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BOREHOLE GEOLOGY OF WELL LH2
IN LAHENDONG HIGH TEMPERATURE AREA
NORTH SULAWESI INDONESIA

Kartijoso Soemodipoero*
UNU Geothermal Training Programme
National Energy Authority
Grensasvegur 9, 108 Reykjavik
ICELAND

*
Permanent address:
Volcanological Survey of Indonesia
Geothermal Division
JL. Diponegoro 57, Bandung
INDONESIA

ABSTRACT

A description is given of the borehole geology of a 228 m deep drillhole, LH2, in the Lahendong high temperature area, North Sulawesi, Indonesia. The drillhole penetrated a total of 17 stratigraphic horizons, which were predominantly andesite and basaltic andesite lavas with interbedded tuff layers of similar compositions. The alteration minerals define four zones: zone I is characterized by quartz-anhydrite (3-6 m); zone II contains epidote-anhydrite- swelling chlorite extending down to 40 m; zone III contains stilbite- smectite which extends to about 145 m; zone IV contains anhydrite-swelling chlorite. The alteration state of primary rock constituents complies well with the above zoning as they show a higher degree of alteration above 50 m and below 150 m than in the intervening depth interval. The alteration zonation suggests that, at least in the strata disected by LH2, the hydrothermal aquifers are controlled by sub-vertical fractures. This agrees well with the surface thermal manifestations. The minimum temperature of over 200°C expressed by the occurrances of epidote, swelling chlorite and albite in zone II does not agree with the temperatures experienced at drillsite and are thus assumed to be relic.

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1 INTRODUCTION

1.1 Scope of study

The author of this report was awarded an UNU Fellowship to attend the 1982 UNU Geothermal Training Programme at The National Energy Authority of Iceland. The Training Programme is supported by the United Nations University and the Government of Iceland.

The training started with an introductory lecture course which lasted for about 5 weeks and covered various aspects of geothermal sciences such as, geological exploration, borehole geology, geophysical exploration, borehole geophysics, geochemistry, geohydrology, reservoir engineering and geothermal utilization. Seminars held by the UNU Fellows dealing with geothermal research in their respective countries were also a part of the introductory lecture course.

The specialized part of the Training Programme included the following main subjects: Training on a drillsite in the duties of a borehole geologist (2 weeks), preparation of drillcuttings for binocular stereo-microscopic inspection and thin sections (1 week), training in binocular microscopic analysis of cuttings (2 weeks) and petrographic analysis (5 weeks), a brief introduction into the techniques of X-ray diffraction analysis of alteration minerals (1 week) and excursions to the main geothermal fields in Iceland (2 weeks).

The samples used during the specialized training were mainly cuttings from the exploration drillhole LH2 in the Lahendong high temperature area. This report which was composed during the last 6 weeks of the training period and is based on the data from the above cuttings analyses. After the completion of this report the author, along with the other 1982 UNU Fellows, will visit the main geothermal fields of Italy before returning to his home country of Indonesia.

1.2 Outline of geothermal investigations in Lahendong

Although geothermal exploration in Indonesia started in the last century under the Netherland East Indies, it was not until about 1926 that the actual geothermal investigation started by exploratory drilling at the Kawah Kamojang geothermal field in West Jawa, about 40 km southeast of Bandung (Zen and Radja, 1970; Healy, 1975).

A systematic survey of geothermal manifestations and inventory works started in 1969 as a part of the First Five-Years Plan Project of the Geological Survey of Indonesia; the survey covered detailed geological mapping, air photo interpretation, geochemical-, geoelectric-, and gravity surveys, and thermal gradient surveys of a number of prospective geothermal fields (Bachri, 1977). The Lahendong field is one of the high temperature geothermal manifestations in the Minahasa District, North Sulawesi. The geothermal area is mainly confined to a large explosion crater which includes a subsidence structure. This subsidence structure is to some extent occupied by an acid water lake (Linau Lake). The rocks underlying this area are believed to be lavas, tuffs and breccias of intermediate composition (Basoeki and Radja, 1979).

Based on the result of preliminary surveys of geothermal manifestations within the Lahendong area one exploration well (LH1) was sited and drilled near the lake in 1979. Its purpose was to investigate the underlying reservoir. At a depth of 327 m the well intersected a large aquifer with a wellhead pressure and temperature surpassing 20 kg/cm^2 and about 200 °C repectively. This led to a blow-out and the hole had to be abandoned leaving the drillstring in the hole. Due to this mishap in LH1, it was decided to drill another exploratory well (LH2), about 100 m northeast from LH1 but at the same elevation. The main purpose was to get more information on the reservoir. This time the drill rig was, however, equipped with an automatic blow-out preventer at the wellhead. The hole is planned to reach down to about 450 m. But as it is at present being drilled, the data presented here is based on cuttings from the upper 228 m of the hole. This is the first serious drilling operation undertaken by the Volcanological Survey of Indonesia in geothermal investigation.

1.3 Summary of the geology of North Sulawesi and the Minahasa district

The Minahasa district is situated (Fig. 1) at the sinuosly outlined north arm of Sulawesi, which structurally is considered to be the volcanic inner arc of a Tertiary orogenic system. The highly volcanically active Minahasa district lies within this inner arc. This arc joints the volcanic Sangihe Ridge to the east, which in turn connects Sulawesi with Mindanao in the Philippine archipelago (Bemmelen, 1949; Hamilton, 1979).

The volcanism in the Minahasa district has been active till Recent times. The district is mostly covered by Quaternary volcanics with the upper Quaternary predominating and with lower Quaternary volcanics only appearing at the eastern bank of Tondano Lake (about 10 km east of Lahendong). Surface geological mapping shows these Quaternary volcanic rocks to consist of tuffs, lavas, and pyroclastics. The volcanic rocks of the Minahasa district are derived mainly from a group of volcanoes. Lahendong is situated in the central part of this group. As with Lahendong, geothermal manifestations are associated with many of these volcanic complexes (Bemmelen, 1949; Jonsson, 1976). No volcanic activity has been reported in historical time, but they are though believed to be geologically young.

1.4 Outline of the geology and electrical resistivity in the Lahendong geothermal area

A geological map of the Lahendong high temperature area is shown in Fig. 2 (from Bachri, 1977). It shows that the

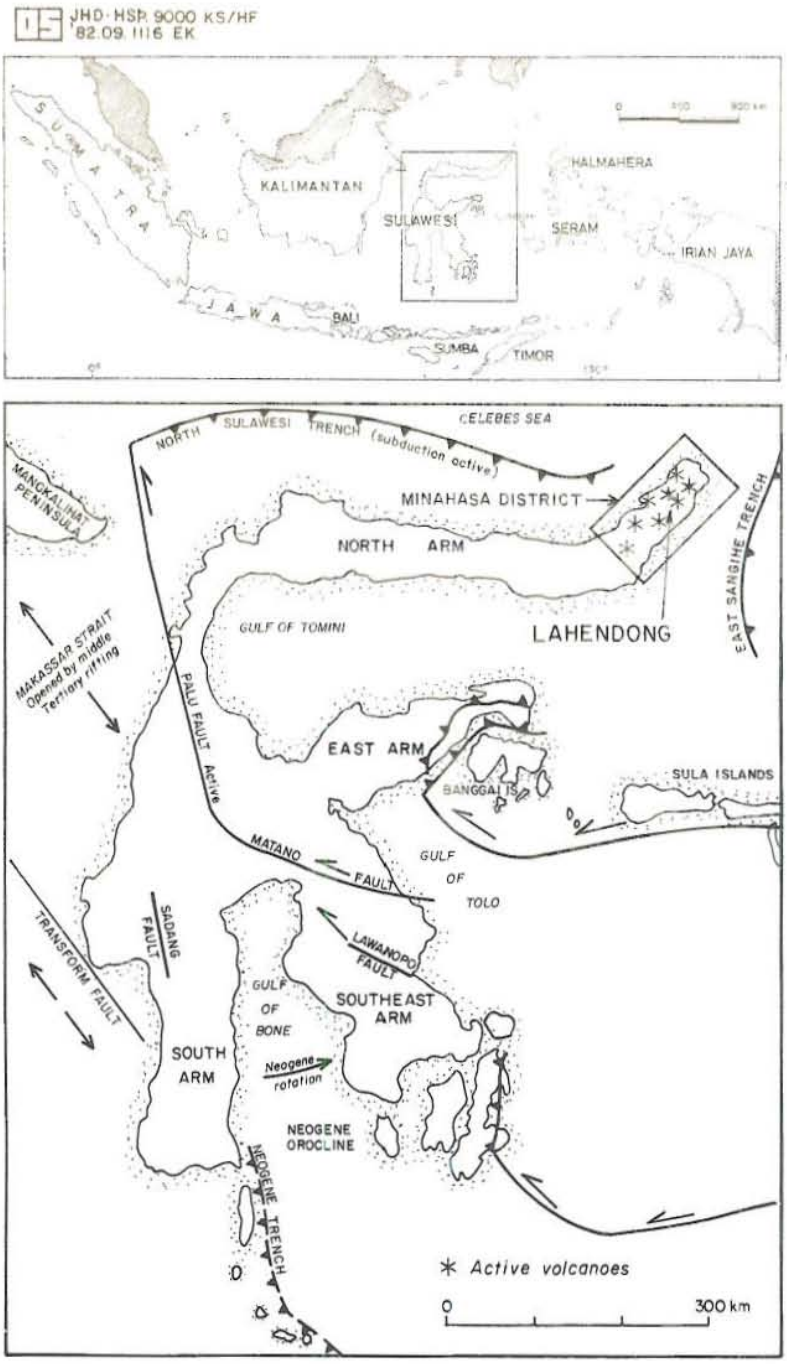

Fig.1 SOME MAJOR STRUCTURAL ELEMENTS OF SULAWESI. ARROWS ILLUSTRATE LOCAL RELATIVE MOTIONS.
(from Hamilton 1979)

base of the Lahendong volcanic complex consists of Neogene pyroclastic rocks overlain by the products of Quaternary volcanics which include andesite lavas, breccias and welded tuffs. Lavas of basaltic andesite compositions are also common and their main mafic constituents are olivine and pyroxene. Most of these lavas are brecciated, and these brecciated zones have sometimes been preferentially altered by geothermal alteration.

The dominant tectonic structure in the Lahendong area (Fig. 2) is a large explosion crater approximately 1 km wide, which on the surface is observed as a circular caldera subsidence feature, and surrounded by a tuff cone ring (Jonsson, 1976; Bachri, 1977). At present the depression is largely occupied by an acid water lake. The native name of this lake is Danau Linau (Linau Lake). There are several hot springs, steaming grounds, mini-geysers, solfataras and fumaroles, with temperatures ranging from 70 to 90 °C. Most of these active manifestations coincide with two NE-SW striking faults one of which cuts the caldera faults. The latter fault has a displacement of several meters. Although not shown in Fig. 3 relic hydrothermal alteration is found along much of the caldera rim.

The main features of the resistivity mapping of the Lahendong geothermal field are shown in Fig. 3 (Marino, 1977). The location of the resistivity cross section is shown in Fig 2. Below the drill site there are two important resistivity layers. The upper one has a resistivity of 2.5-5 ohmm and is interpreted as being a liquid dominated zone. A lower layer which has a considerably higher resistivity of 50-60 ohmm, is believed to represent a boiling (two phase) geothermal reservoir. The upper boundary of the two phase zone, as based on this resistivity mapping and data from the drillhole LH1, is believed to lie at approximately 320-330 m depth.

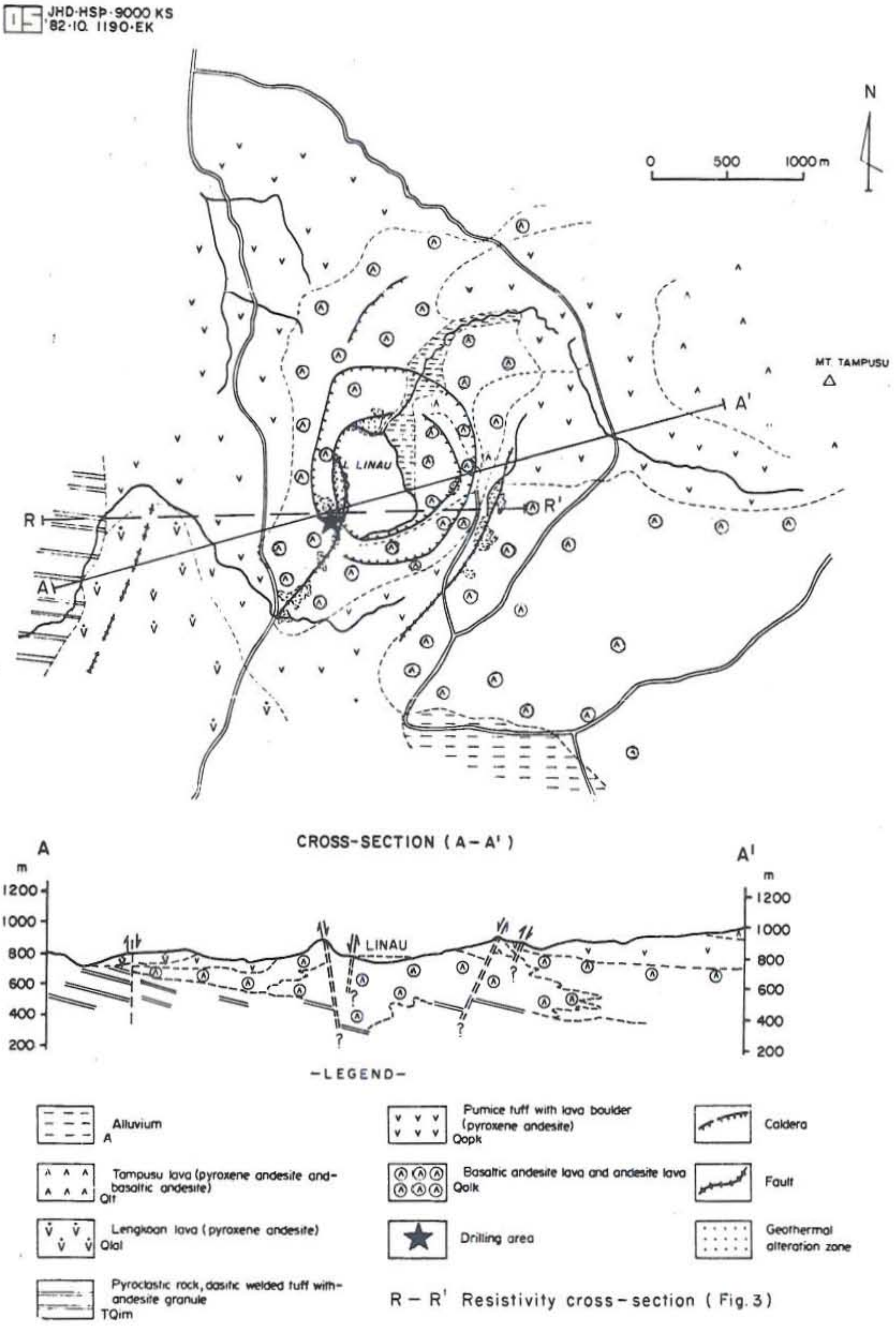

Fig. 2 GEOLOGICAL MAP AND CROSS-SECTION OF THE LAHENDONG HIGH-TEMPERATURE AREA. (*Bachri 1977*)

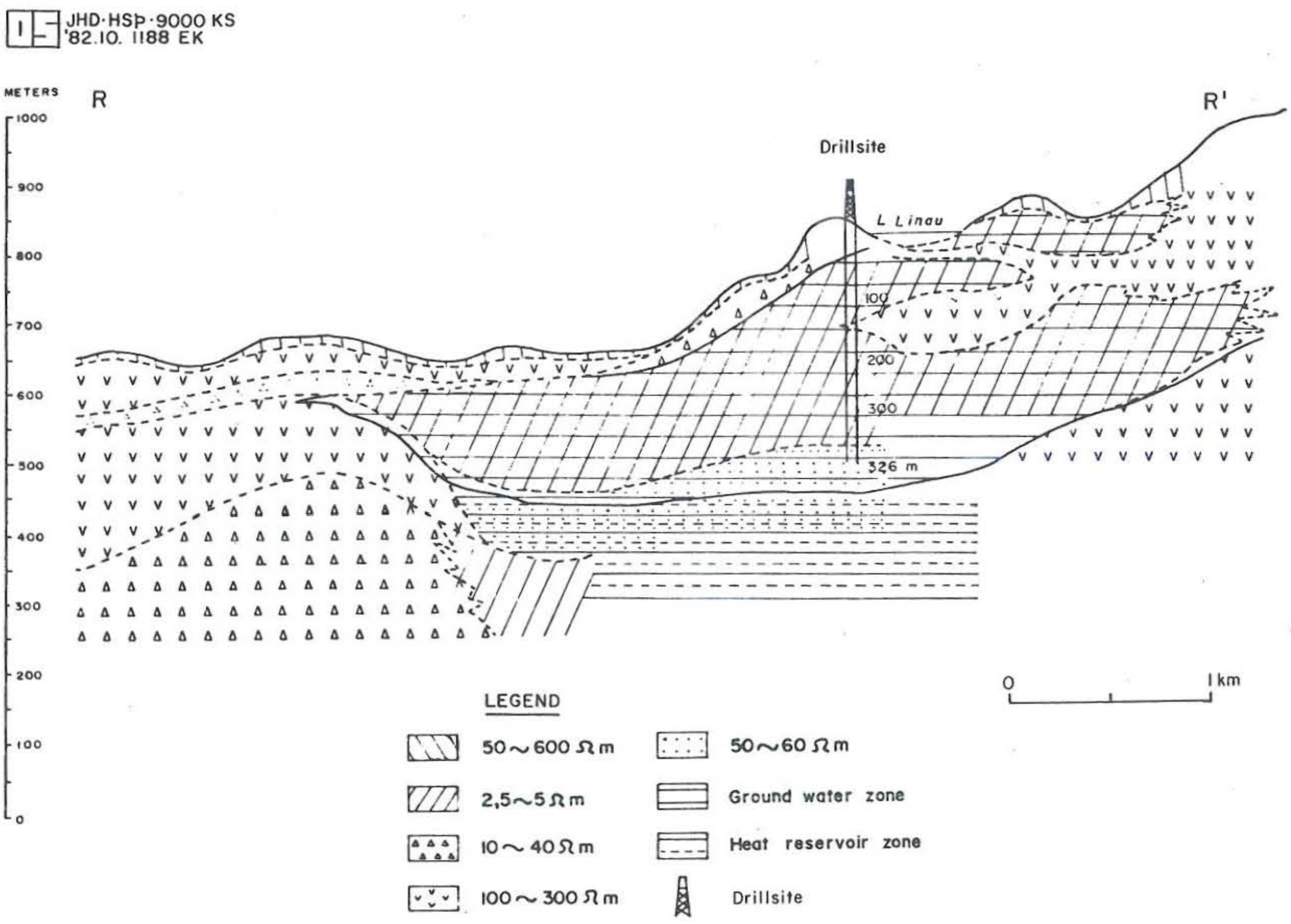

Fig. 3 RESISTIVITY CROSS-SECTION OF THE LAHENDONG HIGH-TEMPERATURE AREA. (*Marino 1977*)

2 BOREHOLE GEOLOGY OF WELL LH2

2.1 Drilling history

As mentioned previously the LH1 was the first hole to be drilled in the Lahendong high-temperature field. At a depth of 326 m the drillhole intersected a powerful aquifer which could not be put under control, and this led to a blow-out. The drill strings became stuck and had to be left behind in the hole. Due to the limited success of LH1 it was decided to drill the second hole, LH2, in the same area at a distance of about 100 m northeast of drillhole LH1.

Due to the softness of the surface soil cover it was deemed necessary to groute the drillsite down to about 15-40 m prior to the drilling. The cellar measures 2,5m x 2,5m and is 1.5 m deep. The drill used was a Cardwell H-50, made in USA in 1952.

A 30 cm thick surface compaction was layed for the 30 tons Cardwell H-50 drilling rig and other equipment (e.g. mud and water tanks, pumps and engines). The hole was rotary drilled down to 45 m with 17 1/2" bit, and cased with a 13 3/8" casing to a depth of 41 m. The drilling continued with a 12 1/2" bit to 123 m after which the 9 5/8" anchore casing was lowered to 116 m depth. The drilling continued using 8 1/2" bit down to 228 m, after which the production casing of 5 1/2" was lowered down to 202 m depth. The surface, anchore and production casings were all successfully cemented after the drilling reached respective depths. During cementing the cement slurry was pumped down through the drillstring using a bottom hole plug, and thus forcing the cement up at the outside of the casing to surface. Drilling mud was used for circulation fluid as high viscosity and density drilling mud is more effective to put high pressure aquifers under control than if water had been used as circulation fluid.

It took 8 months to drill the first 228 m of well LH2. This anomalously long drilling time of eight months can mainly be attributed to the age and poor condition of the drilling equipment resulting in several breakdowns which often took a long time to repair due to inaccessibility of spare parts.

One of the more serious difficulties occurred at a depth of about 150 m where the drillstring became stuck. Prior to this happening, the cuttings from the hole were showing increasing rounding. This could indicate that it was taking the cuttings too long time to reach surface, either, due to large cave formation in which the cuttings had an extended stop on the way to surface, leading to concentration of cuttings and slumping around the drillpipe, or that the rate of fluid circulation in the hole was too low similarly leading to a stuck drillstring. The drillstring became unstuck by lowering a 5 1/2" casing into the hole and increasing the circulation and thus flushing the cuttings to surface. Subsequently the 5 1/2" casing was removed.

A circulation loss of about 10.5 l/s occurred at 228 m depth, but it was successfully blocked by heavy mud. Following that a 5 1/2" casing was run into the hole and cemented. As previously mentioned it is planned that the hole will be drilled down to about 450 m depth, but at the time of writing this report the depth is still at about 228 m.

The penetration rate during drilling was slightly variable depending on the sizes of drillbits, pressure load and of course on the hardness of the rock formation being drilled into.

2.2 Stratigraphy

The following stratigraphic description is based on the analysis of cutting samples which were collected at about 3 m intervals during the drilling. The analytical techniques used were the binocular stereo microscope and 26 petrographic analyses of thin sections of selected samples. The correlation of the stratigraphy of LH2 with that of LH1 was not possible, the main reason being that the cuttings were not analysed in the same manner as was done in this study. Fig. 4 shows the stratigraphic sequence of LH2.

Layer 1 (3-6 m): This layer consists of a moderately altered glassy to fine grained nearly aphyric breccia of probable andesite composition. Rare plagioclase and augite phenocrysts. The rock is relatively porous with many of the pores filled by secondary minerals such as quartz and clays. In thin section it was observed that some of the plagioclase and augite phenocrysts show slight indications of alteration. Beside quartz, anhydrite is also present.

Layer 2 (6-23 m): Very fine grained equigranular and porphyritic andesite lava. The phenocryst species are mainly plagioclase (andesine), hypersthene and augite along with rare magnetite and biotite. The top part of the lava is brecciated but becomes more compact and better crystallized lower down. Flow texture is conspicuous. The main part of the lava is relatively fresh but some parts show a considerable alteration. The main alteration minerals are quartz, pyrite and clay but less commonly found are anhydrite, calcite, barite and epidote. Vesicles are largely filled with clay-minerals and quartz, as are the veins.

Layer 3 (23-48 m): Very fine to fine grained equigranular and porphyritic andesite. The phenocrysts are mainly plagioclase (andesine), augite and hypersthene. The top of the layer is quite porous and appears to be brecciated but grades downwards into more compact and holocrystalline rock. Flow texture is common. The alteration is heterogeneous, in some cuttings the plagioclase and pyroxene are quite fresh while in others they are partially altered. Quartz and clay-minerals are the most common alteration products, but also found are pyrite, calcite, anhydrite, gypsum, barite, epidote and prehnite. Where epidote is found in veins or vesicles it is observed to have crystallized later than calcite and quartz.

Layer 4 (48-60 m): This 12 m thick unit is a light coloured aphyric tuff. In thin section the glass is seen to have altered mostly into clays, some pyrite and quartz. Other alteration minerals are stilbite and calcite.

Layer 5 (60-66 m): A glassy to medium crystalline and porphyritic basaltic andesite breccia. Plagioclase phenocrysts (labradorite) are abundant but augite and hypersthene rare. The rock is highly vesicular. The rock is considered to be relatively fresh as most of the plagioclases and pyroxenes are unaltered. The secondary minerals of quartz, pyrite, calcite, clays and stilbite are commonly found.

Layer 6 (66-87 m): This basaltic andesite layer is different from layer 5 on grounds of the aphyric nature of the former. In layer 6 sparse microphenocrysts of plagioclase (labradorite) and pyroxene are observed. The rock is considered to be relatively fresh as seen by the nearly unaltered state of the plagioclase and pyroxene. Alteration minerals are pyrite, calcite, quartz, clays and stilbite.

Layer 7 (87-96 m): The top of this layer is brecciated but grades downwards into a finely crystalline and less vesicular rock. Its composition is believed to be andesitic on grounds of the andesine microphenocrysts, but hypersthene and augite phenocrysts are also present. The rock is relatively fresh. The main alteration minerals are quartz, calcite, pyrite, clays and stilbite.

Layer 8 (96-110 m): The andesine composition of the sparse plagioclase phenocrysts infers that this light coloured tuff is andesitic in composition. Rare hypersthene phenocrysts are also seen. The glass is all altered but the primary minerals, where present, appear to be largely unaffected by alteration. The main alteration minerals are pyrite, quartz, calcite, and clays.

Layer 9 (110-118 m): Fine to medium crystalline porphyritic basaltic andesite. Plagioclase (labradorite) phenocrysts are very common while phenocrysts of augite and hypersthene are less common. Flow texture is common. The rock is slightly altered. The main alteration minerals are pyrite, clays, quartz, stilbite and calcite.

Layer 10 (118-124 m): A vesicular andesite tuff containing rare phenocrysts of plagioclase (labradorite). The glass is all altered to secondary products whereas the plagioclase is relatively fresh. Pyrite, clays, calcite and quartz are common along with some stilbite. In veins stilbite is the earliest phase to crystallize followed by calcite and quartz.

Layer 11 (124-148 m): This 24 m thick layer is a finely crystalline porphyric basaltic andesite lava. Plagioclase (labradorite) phenocrysts are most common but also found scattered is a relic of a FM mineral most probably olivine. The layer is somewhat altered in the uppermost part but relatively fresh in the central and lower part. Clay and pyrite are the common alteration minerals but less commonly found are quartz and calcite.

Layer 12 (148-153 m): This 5 m thick layer is an aphyric vesicular tuff, where all the glass has been altered, but where the original glass structure is still preserved. The main alteration minerals are clays, pyrite, quartz and calcite along with rare anhydrite and probably ptilolite.

Layer 13 (153-172 m): This rather compact rock layer is chiefly composed of quartz, anhydrite and pyrite. Structures relating it to either igneous or sedimentary origin appear to be absent. The crystallinity of the rock is quite variable, but showing a gradual changes from minute crystals to medium crystallinity.

Layer 14 (172-184 m): A glassy to finely crystallized, vesicular and porphyritic basaltic andesite breccia. The phenocrysts are chiefly plagioclase (labradorite) with subordinate amounts of augite. The rock is somewhat altered, the plagioclase in some instances starting to alter and the pyroxenes also being altered into calcite. Pyrite, quartz, clay, calcite and anhydrite are the common alteration minerals.

Layer 15 (184-201 m): Fine to medium grained basaltic andesite containing plagioclase (labradorite), hypersthene, augite and relic olivine phenocrysts. Flow texture is conspicious. The layer is altered, but gets gradually less altered, darker and more compact towards the bottom. The alteration minerals are calcite, quartz, clay, pyrite, anhydrite and gypsum.

Layer 16 (201-216 m): Fine to medium grained porphyritic basaltic andesite. The phenocrysts are mainly plagioclase (labradorite), but less frequent is a relic FM-phenocryst species, probably olivine. The layer is extensively altered with some of the plagioclases altered to calcite and clays and much of the pyroxene has been altered. Pyrite, quartz, clays, calcite, gypsum and anhydrite are the common alteration minerals. Some of the drillcuttings show some rounding, probably caused by a long travelling time in the drillhole (a possible sign of a cave formation and/or too low rate of circulation).

Layer 17 (216-228 m): Fine grained porphyritic basaltic andesite. The phenocryst species are mostly plagioclase (labradorite) with subordinate amount of augite and probable relic olivine. Although the layer as a whole is extensively altered, it appers to get less altered towards the bottom of the hole. The main hydrothermal minerals are lava

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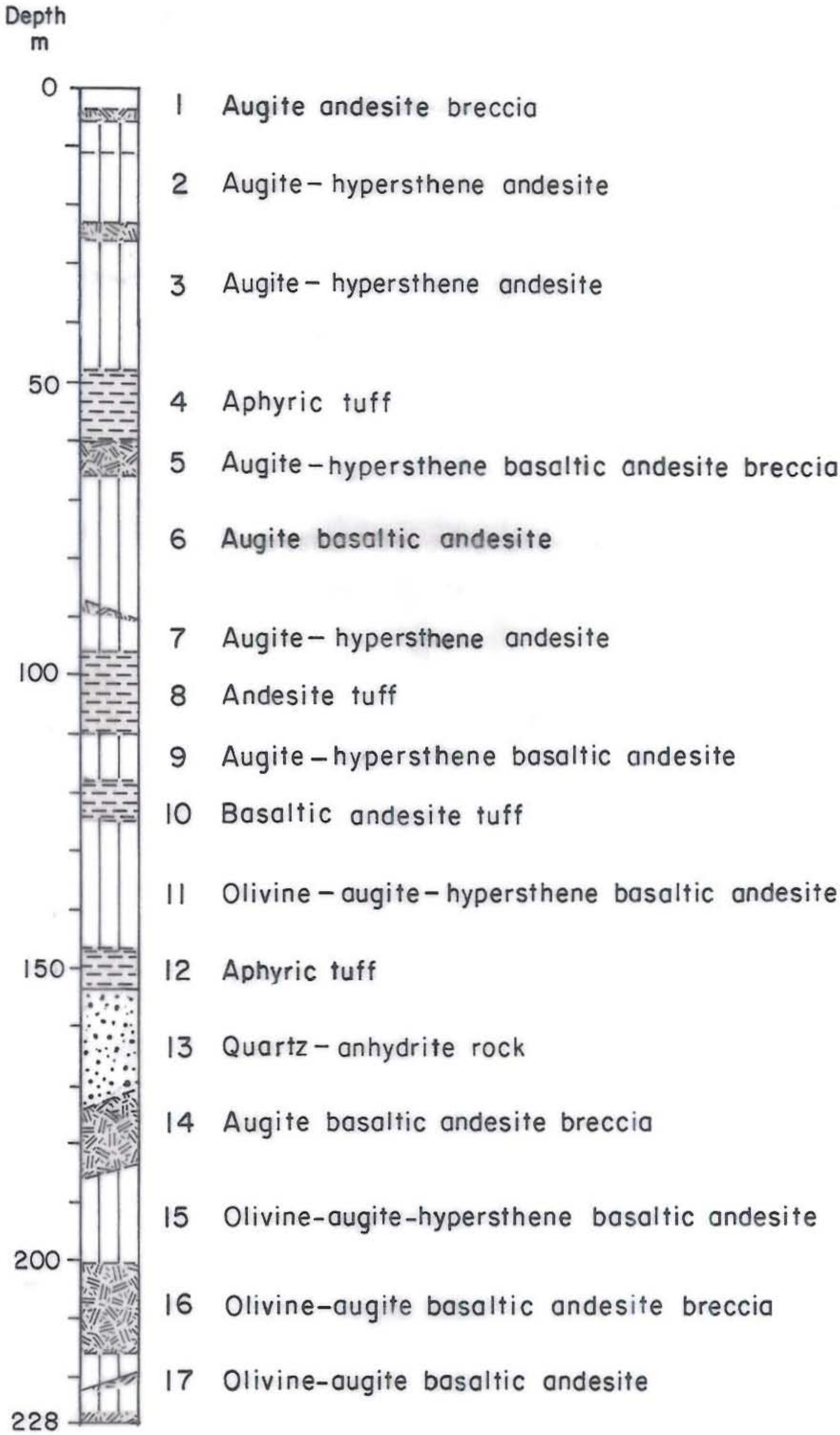
Fig.4

STRATIGRAPHY OF LH2



quartz, calcite, clays along with some pyrite, stilbite and anhydrite.

2.3 Alteration

2.3.1 Alteration of the primary rock constituents

The primary constituents of the rocks encountered in drillhole LH2 are glass, olivine, pyroxene, feldspars and opaque minerals. The susceptibility of these constituents to secondary alteration depends on physical properties such as temperature, pressure, porosity, permeability, chemical composition of the thermal fluid as well as the stability of these rock constituents subjected to the above hydrothermal conditions.

Fig. 5, illustrates the alteration state of the primary constituents in LH2 as observed in thin sections. The glass, is everywhere altered, dominantly to clay. Similarily, olivine, is nowhere observed in an unaltered state. It is believed to have been present as a phenocryst in the lower part of the sequence, i.e. the basaltic andesite rock. The pyroxene shows some alteration above 50 m and below about 180 m depth, but is nowhere totally altered. Similarly feldspar shows definite signs of alteration above 50 m and below 180 m where signs of albitization are evident, but in the intermediate depth interval, the alteration is negligible. The alteration state of the primary constituents may be divided into three depth intervals (Fig. 5); above about 50 m and below about 150 m "high" alteration prevails whereas between 50-150 m a "low" alteration exists. As seen below similar kind of alteration zoning can be deduced from the distribution of the secondary minerals.

2.3.2 Alteration minerals

Calcite was analyzed using petrographical and XRD-methods, as well as using dilute HCl acid. Calcite is found throughout the drillhole below 6 m depth. It is found as vesicle fillings and as an alteration product of the primary constituents. Furthermore, it was commonly found as vein fillings at depth intervals of 6-30 m and 147-170 m.

Quartz, though predominantly identified in thinsections, was also identified by using XRD and binocular microscope. It is present throughout the drillhole, as vesicle and vein fillings as well as the alteration products of primary rock constituents. In rare cases it was difficult to establish whether it is of a primary or secondary origin, due to the evolved composition of the rock.

Chalcedony was recognized through the binocular stereo microscope in samples from 190-200 m depth. Furthermore, it was observed in thin sections from same depth as well as in a sample from 222-225 m depth. It appears to have formed in association with the quartz but earlier.

Pyrite like calcite is found at all depth levels below 6 m. It is very easily recognizable by its bright yellow reflection and cubic shape in the binocular stereo microscope. It is found as vesicle and vein fillings as well as an alteration product of the primary groundmass especially glass.

Anhydrite was chiefly recognized through the petrographic microscope and also from XRD analysis. It is found at two depth intervals from 3 - 35 m as rare vesicle and vein fillings and from 150 - 226 m where it is relatively common. It is found most frequently in association with secondary quartz. In one instance (195 m) anhydrite was observed in a reaction relationship with gypsum.

Gypsum was only detected in thin sections. It is present, like anhydrite, at two levels in the hole, down to 45 m and below 65 m depth. It is relatively rare except at 195-198 m depth where it is common. As presviously mentioned it is likely to have been formed by the hydration of anhydrite.

Barite. This mineral was only identified in thin section through the petrographic microscope. It does resemble anhydrite in many respects except it has slightly higher relief and distinctly lower birefringence. Barite occurs mainly in the upper 35 m of the hole though with two exceptions, one occurrance at about 120 m and the other at about 220 m depth. Like anhydrite it is commonly found associated with quartz.

Stilbite is the predominant zeolite representative. It was recognized in thin section as well as in XRD analyses. It is common as vesicle and vein fillings at the depth interval of about 40 - 90 m, but was identified also at 120 and 220 m depths. In all instances stilbite seems to have been the earliest phase to crystallize before calcite and quartz.

Ptilolite is thought to occur in a thin section at 111 -114 m depth, where it is seen as very minute radially arranged crystal clusters, propagating out from the vesicle rim into quartz which filled the vesicle later. The minute size of the crystals along with their position in a quartz media prevents any detailed study of their optical properties and they can therefore only be inferred to be present.

Epidote was only detected through the petrographic microscope where it is easily detectable. It is found only between 11 -35 m depth, exclusively as vein and vesicle fillings. There it is always found to have been the last mineral to precipitate, i.e. later than quartz and calcite.

Prehnite was only found in one thin section at about 25 m depth.

Albite as discussed previously, is confined to alteration cracks and patches in the plagioclase phenocrysts, and could only be seen in thin section. Indications of this kind of alteration is found in the upper levels of the hole, i.e. at about 14 m, 25 m and in the lower part, below 180 m being most conspicuous at about 220 - 230 m, and this coincides with the depth where the circulation loss occured.

As previously mentioned clays are the dominant alteration product found in the hole, both as a precipitate as well as replacement of the primary rock constituents. Their subdivision into clay groups is, however, difficult using the binocular stereo microscope and petrographic methods, whereas the XRD method has turned out to be the best available. Each clay sample is analyzed in three stages; firstly as an untreated sample, secondly after glycolation and thirdly after heating it above 500°C. In all 21 samples were run and analyzed by the author with the guidance of the staff of NEA. As seen in Fig. 5, two kinds of clays were found:

Smectite appears to be present throughout the hole except in the uppermost 20 meters, and was not detected in a sample at 183 m.

Swelling chlorite is confined to two depth levels; the upper one extending from 10 m down to 40 m, and the upper one from about 150 m down to the bottom of the hole. Furthermore one analysis shows swelling chlorite to be present at about 65 m depth.

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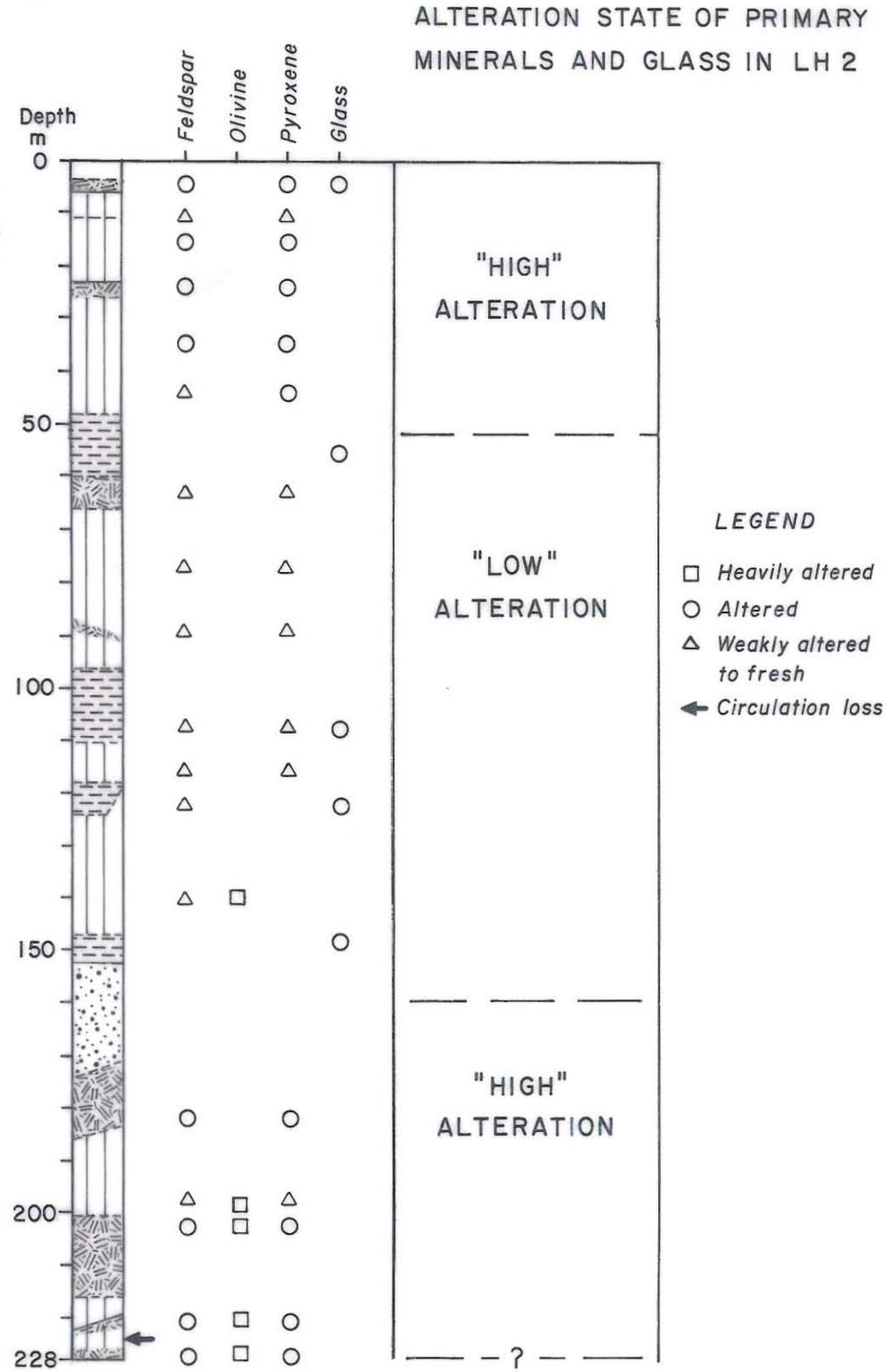
Fig.5



2.3.3. Alteration zonation

The above distribution of the alteration minerals allows the division into four alteration zones. The significance of these zones is further discussed in Chapter 3.

Zone I Quartz-anhydrite (3-6 m):

This zone can only vaguely be inferred as it is based on only one cutting sample and a single thin section. The alteration minerals found in this rock sample, which is thought to represent the surface cover, are quartz and anhydrite. Clay is absent. The gypsum is believed to be retrograde hydration product of anhydrite.

Zone II Epidote-anhydrite-swelling chlorite (6-40 m):

The upper limit of this zone is set by the appearance of epidote, smectite and swelling chlorite and the lower limit by the disappearance of epidote, anhydrite, barite and swelling chlorite. Other minerals of interest in this zone are prehnite and the initiation of albitization is observed in the plagioclase.

Zone III Silbite-smectite (40-145 m):

The upper limit of this zone is deliniated by the disappearance of some of the type minerals of Zone II, but most importantly by the apperance of stilbite. Other minerals, as seen in Fig. 6 are smectite, calcite and quartz. The base of this zone is set by the reappearance of anhydrite and swelling chlorite.

Zone IV Anhydrite-swelling chlorite (144-228 m):

The upper limit of this zone is set by the reappearance of swelling chlorite along with anhydrite, both of which are found to the bottom of the hole at 228 m.

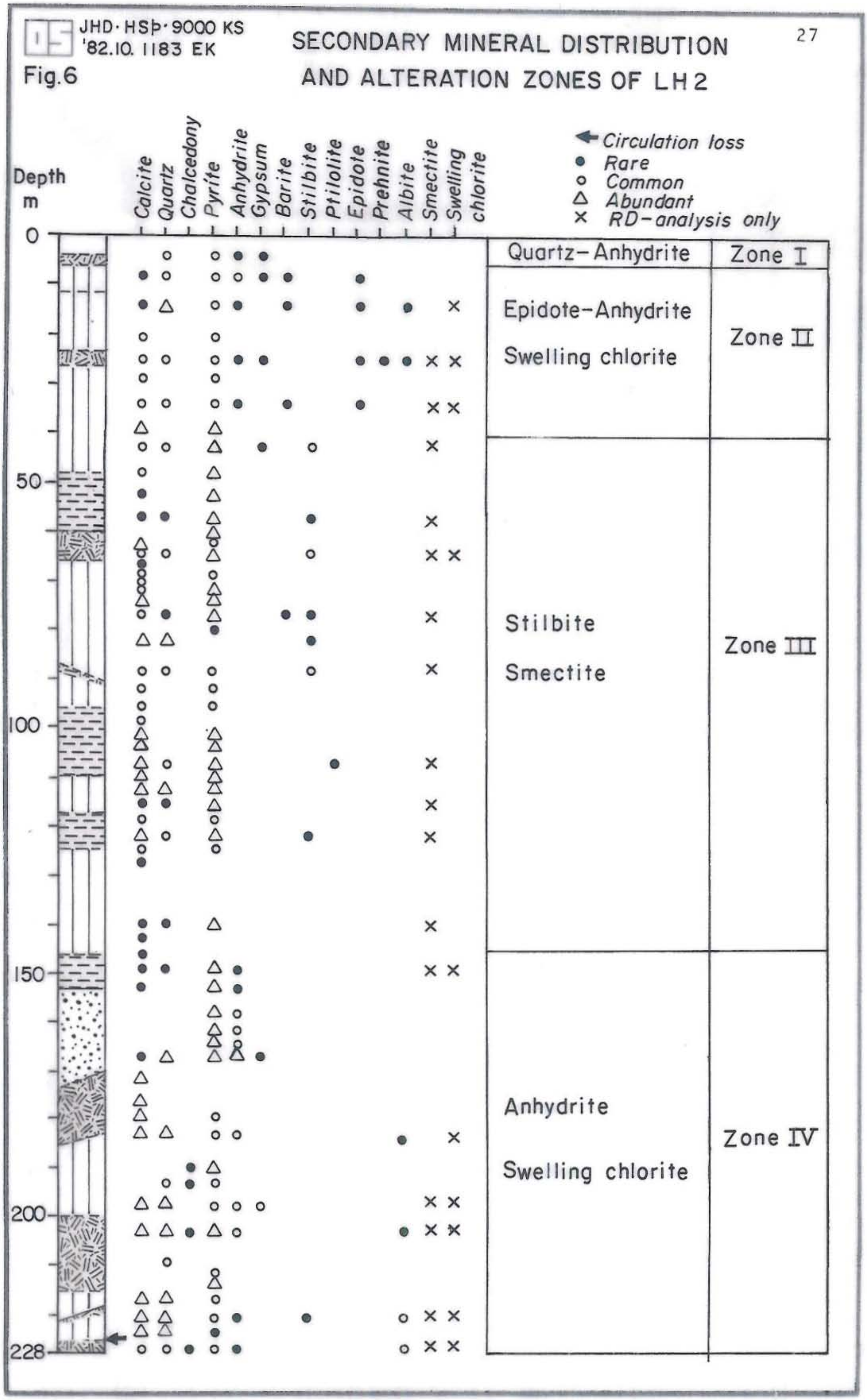

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Fig.6
SECONDARY MINERAL DISTRIBUTION AND ALTERATION ZONES OF LH 2
Depth m
Calcite
Quartz
Chalcedony
Pyrite
Anhydrite
Gypsum
Barite
Stilbite
Ptilolite
Epidote
Prehnite
Albite
Smectite
Swelling chlorite
Circulation loss
Rare
Common
Abundant
RD-analysis only
0
50
100
150
200
228
Quartz-Anhydrite
Zone I
Epidote-Anhydrite
Swelling chlorite
Zone II
Stilbite
Smectite
Zone III
Anhydrite
Swelling chlorite
Zone IV

3 DISCUSSION AND CONCLUSION

The salient features of the data assembled prior to the drilling in the Lahendong high temperature area are:

(1) The thermal manifestations coincide with a volcanic crater or a small caldera of about 1000 m width.

(2) The hydrothermal manifestations are on surface associated with two tectonic features; i.e. a sub-circular fracture/fault system associated with an explosion crater, and NE-SW striking faults, one of which cross-cuts the crater fractures. The hydrothermal activity is most pronounced along the NE-SW fault system, though also evident along the crater fractures. Both these fracture systems are believed to lie sub-vertical and suspected to provide the most promising aquifers. The siting of the first drillhole (LH1) and the second one (LH2) were both with the aim at cutting a NE-SW fault at depth.

This study of the borehole geology of LH2 adds some further information to the Lahondong high temperature area:

(1) The stratigraphic sequence, which can be divided into 17 distinct layers, shows a kind of rythmic layering of interbedded lavas, breccias and tuffs. This kind of a sequence may be expected in an volcanic area like Indonesia where a Plinian phase generally preceeds and/or succeeds lava accumulation. The breccias are in some cases likely to represent the top part of lava flows. Compositionally the successions may be divided into two parts; andesite products overlying a basaltic andesite sequence. The stratigraphic sequence of LH2 does not give a direct information on where these products originated from. If the succession is derived from a single source (e.g. a volcano such as Tampusu) the change in composition may imply the occurrence of a differentiation within that volcano.

Research into hydrothermal alteration in various parts of the world has shown that temperature is one of the most important parameters in the formation of many alteration minerals. Table 1 summarizes the temperature range established by research workers in geothermal systems in Iceland, Japan, New Zealand, Philippines and Mexico for alteration minerals that have also been found in Lahendong.

Fig. 6 shows the division of the secondary minerals into four alteration zones. It shows that the alteration assemblage in Zone II between 6-45 m strongly suggests that during the formation of these alteration minerals (albite, epidote, prehnite, swelling chlorite) temperatures were at least higher than 200°C. The absence of these high temperature minerals in the surface cover (≤6 m) may imply the demise of the high temperature state prior to the surface sedimentation.

Zone III (50-145 m) on the other hand shows that temperatures were unlikely to have surpassed 100°C for any length of time. The lowermost Zone IV shows indications of higher temperatures than Zone III, but the absence of epidote and prehnite may indicate temperatures less than suggested for Zone II.

The alteration state of the primary rock constituents in LH2, especially plagioclase and pyroxene, show a very conforming picture where there is a relatively high alteration state of these above 50 m and below 160 m and a negligible one between these depths.

A common feature generally observed in alteration is the preferential hydrothermal alteration in relatively high porosity strata and a resistance to alteration in low porosity strata. This feature appears not to be a controlling factor in the alteration pattern of LH2 which implies that the hydrothermal aquifers may not be controlled by the stratigraphic layers, at least down to the base of the succession in this hole.

The disconnection of the alteration zonation with the primary features of the strata implies that secondary fractures may control the alteration zonation. Such a solution agrees well with the close association of the tectonic features and hydrothermal activity on the surface.

Table 1. Rough estimates of temperature stability range of alteration minerals in some high temperature areas in Iceland, Japan, New Zealand, Philippines and Mexico.

Secondary mineral	Iceland (5,6,7)	Japan (1)	N.Zealand (1,4)	Philippines (2)	Mexico (5)
	°C	°C	°C	°C	°C
Anhydrite	-	>150	-	>100	<300
Stilbite	>150	<100	<200	<150	<250
Epidote	>230	>150	>230	>230	>250
Albite	>220	>150	-	-	-
Smectite	<200	<100	<160	<200	<150
Swelling chlorite	200-230	100-200	120-230	-	-
Ptilolite	-	-	110-160	-	-

1) Browne, P.R.L., 1978.
2) Reyes, A.G. and Tolentino, B.S., 1981.
3) Hoagland, J.R. and Elders, W.A., 1978.
4) Steiner, A., 1977.
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