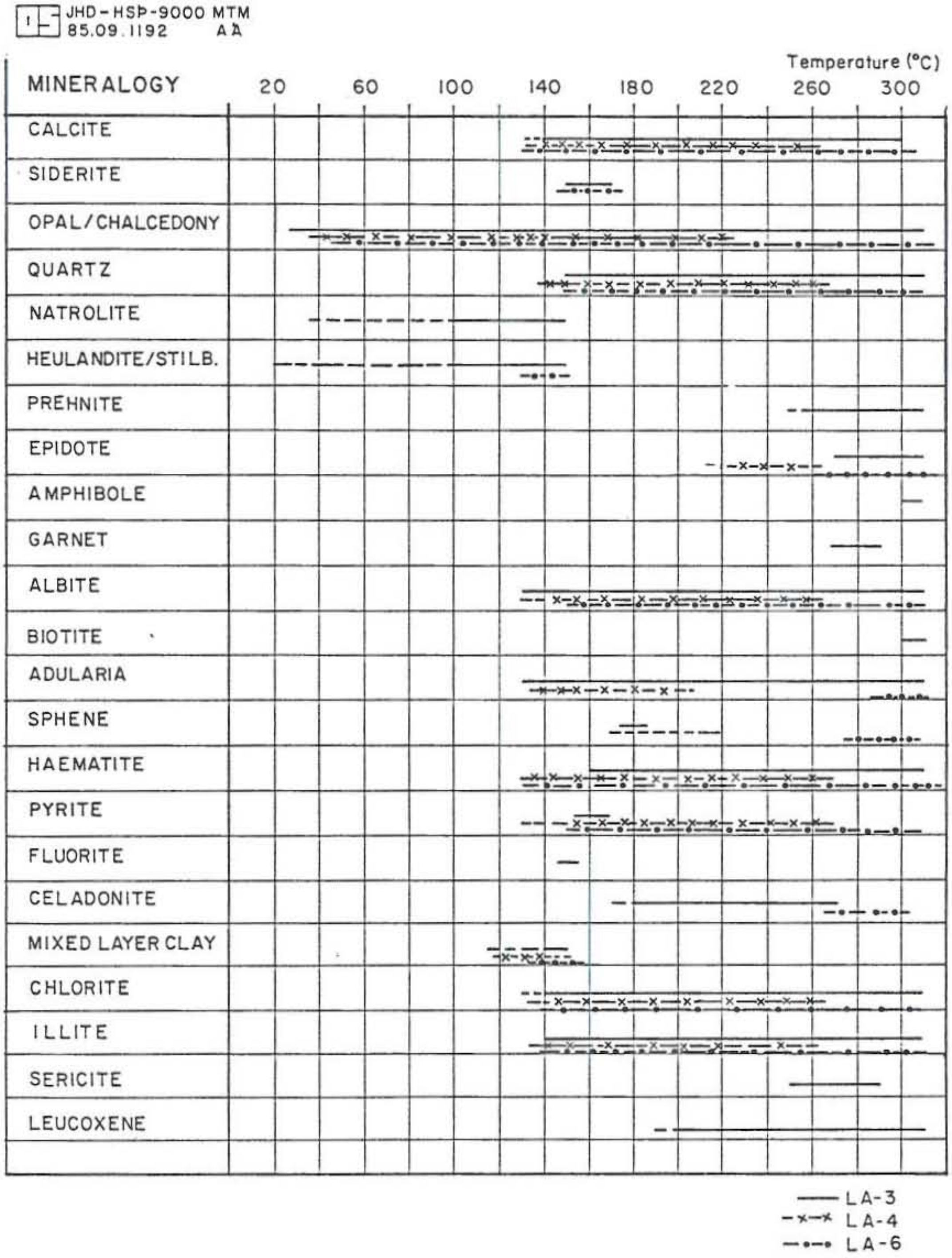


Fig. 5 Distribution of alteration minerals with temperature in wells LA-3, LA-4 and LA-6.

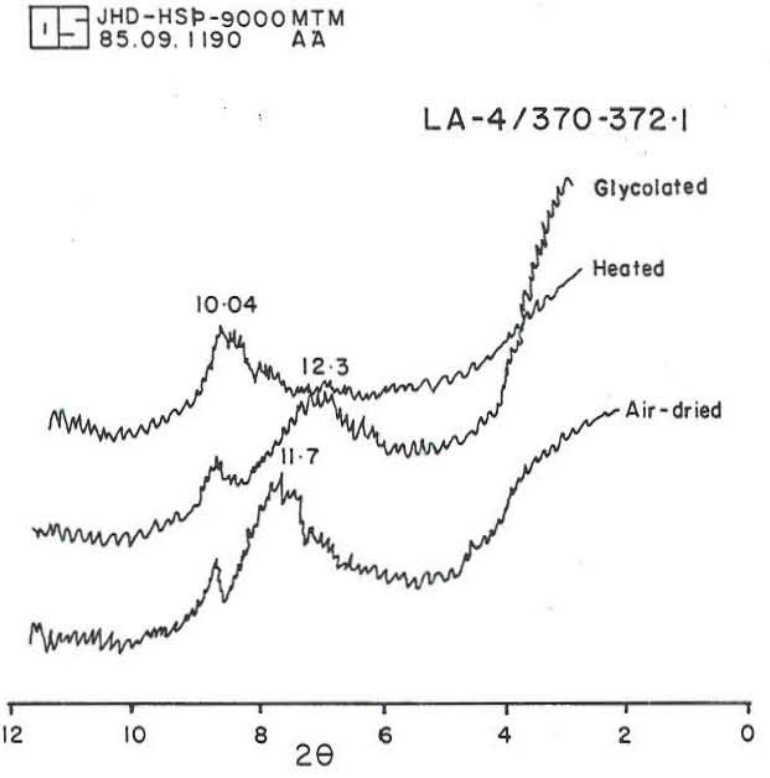


Fig. 6 X-ray diffraction pattern of mixed layer clay.

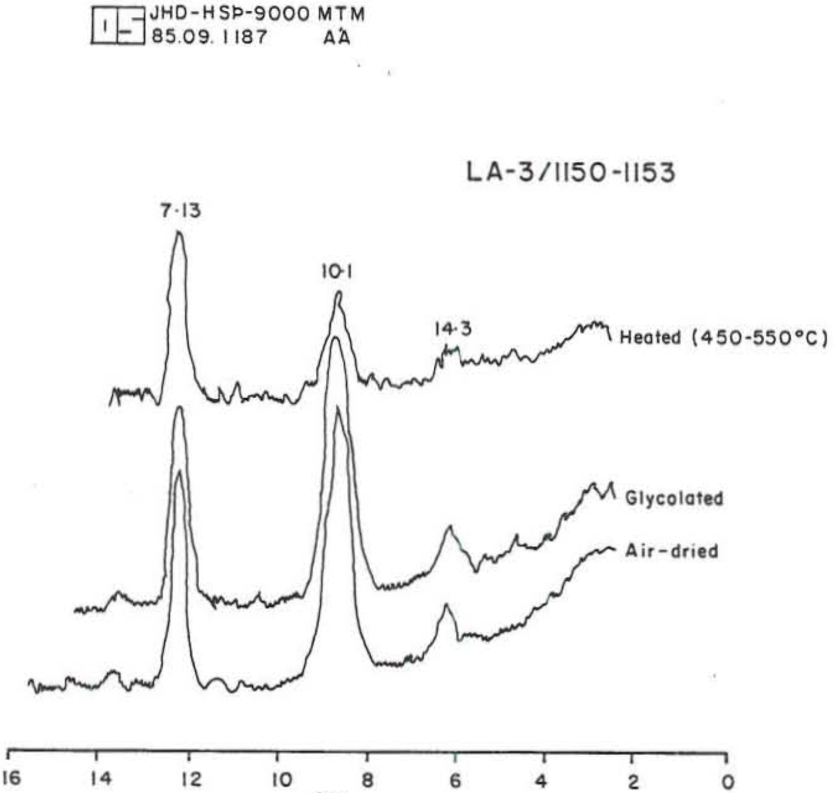


Fig. 7 X-ray diffraction pattern of Illite-Chlorite.

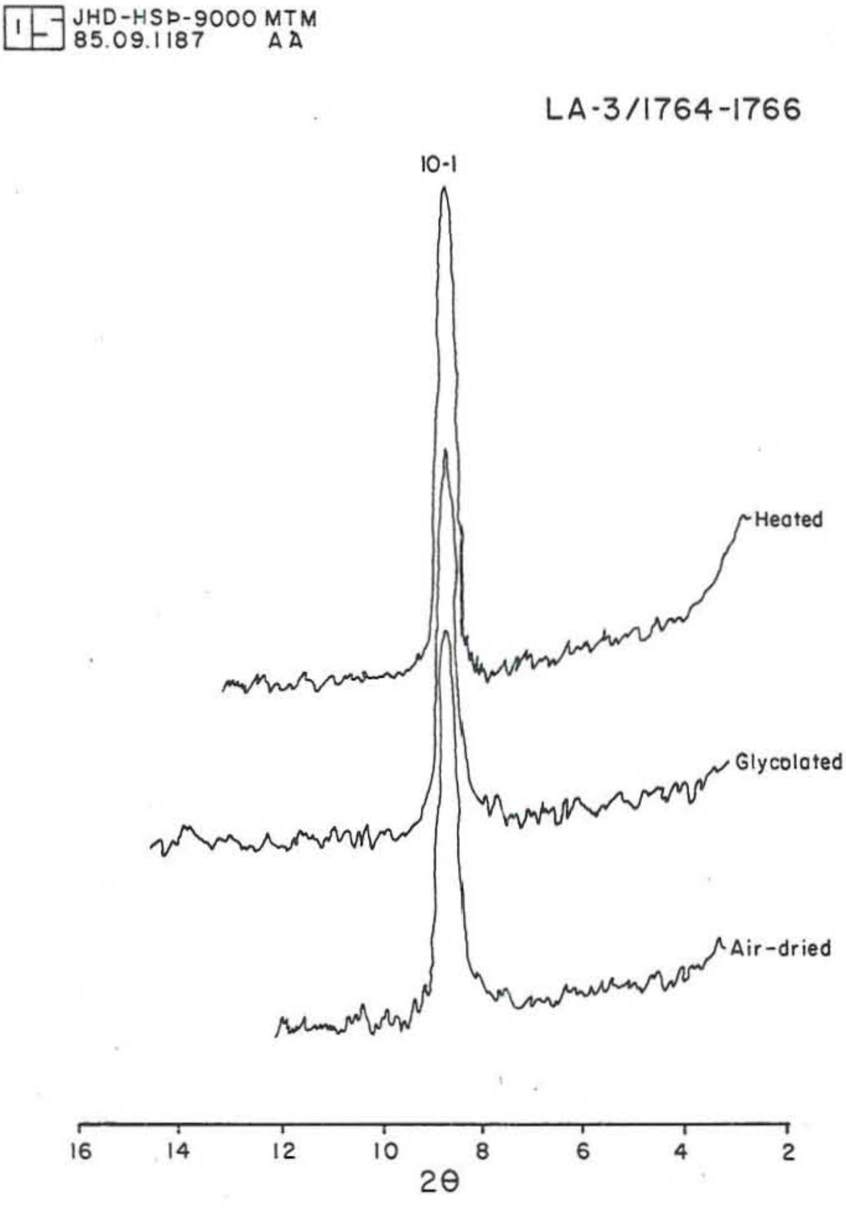


Fig. 8 X-ray diffraction pattern of Illite.

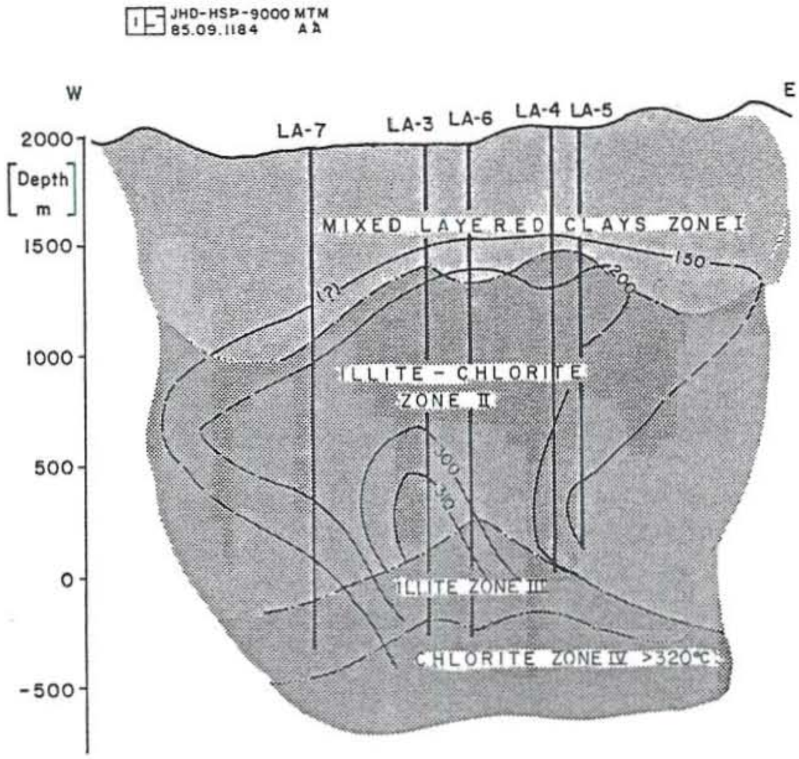


Fig. 9 Isothermal lines and clay mineral zones in LA-3, LA-4 and LA-6.

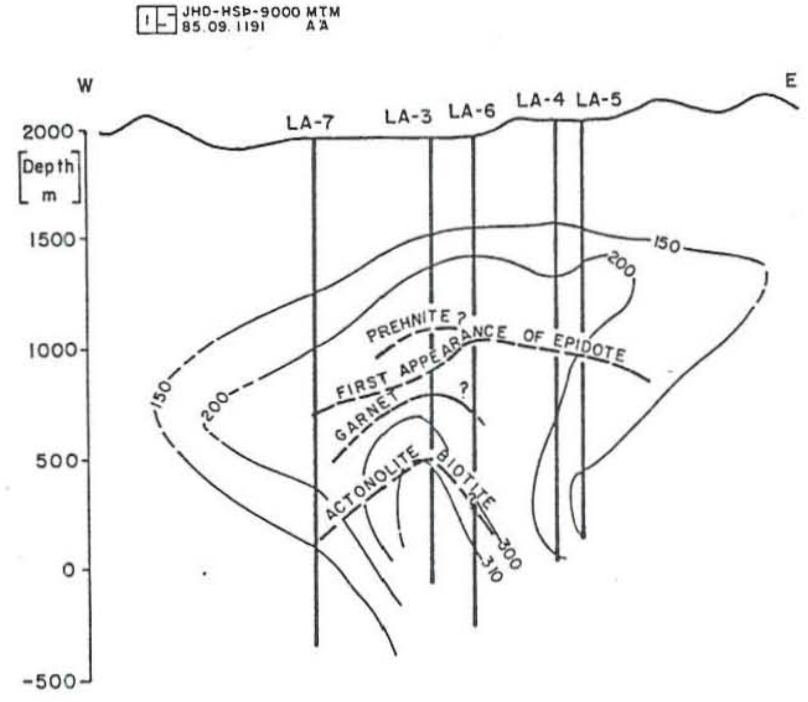


Fig. 10 Isothermal lines and the first appearance of epidote, prehnite, biotite and actinolite in wells LA-3, LA-4 and LA-6.

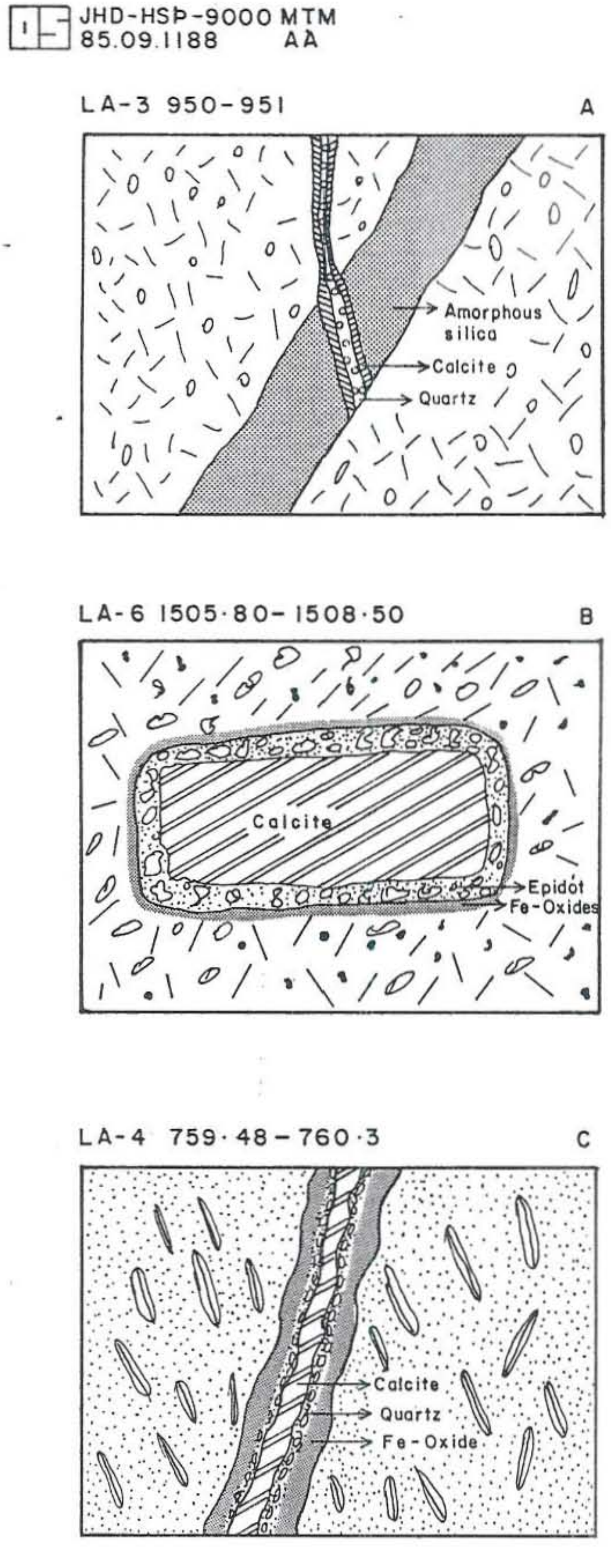


Fig. 11 Cross cutting relationships of veins and depositional sequences in an amygdale observed in core samples of LA-3, LA-4 and LA-6.

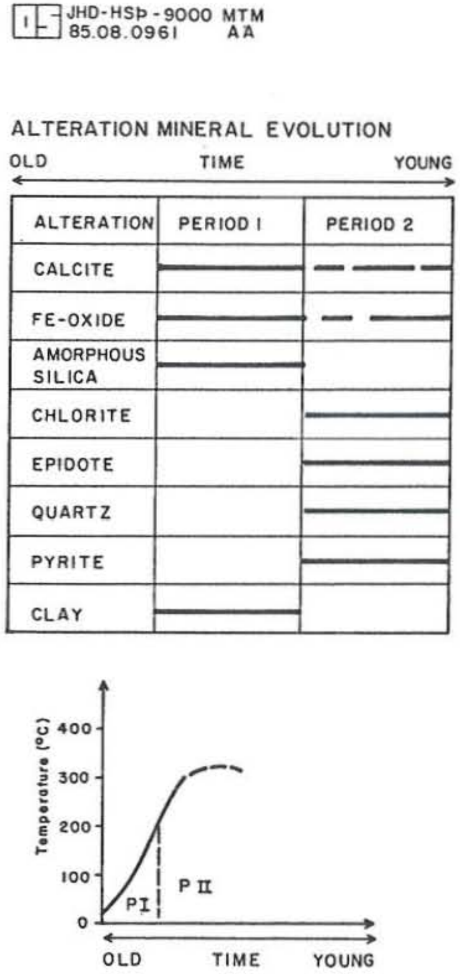


Fig. 12 Alteration evolution history.

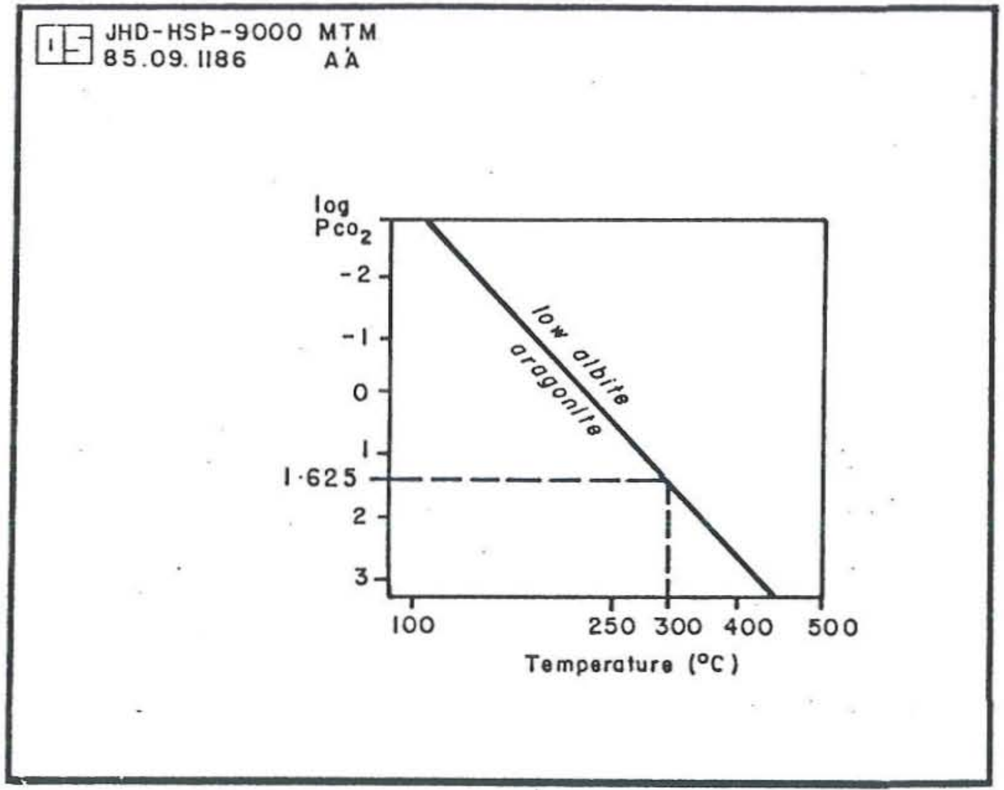


Fig. 13 Stability diagram of low albite/aragonite (from Giggenbach, 1981).

APPENDIX A: XRD results of selected core samples of LA-3, LA-4 and LA-6

Sample no. Depth in m	d(A) Air-dried	d(A) 35% humidity	d(A) Glycolated	d(A) Heated 450-550°C	Identification
			LA-4		
265-266	11.2t/10.05b/7.13t	11.5t/10.05b/7.13t	12.4t/10.05b/7.13t	9.99b/7.13t	Illite/montmorillonite Kaolinite?
370-372.1	11.3t/10.04b/7.13t	11.7b/10.04bt/7.13t	12.3/10.04t/7.13t	9.98b/7.13t	Illite/montmorillonite Kaolinite?
472-474	14.3s/10.1bt/7.13s	14.3s/10.1t/7.13s	14.2s/10.1t/7.13s	14.2s/10.1t/7.13s	Illite/chlorite
615-617	14.2t/10.1s/7.13s	14.2t/10.1s/7.13s	14.2bt/10.04s/7.12s	14.2b/10.04s/7.12s	Illite/chlorite
759-760	14.3t/10.1s/7.13t	14.3t/10.1s/7.13t	14.3t/10.1b/7.13t	14.3t/10.04b/7.13t	Illite/chlorite
1001-1002	14.3s/10.1bt/7.12s	14.2s/10.04t/7.12S	14.2t/10.1t/7.12s	14.2b/10.04b/7.12s	Illite/chlorite
1250-1251	14.2s/10.1t/7.13s	14.2s/10.1t/7.13s	14.2s/10.1t/7.13s	14.2s/10.1t/7.13s	Illite/chlorite
1603.5-1603.9	14.2t/10.1t/7.13t	14.3t/10.2t/7.13t	14.2t/10.0t/7.13t	14.2t/10.1t/7.13t	Illite/chlorite
1660.5-1662.5	14.2t/10.08t/7.13t	14.2t/10.04t/7.12t	14.2t/10.04t/7.12t	14.2t/10.04b/7.13b	Illite/chlorite
1962.9-1968	14.2t/10.08t/7.13t	14.3t/10.04t/7.13t	14.2t/10.04b/7.13b	14.2t/10.4b/7.13b	Illite/chlorite
			LA-6		
450-451	11.3b/10.04t/7.13t	11.7b/10.04t/7.13t	12.3b/10.04b/7.13t	9.99b/7.13t	Illite/montmorillonite Kaolinite?
673-677	14.3s/10.1b/7.13s	14.3b/10.2b/7.13s	14.3s/10.1b/7.13s	14.2s/10.04b/7.13b	Illite/chlorite
1301-1304	14.3s/10.04s/7.13s	14.3s/10.04s/7.13s	14.3s/10.04s/7.13s	14.2b/10.04s/7.12s	Illite/chlorite
1505-1508	14.3s/10.1t/7.13s	14.3s/10.1t/7.13s	14.2s/10.1t/7.12s	14.3s/10.01t/7.13s	Illite/chlorite
1764-1766	10.05s	10.1s	10.1s	10.04s	Illite
2200.79-2203	14.2t/7.13t	14.2t/7.12t	14.2t/7.13t	14.2t/7.13t	Chlorite
			LA-3		
400-402	11.3b/10.04b/7.13t	11.4b/10.04b/7.13t	12.3b/10.04b/7.13t	9.98b/7.13t	Illite/montmorillonite Kaolinite?
500-502	14.2t/10.04s/7.13t	14.2t/10.04s/7.13t	14.2t/10.04s/7.13t	14.2t/10.04s/7.13t	Illite/chlorite
602-604	14.2t/10.1b/7.13s	14.2t/10.1b/7.13s	14.2t/10.1b/7.13s	14.2t/10.04b/7.13b	Illite/chlorite
700-702	14.3t/10.4b/7.13s	14.3t/10.1b/7.13s	14.2b/10.1b/7.13s	14.2b/10.1b/7.13s	Illite/chlorite
750-752	14.3s/10.15b/7.13s	14.2s/10.2b/7.13s	14.3s/10.2b/7.1s	14.2s/10.1b/7.13s	Illite/chlorite
850-851	14.3s/10.2b/7.13s	14.3s/10.1b/7.13s	14.3s/10.1b/7.13s	14.2s/10.1b/7.13s	Illite/chlorite
950-951	14.2t/10.04s/7.13s	14.3t/10.08s/7.13s	14.3t/10.04s/7.12t	14.2s/10.04b/7.13t	Illite/chlorite
1050-1051	14.3t/10.04b/7.13s	14.3t/10.04b/7.13s	14.3t/10.04b/7.13s	14.2t/10.04b/7.12s	Illite/chlorite
1150-1153	14.2t/10.1s/7.13s	14.3t/10.1s/7.13s	14.2t/10.1s/7.13s	14.2t/10.04s/7.12s	Illite/chlorite
1449-1450	14.3b/10.1b/7.13t	14.3t/10.1b/7.13t	14.3t/10.1b/7.13s	14.3b/10.1t/7.13s	Illite/chlorite
1550-1551	14.3b/10.04b/7.13s	14.3t/10.04t/7.13s	14.2/10.1b/7.13s	14.3t/10.1b/7.13s	Illite/chlorite
1778-1779	10.1s	10.1s	10.1s	10.04s	Illite
2117-2120	10.1s	10.1s	10.1s	10.04s	Illite

APPENDIX B: Petrographic descriptions of core samples of LA-3, LA-4 and LA-6

Depth (m)	Textures	Lithological descriptions	Primary minerals	Secondary minerals	XRD analyses (primary + secondary)
			<u>LA-3</u>		
47-49	Flow banded vesicular with spherulitic groundmass texture	Rhyolite lava	K-feldspar, Sandine Quartz, Aenigmatite Magnetite, Aegerine	Natrolite, Amorphous silica	Quartz(P), Heulandite
149.4-149.8	Flow banded and pilotaxitic texture	Rhyolite lava	Sanadine (3-4m), Quartz, Amphibole, Magnetite	Natrolite, Amorphous silica	Heulandite/Stilbite, Celadonite
200-201	Flow banded with spherulitic groundmass texture rhyolite lava	Weakly altered	Sanadine, Amphibole Plagioclase, Magnetite, Quartz	Calcite, Siderite, Chlorite, Pyrite	Quartz(P), Haematite
400-402	Sparcely porphyritic	Moderately altered vitric to crystal vesicular tuff	Plagioclase, K-feldspar	Albite, Calcite, Chlorite, Clays Haematite	Albite, Mixed layered clays (I-M), Kaolinite?
500-502	-	Moderately to highly altered vitric to crystal tuff	Plagioclase, Magnetite/Ilmenite, Quartz	Albite, Calcite, Chlorite, Clays, Haematite	Quartz, Calcite, Celadonite, Illite Chlorite
602-604	-	Moderately altered vitric to crystal tuff	Plagioclase	Calcite, Chlorite, Quartz, Albite	Calcite, Illite Chlorite
700-702	Fine grained subophitic groundmass texture	Highly altered fine grained non vesicular olivine basalt	Plagioclase (An50-53), Olivine, Magnetite, Pyroxene	Calcite, Chlorite, Haematite, Albite, Leucoxene, Quartz	Quartz, Albite, Calcite, Illite, Chlorite
750-752	Fine grained and fluidal texture on the groundmass	Highly altered fine grained olivine basalt	Plagioclase, Olivine, Magnetite, Ilmenite	Albite, Sericite, Calcite, Haematite, Iddingsite, Clay	Quartz, Calcite, Albite, Illite, Chlorite
850-851	Due to intensive alteration it is hard to identfy the original texture	Highly altered, intensively fractured basalt	Plagioclase, Olivine, Pyroxene, Magnetite/Ilmenite	Calcite, Chlorite, Albite, Haematite, Leucoxene, Quartz, Amorphous silica, Prehnite	Quartz, Calcite, Celadonite, Illite, Chlorite
950-951	Fine grained non vesicular fine grained basaltic breccia	Moderately to highly altered	Plagioclase Albite, Illite,	Sericite, Calcite, Illite, Chlorite Quartz, Haematite	Quartz, Celadonite,

Depth (m)	Textures	Lithological descriptions	Primary minerals	Secondary minerals	XRD analyses (primary + secondary)
			LA-3 cont.		
1050-1051	Fine grained sparcely porphyritic	Highly altered basaltic breccia	Plagioclase, Magnetite, Olivine	Quartz, Prehnite, Epidote Calcite, Albite, Chlorite Calcedony, Clay	Quartz, Calcite, Illite, Albite, Chlorite
1150-1153	Fine grained	Highly altered basaltic breccia	Plagioclase, Olivine, Magnetite, Ilmenite	Calcite, Chlorite, Haematite, Albite, Clay, Prehnite, Garnet, Calcedony, Illite	Quartz, Calcite, Albite, Illite, Chlorite
1449-1450	Porphyritic with subophitic texture	Weakly altered porphyritic olivine basalt (Intrusive?)	Plagioclase (labradorte), Olivine, Pyroxene	Calcite, Chlorite, Illite, Quartz, Biotite, Actinolite	Quartz, Illite, Calcite, Chlorite
1550-1551	Fine grained	Altered volcanic ash	-	Quartz, Haematite, Calcite, Illite, Chlorite, Chalcedony	Quartz, Calcite, Illite, Chlorite
1650-1651	Fine grained	Moderately altered basaltic (volcanic) ash	Plagioclase, K-feldspars	Calcite, Chlorite, Epidote, Albite, Haematite, Quartz	Quartz, Albite, Illite, Chlorite
1778-1779	Porphyritic	Moderately altered welded tuff	K-feldspars, Plagioclase	Calcite, Albite, Illite, Clays, Haematite, Epidote, Adularia	Quartz, Calcite, Illite
2117-2120	Fine grained	Moderately to highly altered rhyolite	K-feldspar, Magnetite/Ilmenite	Calcite, Adularia, Albite, Leucoxene, Illite,	Quartz, Albite, K-feldspar, Illite
			LA-4		
265-266	Fluidal and spherulitic texture on the groundmass lava	Moderately altered rhyolite	K-feldspar (sanadine) Quartz, Plagioclase	Calcite, Albite, Clays Pyrite, Haematite, Adularia ?	Mixed layered clays
472-474	Porphyritic	Highly altered vitric to crystal tuff	K-feldspar (sanadine) Plagioclase	Albite, Adularia? Calcite, Amorphous silica, Haematite, Chlorite, Pyrite, Quartz	Quartz, Kaolinite? Mixed layered clay
615-617	Due to intensive alteration it is hard to identify original texture	Highly altered basalt	Olivine, Pyroxene, Plagioclase	Quartz, Pyrite, Illite, Calcite, Chlorite, Sericite, Haematite	Quartz, Illite, Chlorite

Depth (m)	Textures	Lithological descriptions	Primary minerals	Secondary minerals	XRD analyses (primary + secondary)
			LA-4 cont.		
759-760	Porphyritic	Moderately to highly altered basalt	Plagioclase (An50-53), Magnetite	Calcite, Chlorite, Haematite, Quartz, Pyrite, Illite, Sphene	Quartz, Calcite, Illite, Chlorite
1001-1002	Fine grained and vesicular	Highly altered basalt	Plagioclase, Olivine, Pyroxene, Magnetite	Calcite, Chlorite, Haematite, Epidote, Quartz, Pyrite	Quartz, Albite, Calcite, Illite, Chlorite
1250-1251	Porphyritic and subophitic	Moderately altered olivine basalt	Plagioclase (labradorite), Olivine, Pyroxene	Calcite, Chlorite, Albite, Iddingsite, Epidote, Amorphous silica, Quartz, Pyrite	Quartz, Clacite, Albite, Chlorite
1603.5-1603.9	Fine grained	Moderately altered crystalline tuff	Plagioclase	Quartz, Pyrite, Illite, Calcite, Albite, Chlorite, Haematite	Quartz, Albite, Illite, Chlorite
1660-1662	Porphyritic	Moderately altered and highly oxidized rhyolite lava	K-feldspars (sanidine, microcline)	Albite, Illite, Calcite, Haematite, Quartz, Chlorite	Quartz, Albite, Calcite, Illite, Chlorite
1962-1968	Porphyritic	Moderately altered rhyolite lava	K-feldspars	Quartz, Illite, Pyrite, Caclite, Adularia, Epidote	Quartz, Albite, Illite, Calcite, Chlorite
			LA-6		
238-240	Porphyritic and fluidal texture groundmass	Weakly altered rhyolite lava	K-feldspar (sanadine), Aegerine, Magnetite, Quartz,	Haematite	-
450-451	Fluidal and spherulitic texture	Moderately to highly altered porphyritic rhyolitic breccia	Quartz, K-feldspar (sanadine)	Calcite, Siderite, Haematite, Pyrite, Clay	Quartz, Calcite, Albite, Mixed layered clay
677-679	Fine grained	Weakly altered muddy siltstone	Quartz, Plagioclase	Pyrite, Haematite, Clacite, Clay	Quartz, Calcite, Illite, Chlorite
1301-1304	Fine grained	Highly altered rhyolitic ash	Plagioclase, Quartz, Magnetite	Calcite, Quartz, Chlorite, Haematite, Epidote, Albite, Clay, Pyrite, Sphene	Quartz, Albite, Celadonite, Illite, Chlorite

Depth (m)	Textures	Lithological descriptions	Primary minerals	Secondary minerals	XRD analyses (primary + secondary)
			LA-6 cont.		
1505-1508	Microporphyritic and vesicular	Highly altered basalt	Plagioclase (labradorite), Olivine, - Pyroxene	Calcite, Chlorite, Albite, Haematite, Clays Pyrite, Sphene, Amorphous silica	Quartz, Albite, Calcite, Illite, Chlorite
1764-1766	-	Moderately altered crystal tuff	Feldspars, Magnetite	Albite, Clacite, Adularia, Epidote, Pyrite, Sphene, Quartz	Quartz, Albite, Sphene
2200-2203	Very fine grained	Siltstone (sediment)	Feldspars, Quartz	Calcite, Haematite	Quartz(p), Chlorite