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# THE BOREHOLE GEOLOGY AND ALTERATION MINERALOGY OF MALITBOG-1, TONGONAN, LEYTE, PHILIPPINES

*Agnes G. Reyes*

UNU Geothermal Training Programme. *Report 1979-1*

# THE BOREHOLE GEOLOGY AND ALTERATION MINERALOGY OF MALITBOG-1, TONGONAN, LEYTE, PHILIPPINES

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ABSTRACT

Three clay zones are recognized in the Malitbog 1: smectite, interlayered illite, and illite zones. The boundaries between the zones cover a large depth interval and are relict at shallow depths.

Cataclastic textures found in the rocks drilled through by Malitbog 1, the repetition of sedimentary and volcanic sequences, and the broadening of boundaries between temperature- dependent mineral assemblages, are mainly attributed to a large fault having a displacement of about 500 m, with its locus on the calc-silicate zone.

The complex thermal history of Malitbog is marked by faulting, uplift, and intrusions. Throughout its history, hydrothermal activity was continuous.

# 1. INTRODUCTION

## 1.1 Scope of work and analytical methods used

The present author was awarded a UNU Fellowship to attend the UNU Geothermal Training Programme at the National Energy Authority in Iceland in 1979. After the introductory lecture course the author received specialized training in borehole geology, which included theoretical aspects of x-ray analyses(3 weeks), mineral separation techniques (1 week), analytical methods for clay minerals (3 weeks), electron microprobe analyses (1 week), and practical introduction to various geophysical logging methods (1 week). The present report represents a research project carried out mainly during the last 8 weeks of the specialized training. The various analytical methods studied during the specialized training were applied to a drillhole from the Tongonan geothermal field in the Philippines. Raw data from the project together with cores, cuttings, and a few thin sections from Malitbog- 1, a deep exploratory well in the Tongonan geothermal field, were shipped to Iceland at the start of the training. Samples from the well were used in some laboratory exercises during the early months of the specialized training but intensive work on the project, from petrographic data gathering to report writing began in early September and ended in early November.

This report pivots from the study of the alteration mineralogy of Malitbog- 1, using several petrographic techniques. Cores and samples of cuttings were taken from zones of circulation losses and from depths which showed marked changes in a) lithology, b) secondary mineral assemblages and c) temperature. These were subjected to XRD analysis mainly for clay identification, and thin- sectioned in order to observe the interrelationships among minerals, to determine the rock texture, and to identify crystals not detected by the x- ray. In some cases where clay identification was doubtful, samples were run in the infrared spectrometer. This gave positive results for vermiculite and pyrophyllite, but gave no definite answer for the chlorite species. For this and other minerals such as alkali feldspar and epidote, the microprobe in the University of Iceland was used.

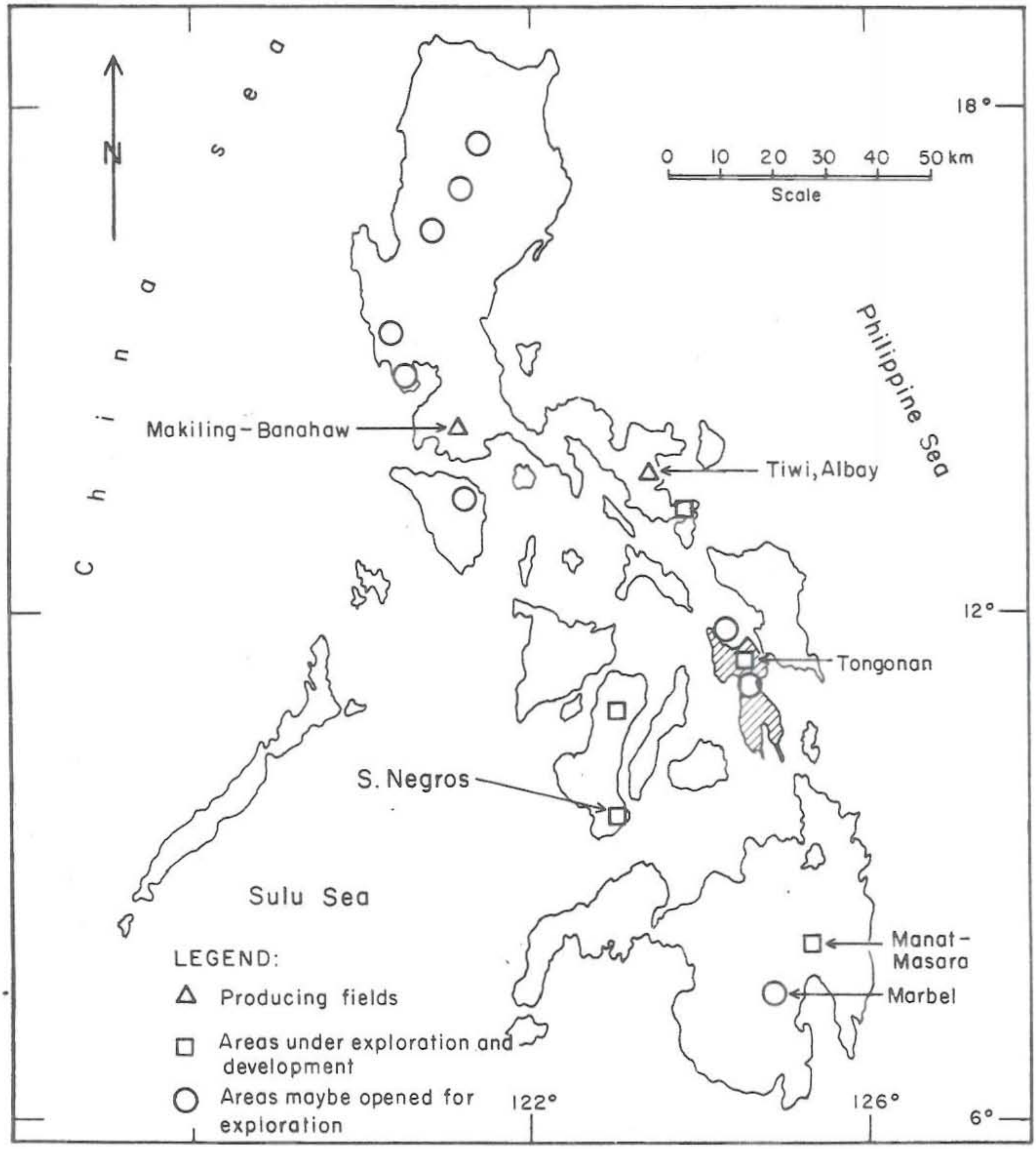


Fig. 1 Philippine geothermal areas

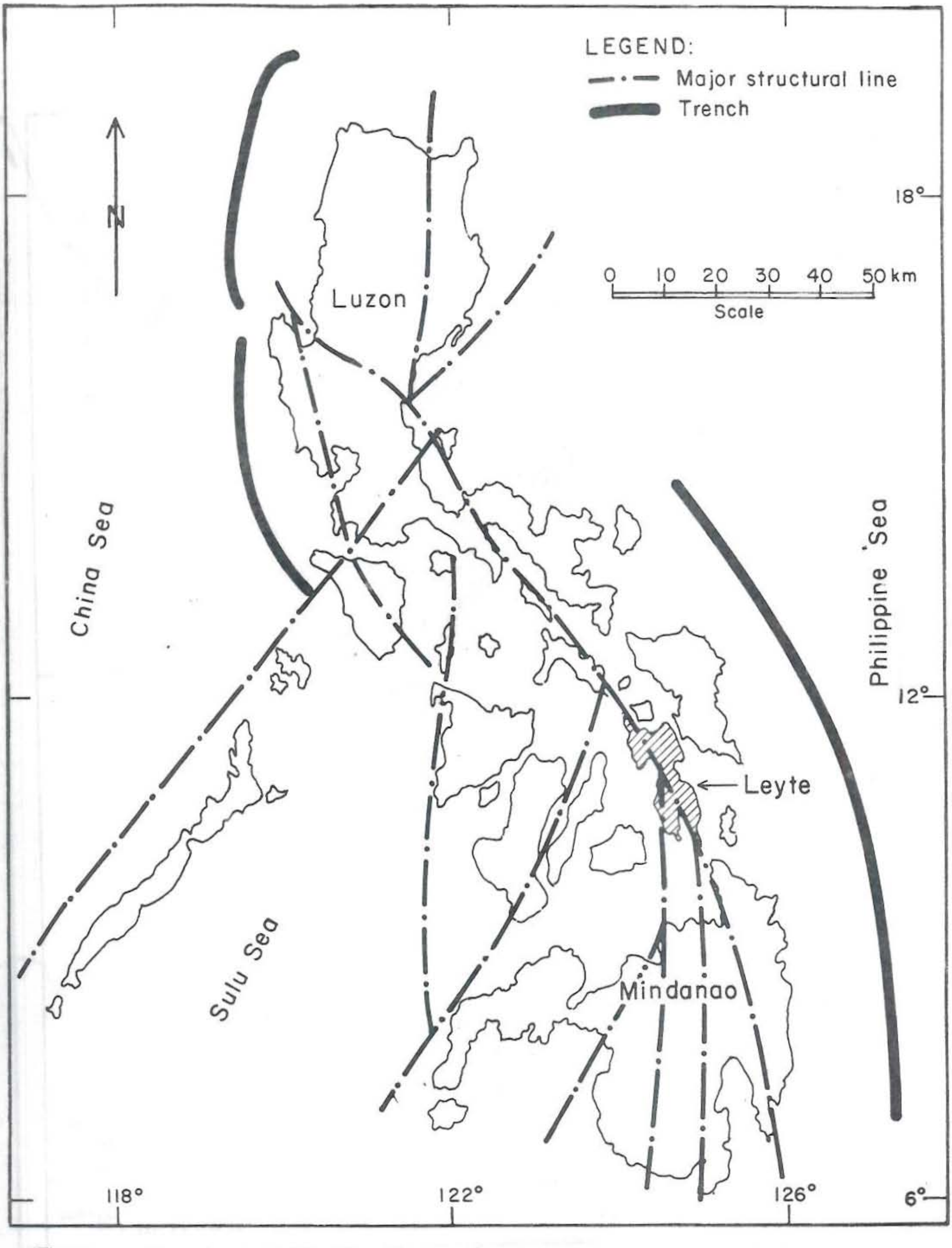
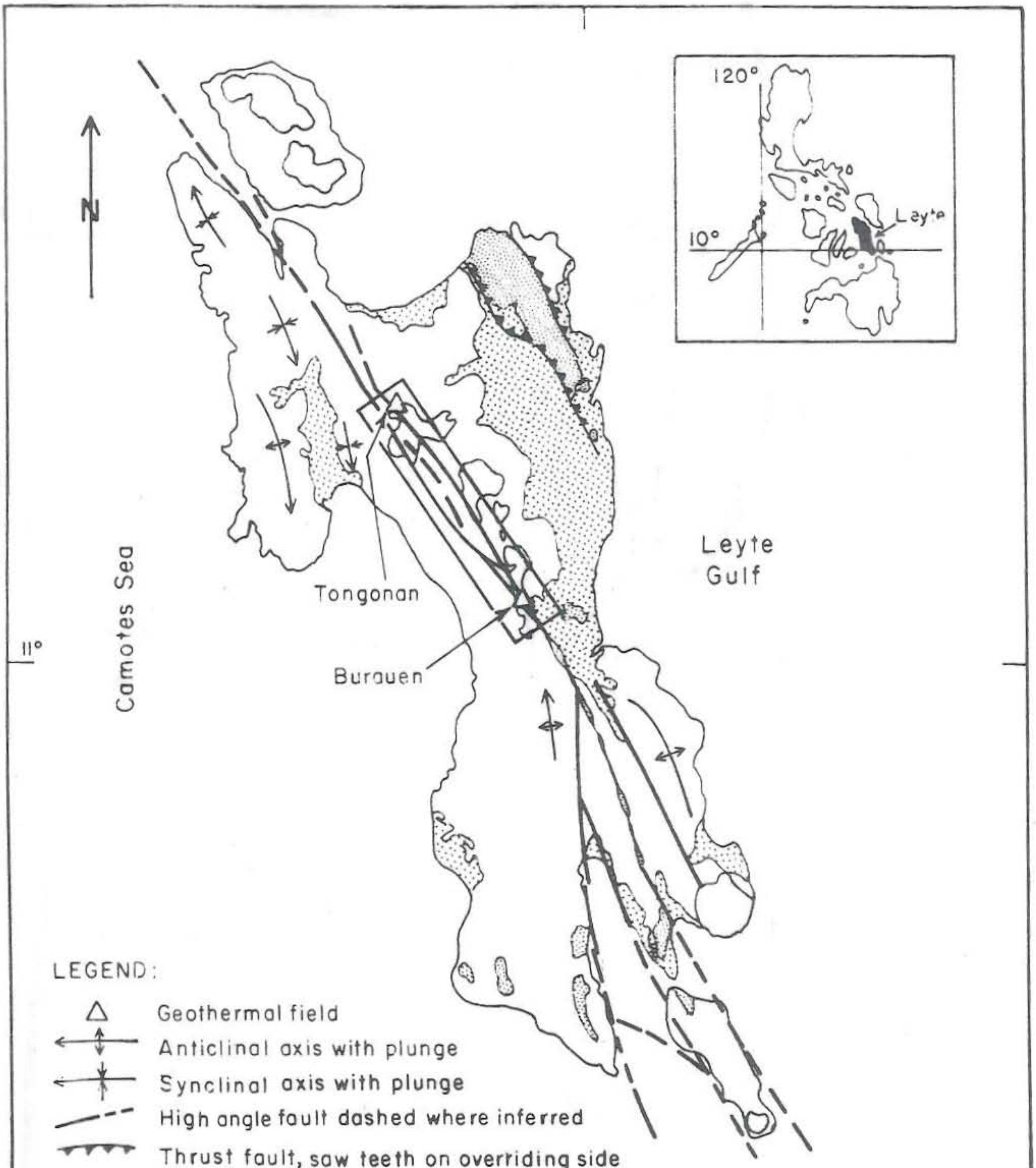


Fig.2 Sketch map showing the main structural features of the Philippines



Adapted from Bureau of Mines 1963

Fig. 3 Generalized geological map of Leyte showing the major structural lines and rock types. Enclosure delimits the Leyte geothermal reservation.

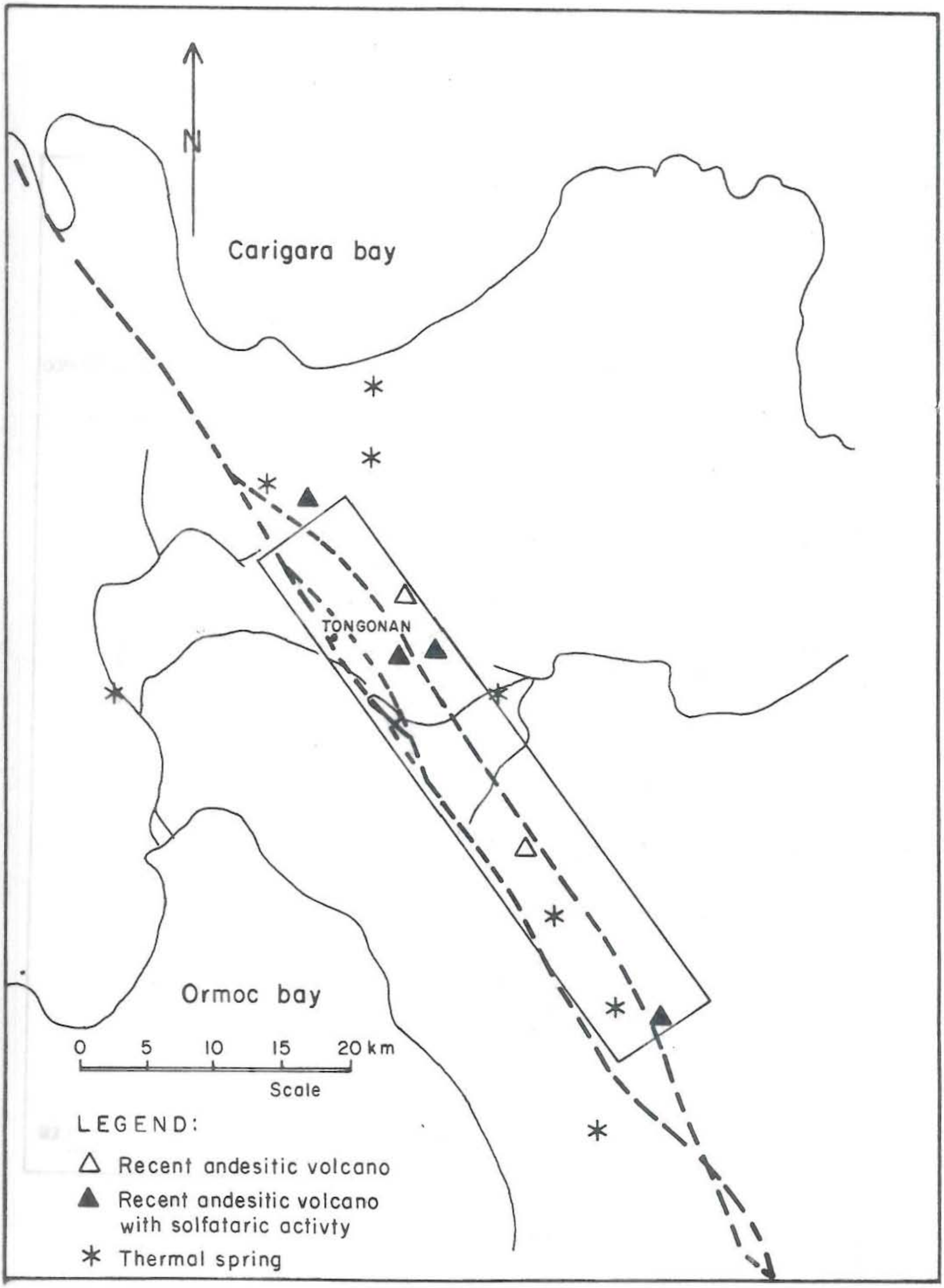


Fig. 4 Aligned along the East fault is a belt of andesitic volcanoes Also shown are major occurrences of thermal springs.

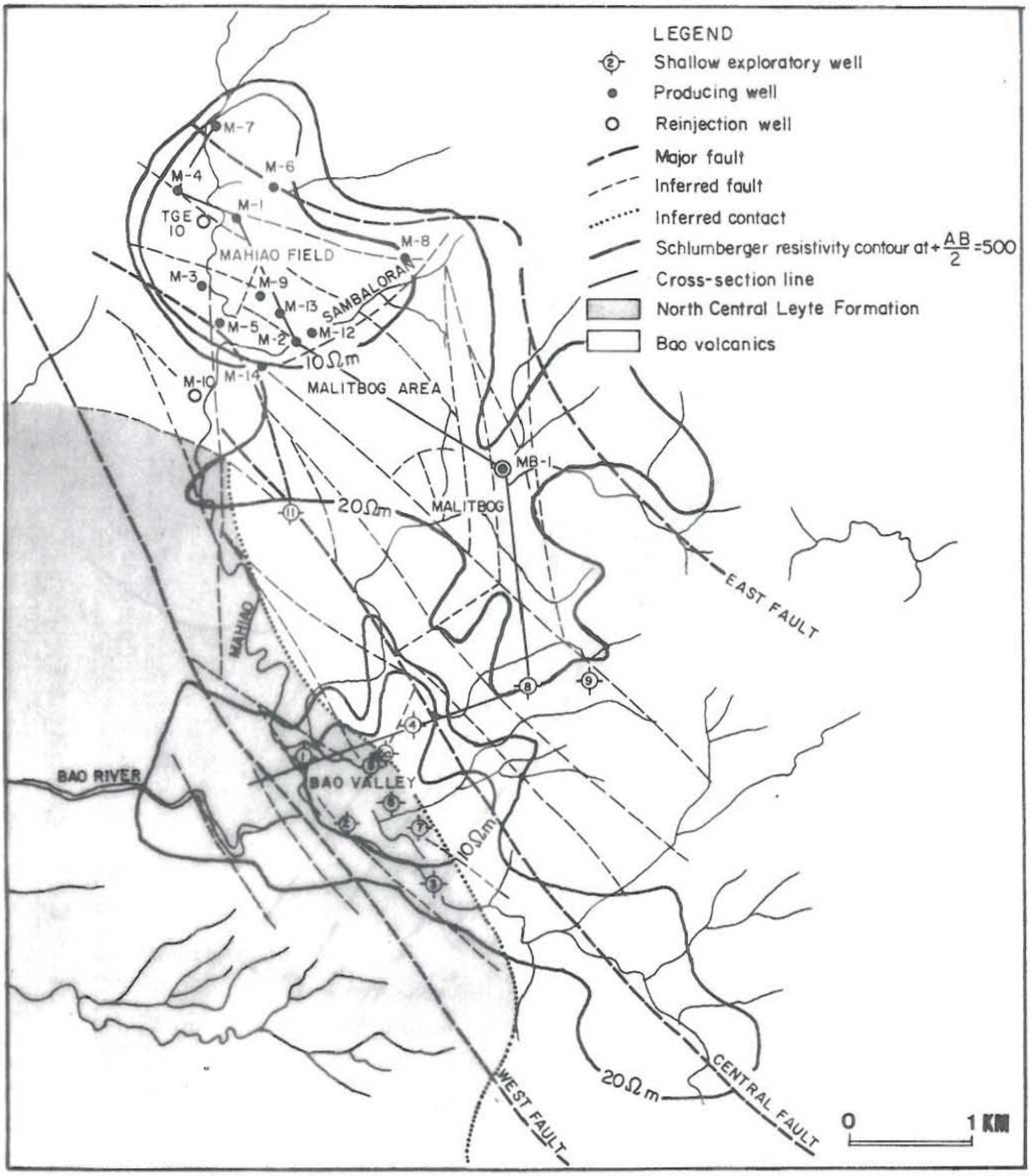


Fig. 5 Geological map of the Tongonan geothermal field showing well sites and resistivity contours at $\frac{AB}{2}$ = 500m

## 1.2 Regional setting and the geothermal potential of the Philippines

The Philippines is marked by active volcanism and frequent earthquakes. Yet it is by its very instability that the country derives its large reserves of geothermal energy.

The exploration of geothermal energy as a power source was initiated during the sixties in the country. With its recognition as a viable source of power, the Philippines is now engaged in an intensive program that would result in the production of 1895 MWe by 1988, about 5% of the country's energy needs. At present however, seven of its geothermal areas are being developed (Fig. 1), two of which are in the early stages of exploitation, giving a total output of 220 MWe.

The Philippines is one of the island arcs that circumscribe the Pacific seismic zone. It is marginned on the east, northwest, and southwest by trenches and traversed along the length of its western part by the strong generally left- lateral transcurrent Philippine fault, which curves its way from central Mindanao northwestwards towards the island of Luzon, a total length of 1000 km (Fig. 2). As in other arc-trench systems, dacitic to andesitic volcanoes line the inner side of the trenches, and it is with such volcanic clusters, of Plio-Quaternary age, that the Philippine geothermal areas are associated (2). Some of the geothermal fields occur along the Philippine fault, and the relationship between the fault, the line of andesitic volcanoes, and the geothermal field is quite marked in the island of Leyte.

## 1.3 The Tongonan geothermal field, Leyte

### 1.3.1 Geology of Tongonan

In the island of Leyte, a strip of land measuring 52 x 2.5 $km^2$ was designated a geothermal reservation as early as 1973 (Fig. 3). Within its boundaries is a segment of the Philippine fault, a line of inactive Quaternary andesitic volcanoes and associated thermal springs (Fig. 4). The Tongonan geothermal area, one of the fields on the brink of exploitation,is to the northwest of the reservation.

The Philippine fault in Tongonan bifurcates into three left lateral transcurrent branches which are referred to as the West, Central, and East faults (Fig. 5)(9). Between these major branches are a series of cross-faults which similarly exhibit both horizontal and vertical movements and are believed to have accommodated the compressive and tensional stresses between the major faults. Aligned along the East fault are inactive Quaternary volcano clusters, some of which display solfataric activity. Grindley (1973), commenting on the symmetry of the fault pattern and the youth of both the fault and the hydrothermal systems (late Pleistocene to Recent), speculated on the probable close relationship of the nearby volcanoes and the hydrothermal activity in Tongonan.

The Tongonan geothermal area is presently divided into the Mahiao proven field, the Malitbog exploratory area, and the Bao valley. Though differences in the chemistry between the Bao and the areas of Mahiao - Malitbog, are reported, the main divisions in this report is based on the occurrence of isoresistivity contours at AB/2 = 500 m. In the text the resistivity values mentioned refer to AB/2=500 m. The Mahiao is delineated by the 10 Ωm anomaly, the Malitbog area, southeast of Mahiao is confined within the 20 Ωm contour line and the Bao area, south of Mahiao, is within a 10 Ωm lobe (Fig. 5).

The resistivity anomalies are elongated parallel to the northwesterly strike of the major structures and an apparent correlation of abundant cross-faulting with low resistivity is observed. The Bao area is marginned on the west by the West Philippine Fault, and on the east by the Central Philippine Fault. Eight shallow wells were drilled in the area where all displayed temperature reversals. The hottest wells are nearest to the Central Philippine Fault and encountered the high chloride waters (2830 ppm) as was found discharging at one of the springs in the Bao valley. The highest temperature attained in the hottest well is less than 200°C. The holes closest to the West Fault are relatively cold and contain steam heated waters only (5).

The Mahiao - Malitbog anomalies are marginned to the west by the Central Philippine Fault and the eastern boundary of the anomalies is still undefined. The drilling of TGE- 10 in Mahiao shifted the operations from the Bao valley to Mahiao. This well proved to have the highest temperatures of 250°C at 590 m. The drilling of Mahiao deep wells with average temperatures reaching 300°C further established the high temperature of the geothermal system (10). Three years after its first deep well, the Mahiao field has now reached a stage where 4 $km^2$ (as delineated by the 10 Ωm contour) is considered a proven field (Fig. 5)(12). Temperatures of up to 300°C are found in permeable zones at average depths of 650-1000 m below sea level (7). Calculations indicate that the area has a capacity of 3000 MWe years. With the promise shown by the exploratory drilling within the 20 Ωm anomaly south of the proven field, an additional 6000 Mwe years are envisaged for the area.

Generally, the Mahiao wells become hotter eastwards: Mahiao- 8, the easternmost drillhole, has a bottom temperature of 339°C. It seems that the East Fault has an active role in the hydrothermal activity in both the Malitbog and Mahiao areas. The Central Fault is more of a barrier that separates the Bao hydrothermal system with that of Mahiao.

A cross- sectional sketch across Bao, Malitbog, and Mahiao is depicted in Figure 6. It should be noted that the apparent sparsity of faults in the Malitbog vicinity is due to the parallelism of the cross section to the fault lines in that area. The main points are enumerated below:

1. The isotherms from the Mahiao wells dip down towards Malitbog- 1 and a thermal trough is formed between TGE- 8 east of the Central Fault and TGE- 4 west of the Central Fault. Temperature reversals occur in the Bao valley shallow wells. Coinciding with the thermal trough are two fault blocks, and a gap in the apparent resistivity block at AB/2= 500 m signifies resistivity values greater than 20 Ωm.

2. Diorite is encountered in several of the Mahiao wells where it intrudes the Bao volcanics. Two diorite dikes were encountered in Malitbog- 1 which coincide with a zone of permeability. The heat source is believed to be related to the subsurface diorites encountered in Mahiao (13).

3. The Mahiao sedimentary horizon was used as a marker bed in the evaluation of fault displacements. Vertical movements of 25-200 m were measured. The sedimentary formation encountered in Malitbog- 1 is correlated with the Mahiao sedimentary horizon.

### 1.3.2 General Stratigraphy of Tongonan

Miocene to Quaternary volcanics of varied depositional environments outcrop in Tongonan (9). Drilling data has added to the stratigraphic information and shown that there are calcareous and fossiliferous sediments interbedded with the volcanics. Reef limestone, underlying the volcanics and calcareous sediments, was encountered in two shallow drillholes in the Bao valley south of the Mahiao and Malitbog areas. A plutonic complex forms the base of the pile of volcanics in Mahiao (Table I).

The most important formation in the field are the late Miocene to Pleistocene Bao Volcanics which are hornblende andesites occurring as lava flows, lahars, tuffs, and breccias. Where impermeable or rendered impermeable by past hydrothermal action, it acts as a caprock and where fracture zones at deep levels occur, caused either by faulting or the intrusion of the diorite, it forms a geothermal reservoir. The Bao volcanic complex underlies more than 50% of the Tongonan geothermal field and appears to taper towards the Bao valley, found southwest of the Mahiao and Malitbog areas. Shallow drillholes in the Bao valley encountered the Bao volcanics beneath the sedimentary North Central Leyte Formation, and in two wells, this formation bottomed on limestone. It attains a minimum thickness of 247 m in the shallow well TGE- 1. In the Mahiao area, the formation is encountered from surface till it bottoms on the diorite. It attains a thickness of greater than 1500 m in the Mahiao wells and a maximum of 1710 m was drilled through in well Mahiao- 14.

The Bao volcanics were erupted in a sub-aerial environment and the distribution of the volcanics has led investigators to conclude that these were erupted by several widely distributed volcanic loci (9,4,11).

TABLE I. GENERALIZED STRATIGRAPHY OF THE TONGONAN GEOTHERMAL AREA

TABLE I. GENERALIZED STRATIGRAPHY OF THE TONGONAN GEOTHERMAL AREA

| FORMATION | PROBABLE AGE | DESCRIPTION |
|---|---|---|
| Janagdan Andesite | Quaternary | Two- pyroxene lava flows exposed south of the drilled area and not encountered in any of the wells. |
| North Central Leyte Formation | Lower Pleistocene to Upper Pleistocene | Conglomerates and sandstones with thin lenses of tuffaceous siltstones. Tapers off towards the Mahiao valley but was encountered by several Bao valley shallow wells. A thickness of 600 m was encountered in TGE- 3 . |
| Bao Volcanic Complex | Upper Miocene to Middle Pleistocene | Hornblende andesite flows intercalated with volcaniclastics. This is widely distributed in the geothermal area and is encountered in all wells. A sedimentary horizon consisting of limestone, siltstone, sandstone, and breccias interrupt the thick Bao Volcanic sequence in some Mahiao wells and in Malitbog- 1. A maximum thickness of 1710 m was drilled through in Mahiao-14. |
| Reefal Limestone | Upper Miocene to Pliocene ? | Underlies calcareous sediments in shallow wells TGE- 1 and TGE- 2 in the Bao valley. Thickness unknown. |
| Plutonic Complex | ?<br>but younger than the Bao Volcanic Complex | Massive dioritic to granitic intrusives encountered in some Mahiao wells. |

A thin sedimentary bed, referred to here as the Mahiao sedimentary Horizon, interrupts the thick Bao volcanic sequence in several Mahiao drillholes. This could be used as a marker bed where present (Fig. 6). The thickness of the horizon varies from a few meters to a maximum of 400 m in well Mahiao- 6. This consists of volcaniclastics intercalated with shallow marine to lagoonal sediments such as limestone, fossiliferous sandstone, black shale, brown siltstone, and conglomerate. Invariably, these contain volcanic detritus. The 150 m thick altered tuffaceous sediments intercalating the lava flows in Malitbog- 1 are correlated with the Mahiao sedimentary horizon.

## 1.4 Alteration in the Mahiao field

Wells in the area enclosed by the 10 Ωm resistivity contour (Mahiao anomaly/field) are found to tap reservoir waters which are marginally acidic, low in bicarbonate, high in chloride (11600-16500 ppm) and total dissolved solids, with significant amounts of arsenic (6.4-7.8 ppm) and boron (220-410 ppm)(5).

In response to temperature and permeability conditions, the sequence of andesites and the plutonic complex are altered to a propylitic assemblage of chlorite, calcite, quartz, epidote, and alkali feldspars. In terms of increasing depth and temperature, the sequence of alteration, generalized from the zonal scheme established by C.P.Wood (1979) is enumerated below.

1. Low temperature zone with a maximum of 130°C. Montmorillonite is the dominant clay mineral and is associated with quartz, calcite, and pyrite.

2. Intermediate temperature zone ranging from 130-250°C. Montmorillonite becomes interlayered with illite, and occurring together with this are chlorite, albite, calcite, and pyrite.

3. High temperature zone with a temperature range from 230°C to above 300°C. Illite is the dominant sheet silicate up to 300°C but is succeeded by the more stable chlorite at higher temperatures. Associated minerals are epidote, alkali feldspars, and abundant quartz. In some wells, tremolite-actinolite is found at temperatures above 300°C (Appendix 1).

Similar zonations have been described in New Zealand by Steiner and Browne (42 , 15).

# 2. THE MALITBOG- I EXPLORATORY WELL

## 2.1 Introduction

The Malitbog- 1 well was drilled to test the potential of the area defined by the 20 Ωm resistivity anomaly southeast of the proven field of Mahiao. The well was sited 100 m east of a fault, and about 2.3 km from the nearest Mahiao well (Fig. 5). No active thermal springs are in the vicinity but the site is characterized by remnant hydrothermal alteration.

The well was drilled through 1665 m of altered volcanics and sedimentary horizons interspersed with a metamorphic calc- silicate zone and some diorite dikes. A thick zone of high permeability was encountered at 1430 m to the base of the hole. Downhole measurements recorded temperatures with a maximum of 284°C. However, the well did not flow during initial tests and had to be stimulated by pumping air into it. Four months after the well was completed, it was opened and yielded a total mass flow of 118 kg/s with an enthalpy of 1300 kJ/kg and manifested a capacity rated at 16.5 MWe (Table II).

The hole was drilled with mud except during blind drilling when water was used. Minor losses were encountered from 1125 m till 1420 m, where massive losses occurred. Partial circulation was regained within the interval 1420-1547.5 m. The interval from 1547.5 m to 1665 m was drilled blind. Samples of cuttings were obtained at 3 m intervals. Cores were cut from the following depths: 673, 876, 1232, 1481, and 1650 m (6).

## 2.2 Previous studies

Two interim reports had been written on the Malitbog- 1 exploratory well. R.D. Ablazo (1978) had drawn a cross- section across M- 7, the northernmost Mahiao well to Malitbog- 1 and remarked on the nearly identical plunge of the isothermal lines as Malitbog- 1 and M-7 are approached. He suggested that the Malitbog- 1 may lie at the edge of a reservoir which encompasses both the Mahiao and Malitbog areas.

TABLE II. MALITBOG-1 BASIC WELL DATA

| | |
|---|---|
| LOCATION | 1233432.8 N 462628.8 E<br>Philippine metric grid |
| CHF elevation (mean sea level) | 463 m* |
| COMPLETION DATA° | |
| Total depth | 1665 m |
| Shoe of 9 5/8" | 670.4 m |
| Slotted liner landed at | 1661 m |
| PERMEABILITY | |
| Completion test index | Excellent |
| DISCHARGE DATA | |
| Main production zone | 1300- 1661 m |
| Mass flow rate (kg/s) | 118 |
| Enthalpy (kJ/kg) | 1300 |
| POWER POTENTIAL | 16.5 MWe |
| MAXIMUM TEMPERATURE | 284°C |

*depths with reference to CHF

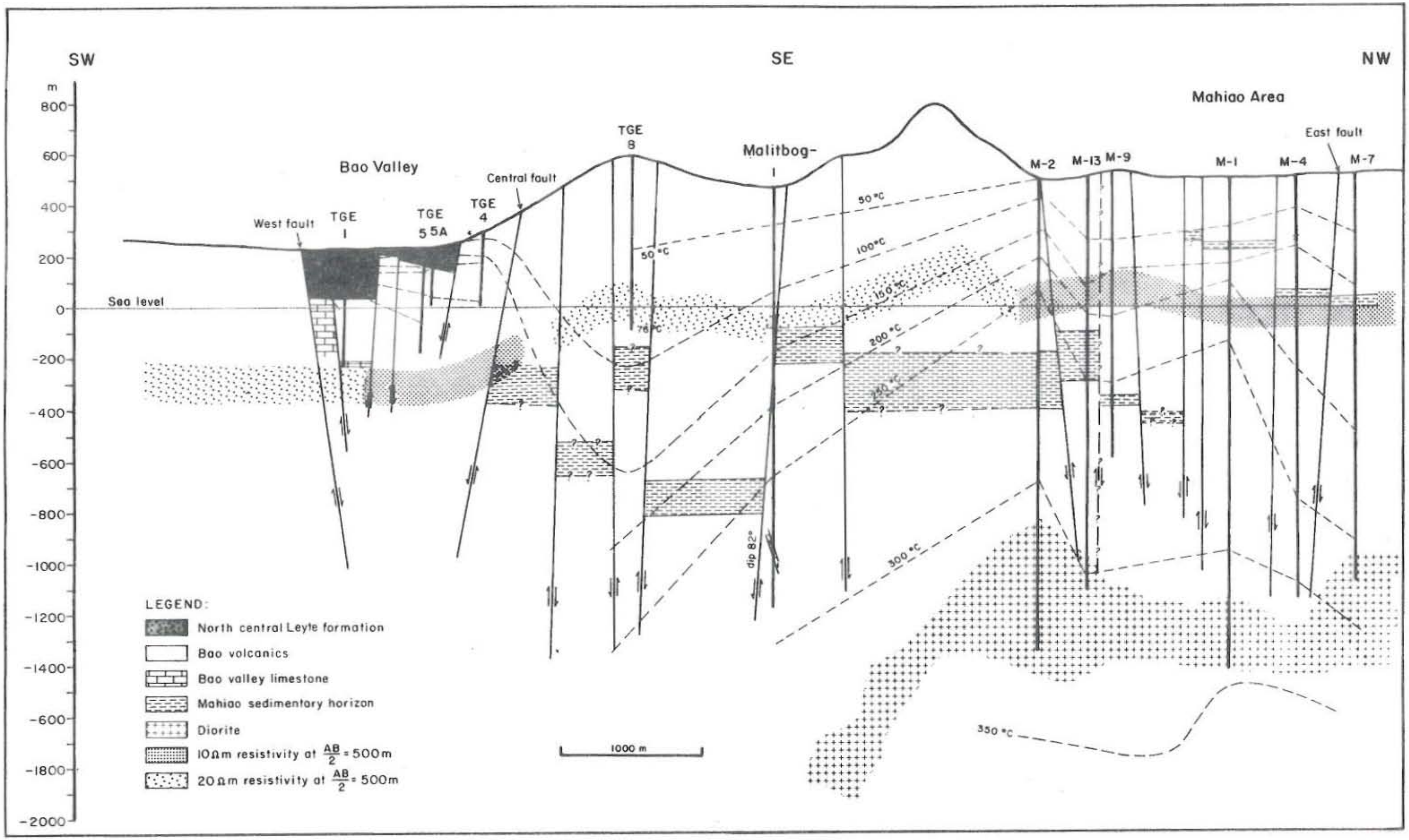


Fig. 6 Cross-section across the Bao and Mahiao-Malitbog areas showing structures, isotherms, lithology, well locations, and resistivity anomalies at $\frac{AB}{2}$ = 500m

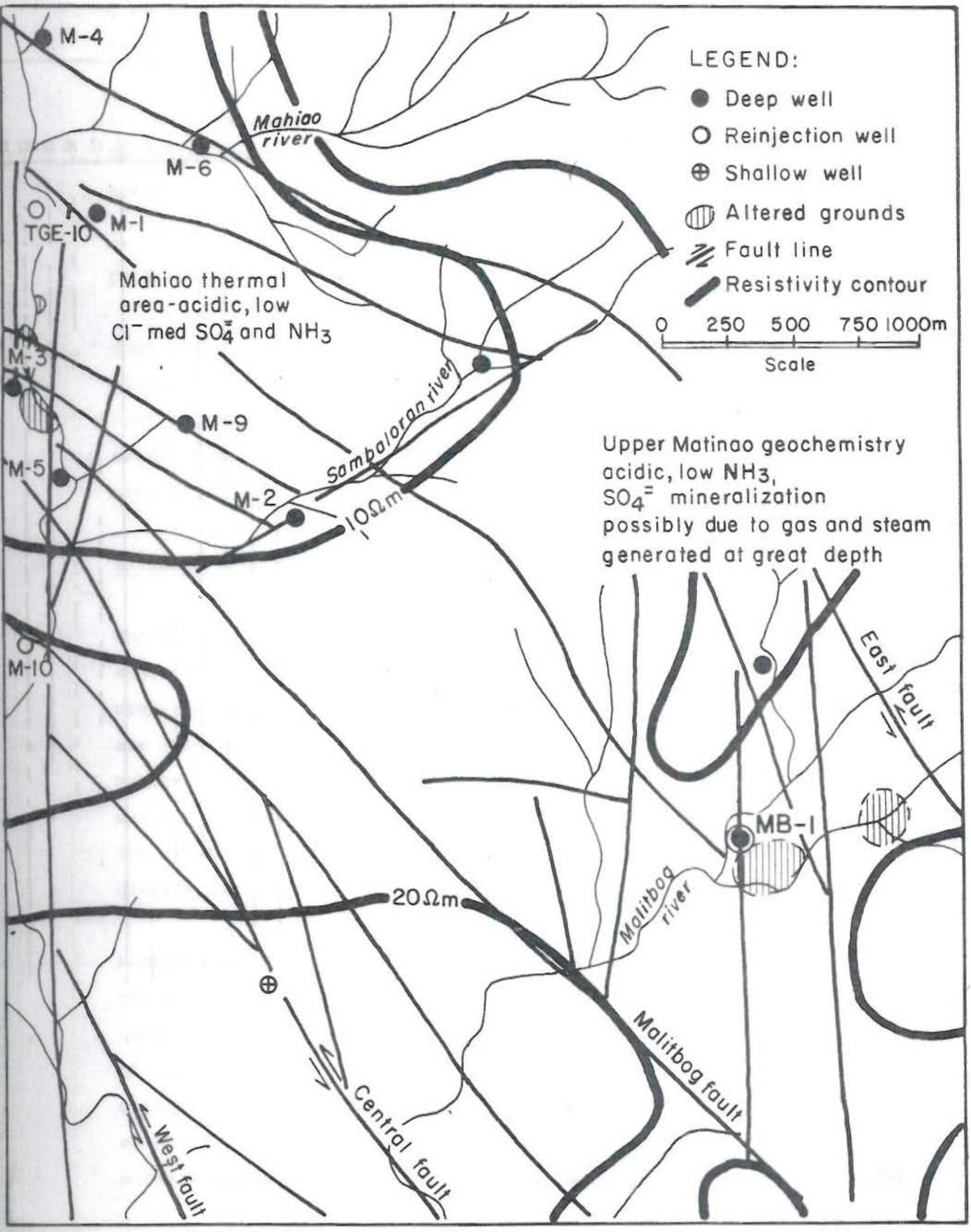


Fig. 7 Structural geology and geochemistry of the Mahiao-Malitbog area. Resistivity contours based on $\frac{AB}{2} = 500$ m.

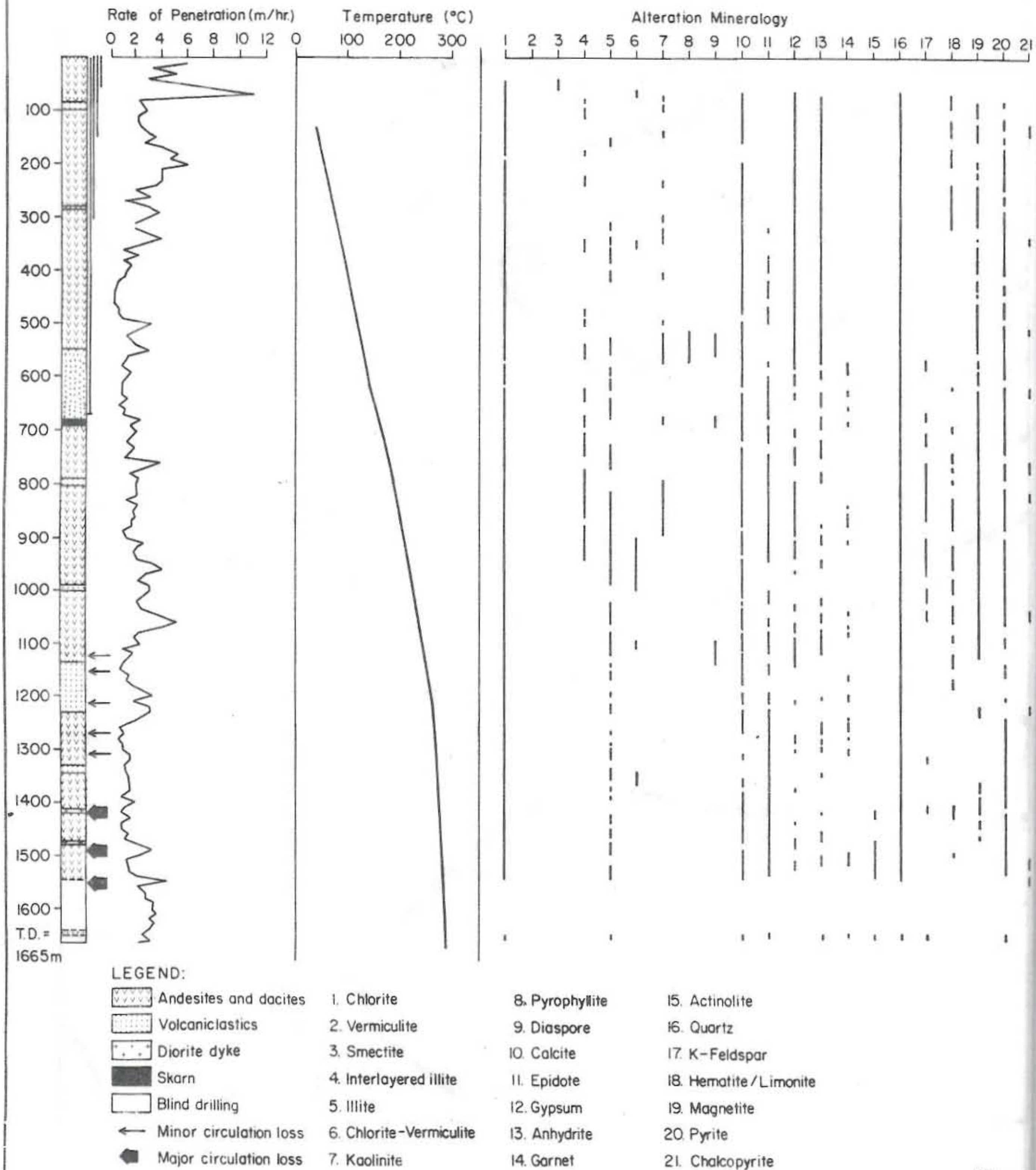

Rate of Penetration (m/hr.)
0 2 4 6 8 10 12
Temperature (°C)
0 100 200 300
Alteration Mineralogy
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
T.D. =
1665m
LEGEND:
Andesites and dacites
Volcaniclastics
Diorite dyke
Skarn
Blind drilling
Minor circulation loss
Major circulation loss
1. Chlorite
2. Vermiculite
3. Smectite
4. Interlayered illite
5. Illite
6. Chlorite-Vermiculite
7. Kaolinite
8. Pyrophyllite
9. Diaspore
10. Calcite
11. Epidote
12. Gypsum
13. Anhydrite
14. Garnet
15. Actinolite
16. Quartz
17. K-Feldspar
18. Hematite/Limonite
19. Magnetite
20. Pyrite
21. Chalcopyrite

Fig. 8

C.P. Wood (14) commented that the Malitbog area was originally the site of a very high temperature system. He speculated that either:

1. A dying system (on a geological time scale) still supplies the hot water tapped by the well and whose center may have migrated northwest to become the Mahiao field, or

2. The Malitbog fluids come from the active Mahiao field and are penetrating south into the alteration zones of an extinct system.

Wood (13) suggested that the migration of volcanic centers along main structural trends could be applied to the migration of the heat source to Mahiao. There is a straight line along the structural trend from Janagdan, a volcano with solfataric activity south of the area (13).

## 2.3 Borehole geology

The well was drilled through a predominantly volcanic sequence of andesitic and dacitic composition with hornblende as the main ferromagnesian. Pyroxenes are rare. Thin beds of siltstone and microbreccia are intercalated with andesite flows. These are correlated with the Mahiao Sedimentary Horizon. A thin metamorphic calc- silicate zone was encountered at 683-692 m and diorite dikes at 1415 and 1476 m. The first major circulation loss occurred at 1420 m, just by the first diorite dike.

Megascopically, the volcanics range from being bleached with silicification to greenish grey when weakly altered. Both dacite and andesite lavas are porphyritic hypo- to holo- crystalline containing phenocrysts of plagioclases and ferromagnesians laid in a glassy or feldspathic matrix. The dacites are distinguished from the andesites by the presence of interstitial quartz. A thick pyroxene bearing hornblende andesite occurs at 405- 494 m and at 908- 994 m.

The sedimentary horizon consists of brown siltstone, breccia, sandstone, and banded shale- like rocks intercalated with lava flows. The common constituents of the sedimentary horizon are volcanic detritus ranging from fragmental plagioclases to sub- rounded lava fragments laid in a fine- grained matrix. Two major occurrences are recognized ; above the calc- silicate zone at 550- 680 m and at 1135- 1230 m.

The diorites consist of interlocking laths of twinned plagioclases blemished by incipient alteration and relict ferromagnesians pseudomorphed by chlorite.

The appearance of black calcareous rocks marks the calc- silicate zone. Calcite, anhydrite, idocrase, and wollastonite form granoblastic masses upon which abundant garnets are found clustered. A contact metamorphic origin had been thought of to explain this localized 9 m thick zone, but no large intrusive body that would cause high temperatures could be found in the vicinity. A number of evidences, enumerated below suggest that this calc- silicate zone could be the locus of a large fault:

1. Matching sequences separated by about 500 m interval. Just above the calc-silicate zone is a sedimentary horizon with a total thickness of approximately 130 m and these are topped by about 90 m of pyroxene bearing hornblende andesite. A pyroxene bearing hornblende andesite is found at 908-994 m with a similar thickness. Alteration had obliterated some of the original structures of the rock but the presence of pyroxene is distinct. Thin sections of three corresponding sedimentary horizons at depths 268 and 780 m, 475 and 945 m, 515 and 1049 m, displayed distinct similarities in texture. There is little mixing of cuttings from the upthrown block and the downthrown block since the hole above 670 m had been cased off.

2. Petrographic evidence for rock stress within the calc silicate zone and the formations 120 m above and below the calc silicate zone were observed:

a. i) In the calc silicate zone the wollastonite crystallographic axes show a parallelism within a given fragment; ii) some calcite crystals exhibit undulatory extinction, curvature of lamellae and twinning lamallae which, according to Moorehouse (35) are due to rock deformation, iii) flow bands defined by black isotropic material were observed in some calc- silicate chips.

b. In both downthrown and upthrown blocks, the following features were found :

i. Curved twinned plagioclases

ii. Fifty meters above the calc-silicate zone is a highly altered rock with secondary mineralogy forming marked flow bands, while 18 m below the zone are fine grained chips highly altered to illite and anhydrite. The illite follows curved flow lines which are relict.

iii. Sheared volcanics are common. Granulated plagioclase and quartz are arranged with their long axes parallel to each other.

Cataclastic features in the rock chips are observed at deeper levels, and extend to the permeable zone implying that 1) either the hole was drilled through a fault plane which seems unlikely or several faults cut the rock 2) one of the factors for the fracturing in the permeable zone is due to faulting.

The major fault encountered in the well is correlated with the surface fault found 100 m west of Malitbog- 1. According to the drillhole data presented here it has a displacement of about 500 m and dips 82° to the east.

The Malitbog calc silicate zone exhibits both cataclastic and crystalloblastic features. Petrographic evidence shows that the calc- silicate zone was formed under stress conditions.

The calc- silicate zone is characterized by high temperature silicate minerals such as garnets, wollastonite, and idocrase associated with coarse mosaics of calcite. Such mineral assemblages are discussed in the available literature in relation to high grade contact metamorphism of impure limestones (33, 45, 28, 34, 16). The presence of wollastonite indicates a temperature of about 400-600°C.

It is likely that the intensity of the fault was such that high frictional heat was generated and the recrystallization of the calcareous rock was further enhanced by the presence of fluids probably hydrothermal (35).

Minor circulation losses from 1125- 1420 m may mark the intersection of a fault. Significant losses encountered from 1420- 1665 m are probably due to a secondary permeability created by faulting and the subsequent intrusions of the dikes.

Fractures and vugs above 1125 m are tightly sealed off with quartz, alkali feldspars, and anhydrite.

## 2.4 Alteration

### 2.4.1 Alteration Minerals

#### Clay Mineralogy

The formation of clay minerals is sensitive to chemical conditions, temperatures and pressures and their abundance facilitates their use as environmental indicators. With clay minerals as a base, mineral associations are used as a means of determining temperature ranges at a given depth and in effect, the thermal history of a well (14, 29).

Clay minerals in the present study were identified using a Philips PW 1050/25 wide range goniometer connected to a PW 1130/00 X-ray generator. Oriented samples were air- dried, glycolated, and heated to 550°C for two hours. In a few cases, further heating to 700°C for one hour was done. For the 060 reflection unoriented samples were run. After recognizing the reflections, thin sections from similar depths were examined and correlated with the XRD results. Where identification is doubtful, auxiliary techniques such as infra- red spectrometry and microprobe were used. (See Appendix VI).

CHLORITE occurs from the surface to the bottom of the well where it permeates the formerly glassy matrix and renders the rock green. It is usually found altering hornblende. It fills interstices, lines vugs and fractures and is sometimes seen to grow from plagioclases. It is more common than illitic clay in the lavas and the diorites but is overwhelmed by illitic clay in tuffaceous rocks. The main reason for the abundance of chlorite in the lavas and diorites is the presence of ferromagnesian minerals which could easily contribute the necessary Fe

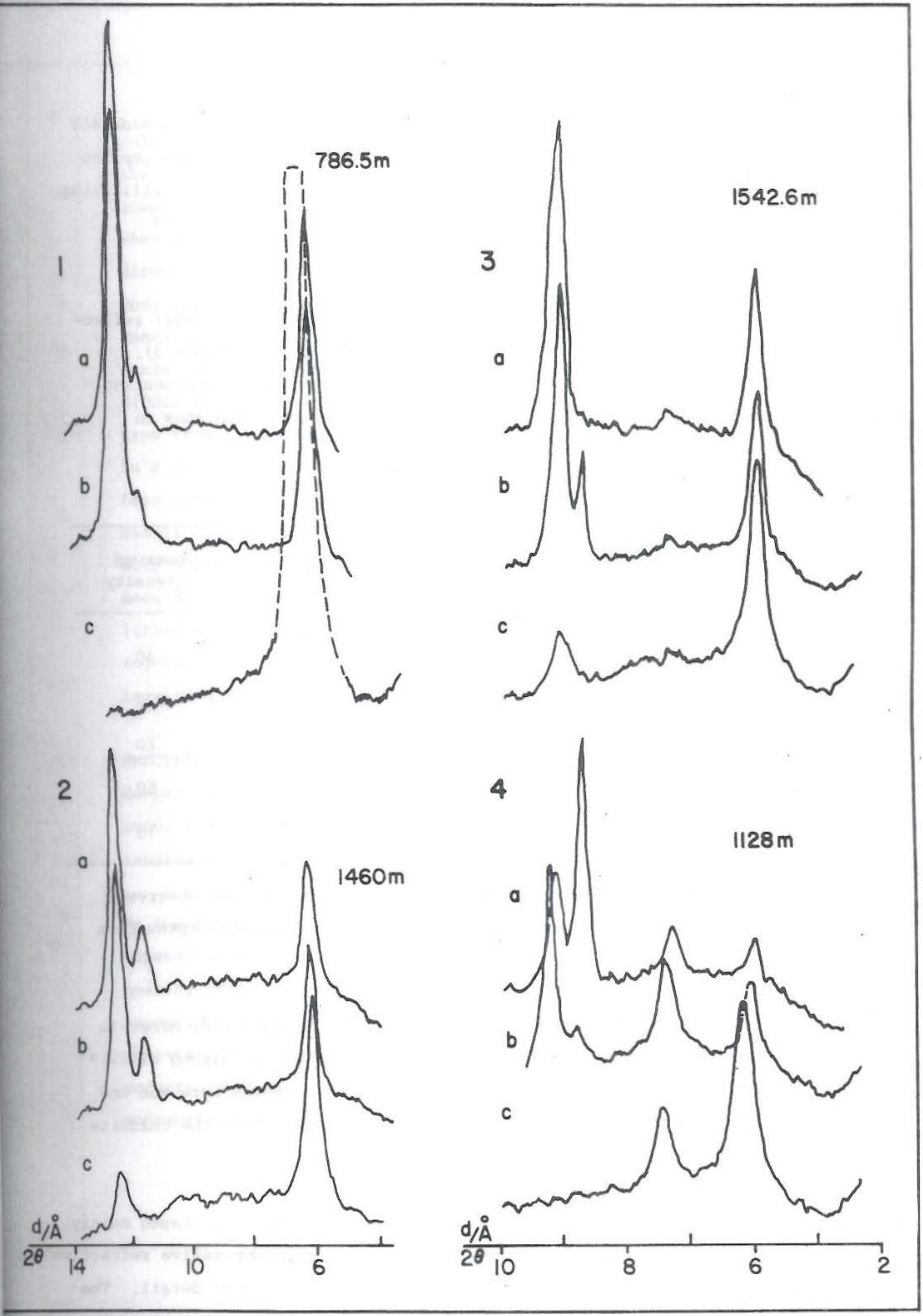


Fig. 9 Mg- Fe chlorites from various depths.

and Mg needed for the formation of chlorite. Ferromagnesian minerals were seldom observed in the tuffaceous rocks. The data also implies that porosity, and conceivably permeability plays a role in illitizing a tuff. This does not disprove the temperature dependence of illite or chlorite formation.

For 16 samples, XRD shows a large range for d(001) and d(002) reflections but with little change in the d(003) to d(005) (Table 3). Glycolation has little effect on most of the chlorites and heating enhances d(001) while d(002) either disappears or diminishes in intensity (Fig. 9)

| d(001) | Range Å | Average | Observed intensity |
|---|---|---|---|
| 001 | 14.15- 14.717 | 14.44 | 40 |
| 002 | 7.07- 7.28 | 7.16 | 100 |
| 003 | 4.72- 4.79 | 4.74 | 20 |
| 004 | 3.53- 3.58 | 3.55 | 60 |
| 005 | 2.84- 2.86 | 2.84 | 13 |

Table 3. Range of d(001) reflections, average values and observed intensity of chlorites from 16 samples taken at various depths from Malitbog-1.

The chlorites are usually associated with one or more clay minerals and in addition the d(004) is sometimes masked by the strong d(020)= 3.49Å of anhydrite. A few unoriented chlorite samples were run and the characteristic 060 reflection at 1.536 Å shows that the chlorite is trioctahedral.

Three types of chlorite could be distinguished optically, based mainly on differences in birefringence, orientation, and comparative refractive indices, since the fibers are too tiny to be examined in detail. The colours exhibited in the chlorites are most likely a function of the iron content. In thin section the chlorites are pleochroic, green filaments occurring as aggregates which have maximum absorption when the length of the fibers are perpendicular to the vibration direction of the lower polarizer. The birefringence is low. The most common type shows anomalous dark blue to blue- violet interference colours and the minerals are length- slow. The use of Albee's table shows that it is a Mg-Fe chlorite, and the relatively stronger d(002) and d(004) corroborates optical findings. A chlorite of this type from 1122 m was probed, and the analysis shows that the chlorite is a pycnochlorite (after Hey's classification, (16) (see Appendix IV). Less common are length- fast, anomalously brown chlorites which are nearly colourless in plain light. The third type is a green chlorite with normal grey interference colours. This type is rare and has only been found as a fracture fill. Since these don't show any marked lithological, temperature or depth preference and are often found together in a single thin section, their differences may be due to localized conditions, such as chemical differences and/or permeability.

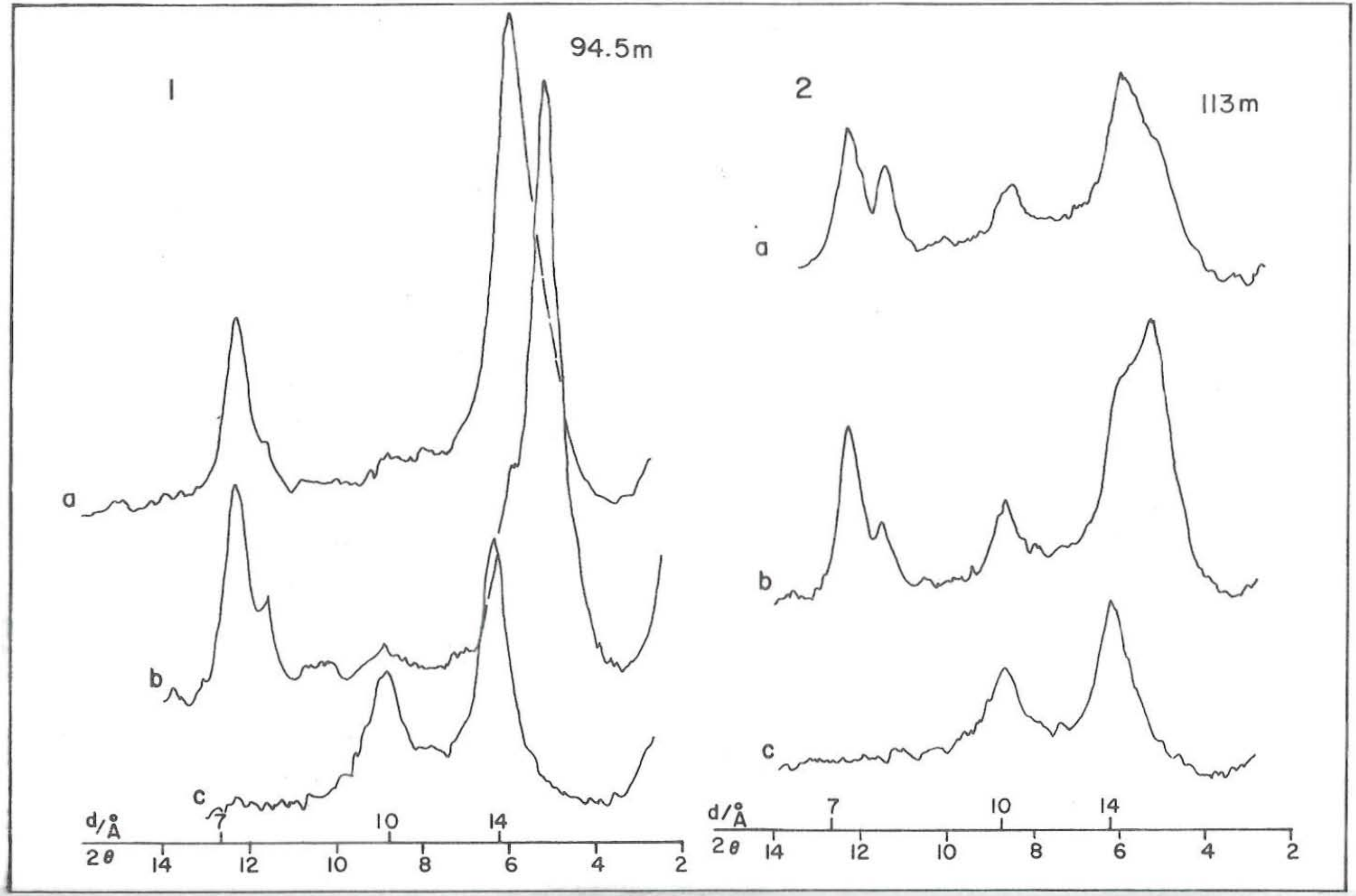
SMECTITE has a very narrow depth and temperature range, occurring not deeper than 113 m and at temperatures less than 40°C. The smectites occur in a volcanic breccia and a porphyritic hornblende andesite lava ranging from weakly to highly altered.

In the two oriented samples analysed, it shows a 14.7 Å peak which expands to 17.25 Å with glycolation and shrinks to 9.95- 10 Å upon heating (Fig. 10). It is found associated with chlorite and interlayered illite in both samples, and since its d(060) could not be ascertained, the smectite species is not identified though its occurrence in an andesite along with illite hints at it being montmorillonite.

| Depth m | Air- dried | Glycolated | Heated |
|---|---|---|---|
| 94 | 14.7 | 17.25 | 9.95 |
| 113 | 14.84 | 16.98 | 10.155 |

Table 4 d(001) values of smectite in Å

Fig. 10  1. Smectite and chlorite with gypsum  2. Smectite, interlayered illite, chlorite and gysum at 113 m.  a. untreated  b. blycolated  c. heated at 550°C for two hours.



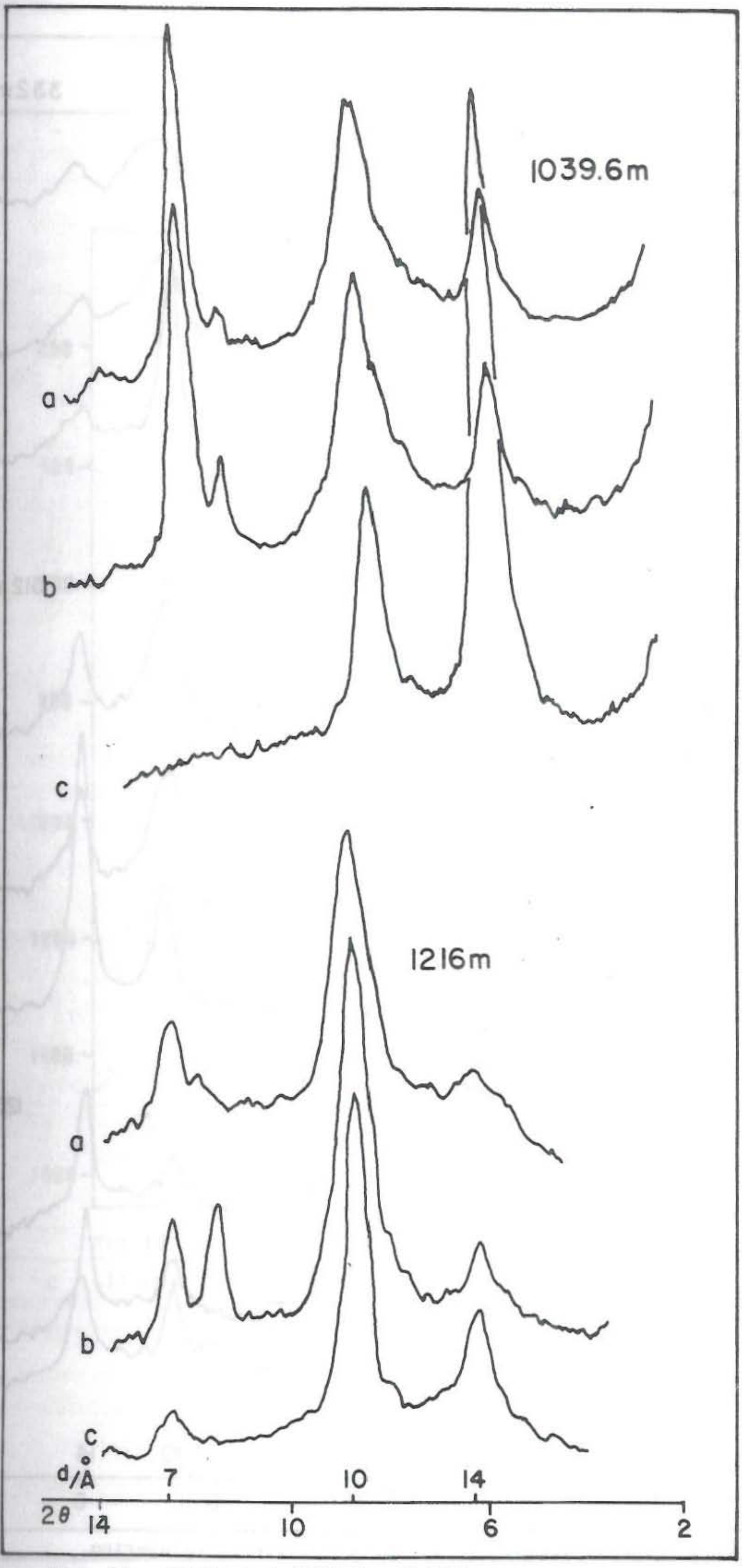


Fig. 11   Illites at 1039.6 and 1216 m.

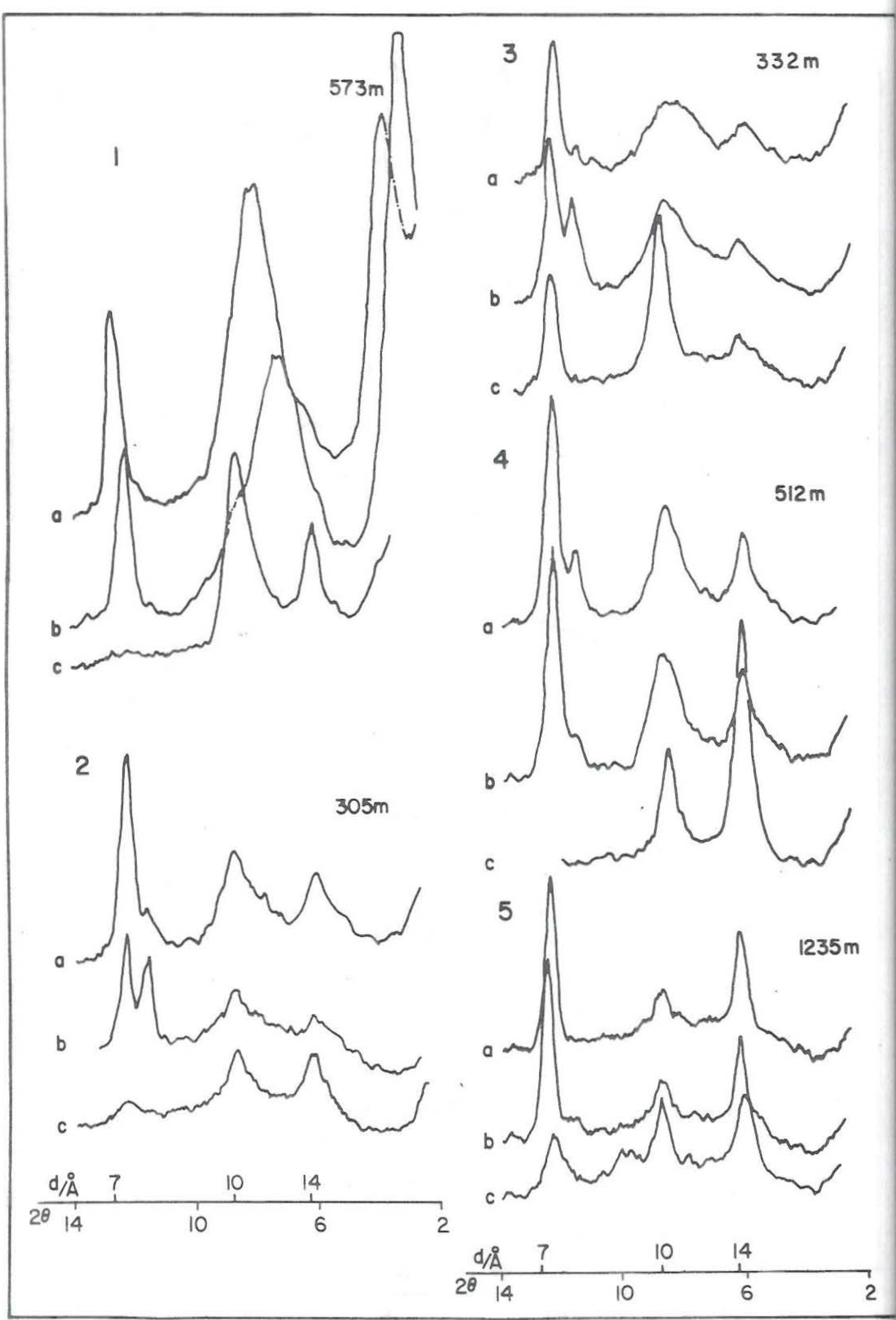


Fig. 12 Various degrees of smectite- illite interlayering.

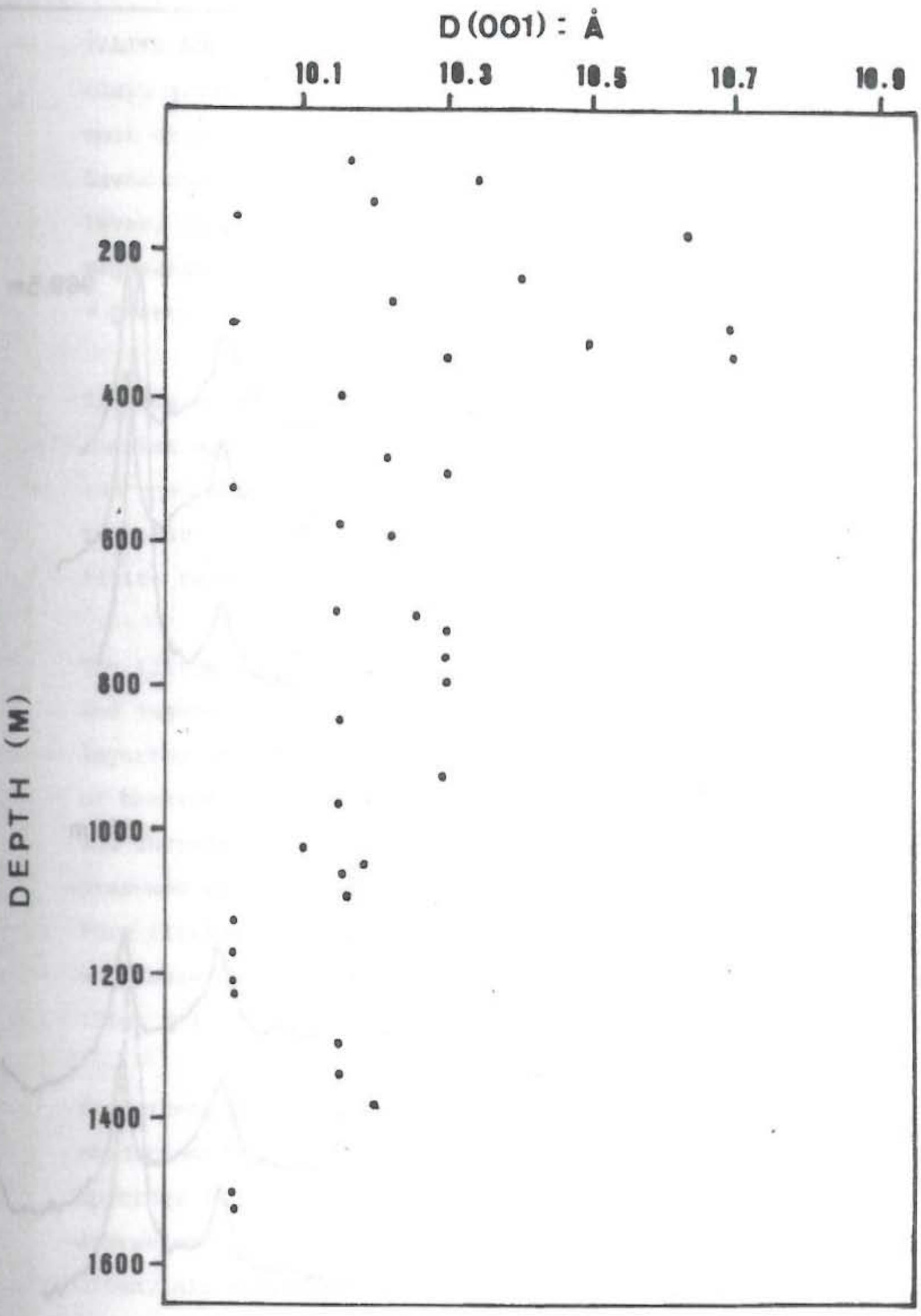


Fig. 13 The distribution of illite and interlayered illite d(001) with respect to depth.

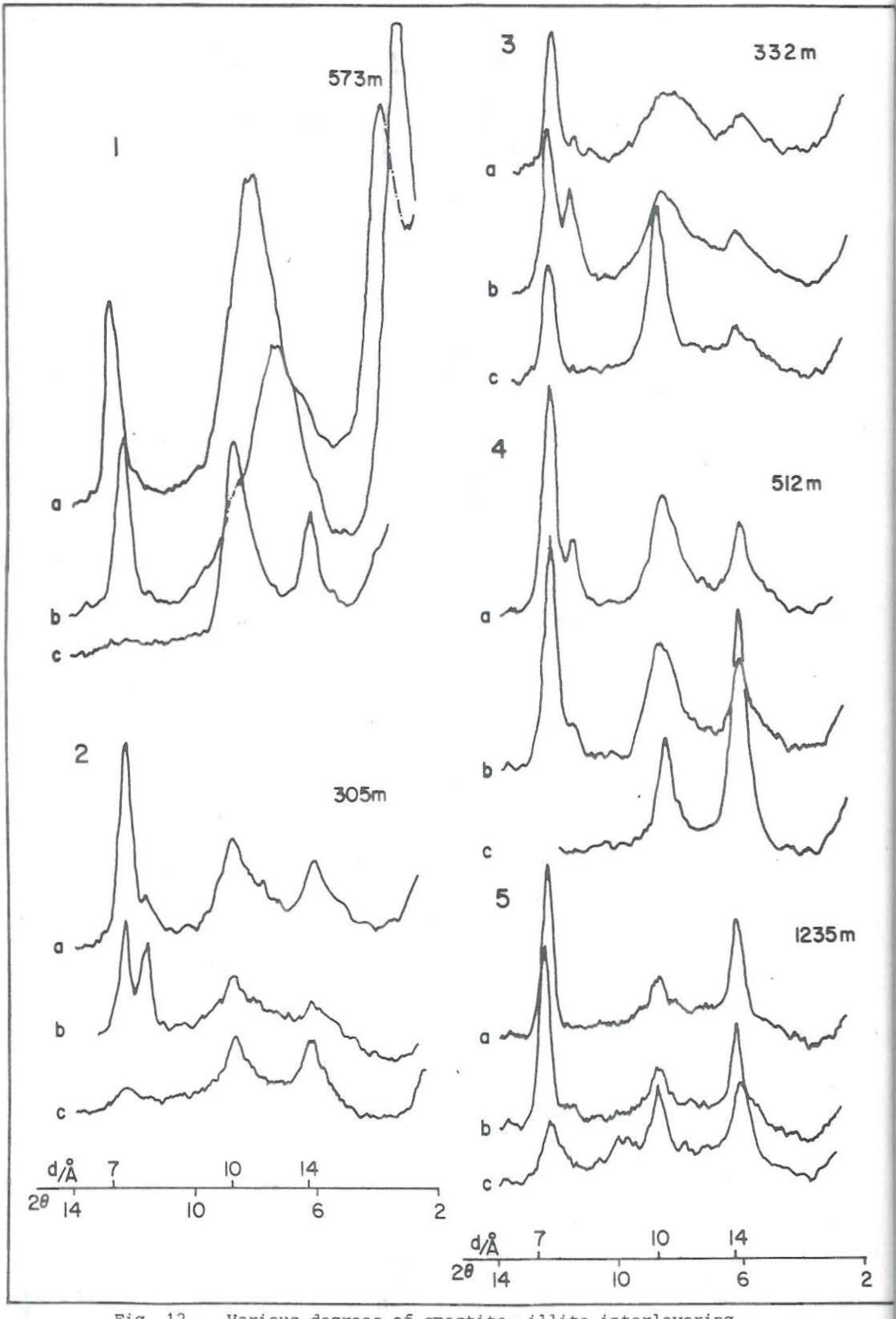


Fig. 12 Various degrees of smectite- illite interlayering.

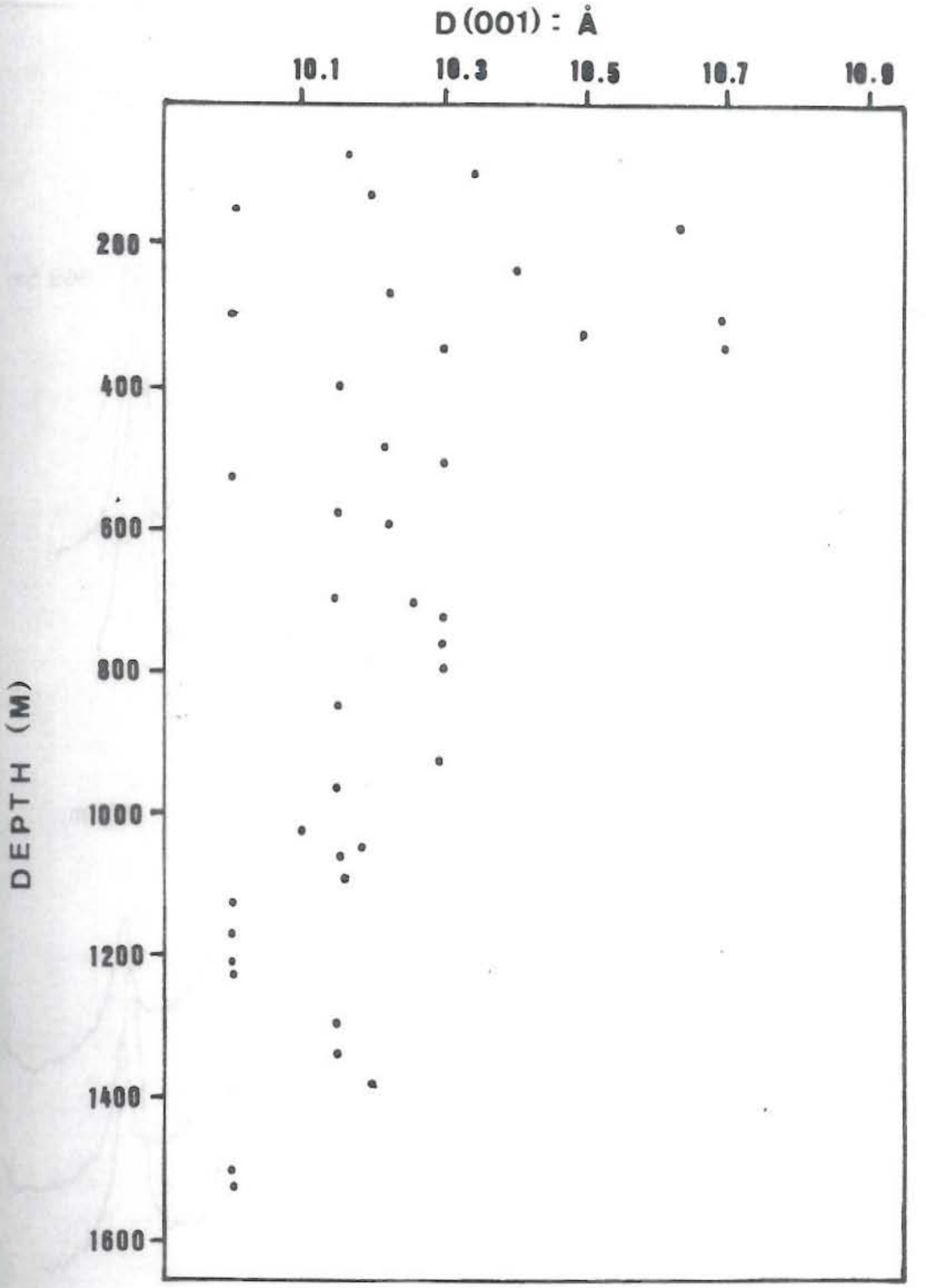


Fig. 13 The distribution of illite and interlayered illite d(001) with respect to depth.

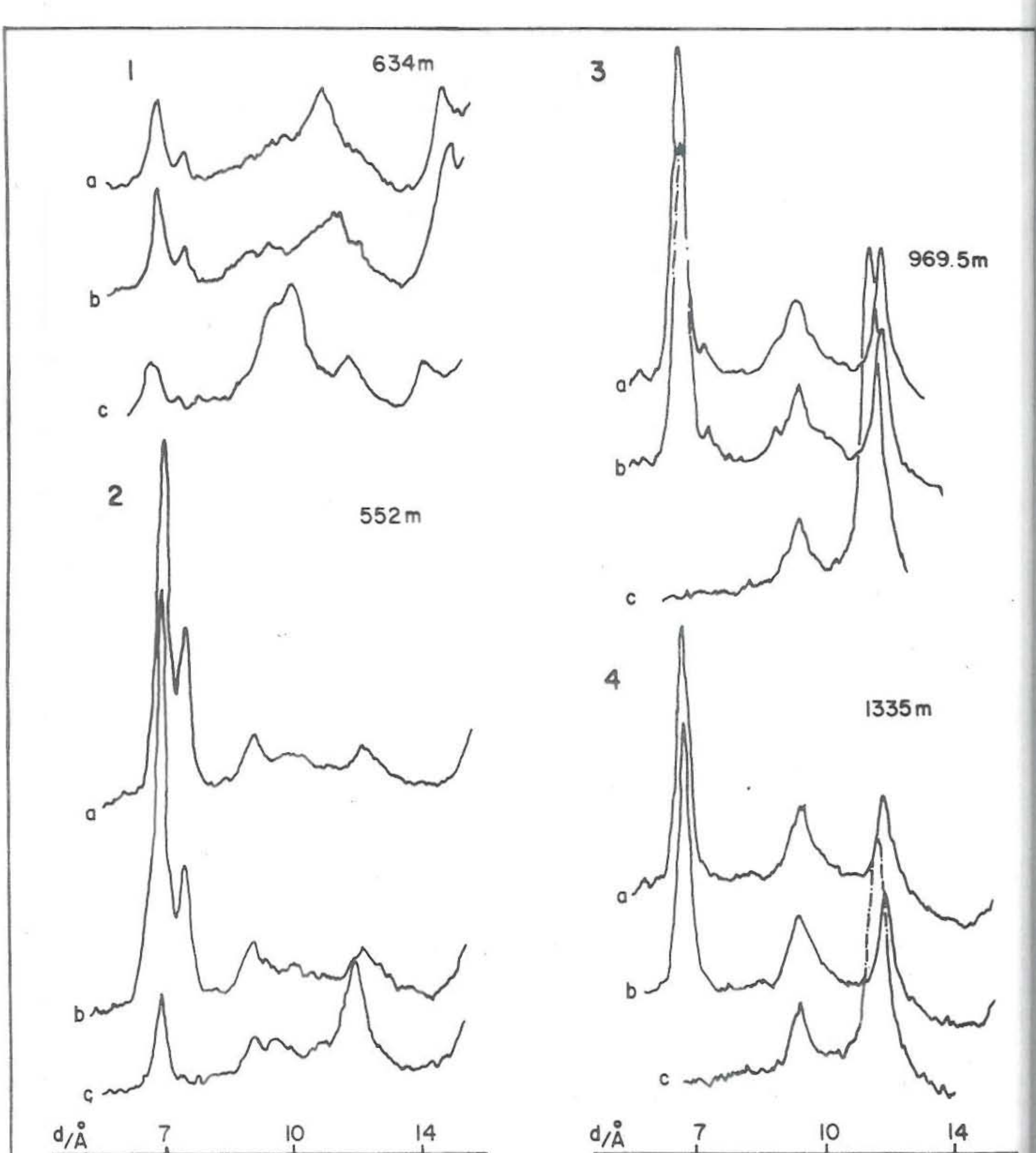


Fig. 14 1. Mixed- layered chlorite- smectite at 634 m 2. Random interlayering of chlorite- smectite- illite at 552 m.
3. Mixed- layered chlorite- vermiculite at 969.5 m
4. Mixed- layered chlorite- vermiculite at 1335 m.

ILLITE AND INTERLAYERED ILLITE- SMECTITE. The abundance of these clays gives the rock mass a greyish tinge. These are found to be most abundant in tuffs or breccias with a tuffaceous groundmass. Lavas and intrusives are less illitized and when illite occurs in lavas, it preferentially attacks the plagioclases with the ferromagnesians altering to chlorite and the groundmass to Illite + Chlorite + Quartz.

Illites with 10- 10.16 Å peaks were first noted at 143 m. These coexist sporadically with interlayered illite down to about 1000 m and then persists to the bottom as relatively pure illites. The temperature range at these depths is 65- 284°C as compared to the illite range in Mahiao of 230° - 300°C. (Wood, see Appendix I).

The illite d(001) peaks are seldom well defined but are usually broad and jagged (Fig. 12). The broadness may be due to irregular interlayering of different micas, which is not affected by either glycolation or heating. The jaggedness which becomes distinct upon glycolation and shrinks to a sharp peak on heating is probably attributed to the presence of some smectite layers (Kristmannsdottir, pers. comm.). Pure illites are here defined as having peaks at d(001)= 9.93- 10.155 Å and these do not exhibit any deviation upon glycolation and heating (Fig. 11).

Smectites, in response to increasing temperature and pressure conditions are gradually changed to illites which show lesser basal spacings (40). It is only in few cases that smectite occurs in appreciable amounts in interlayered illite- smectite (Fig. 12.1 Often, air dried samples exhibit jagged humps with undefined peaks around d(001)= 10.155- 10.64Å.

Steiner (1977) divided the (001) of illite and interlayered illites into high (10.4- 11.78Å), intermediate (10.28- 10.4) and low (9.93- 10.4) values and correlated the decrease of the basal spacing with increasing temperatures and nearness to aquifers. Using his definition, the d(001) of the illites in Malitbog-1 were plotted (Fig. 13 ). Above 671 m, where temperatures are <40°- 160°C, points are scattered and intermediate, high and low values are superimposed. Below 1006 m, where temperatures are >225°C, the points cluster around 10 Å. His studies show that the low values exist at temperatures greater than 230°C.

This implies that the illites below 1006 m are in equilibrium with present temperatures but the scattered values at shallower depths do not necessarily mean disequilibrium since varied permeability conditions may have the same effect.

Besides altering plagioclase and the groundmass, illite occurs as interstitial wisps, and as crevice- and fracture- fills. It is often associated with quartz, alkali feldspar, calcite, chlorite, and sometimes epidote, anhydrite and pyrite.

In thin section illite occurs as colourless filaments arranged in radial clusters, in matted flakes or fibrous aggregates with a parallel arrangement. Refractive indices and birefringence vary with the degree of interlayering with smectite. Interference colours range from first order white to colours similar to calcite.

A dark green somewhat pleochroic sheet silicate with yellow green interference colours and found to pseudomorph tabular primary minerals, has been observed at 1122 m. This is associated with a highly illitized tuff. The chemical formula calculated from the microprobe results, shows an illitic clay grading to nontronite (Appendix IV). Similar occurrences are found at 408.5 m, 969 m, 1097 m, and 1335 m. Diffractograms exhibit broad illite peaks (Fig. 13.4).

MIXED LAYERED CLAYS. Except for the interlayered chlorite- vermiculite, the randomly interlayered clays are confined to narrow zones.

Irregularly mixed layers of chlorite- smectite- illite at 634 m (45) are associated with chloritized andesite (Fig. 16.1). The measured temperature is 150°C.

Mixed layer chlorite- smectite at 552 m showed a 14.7 Å peak in the air- dried sample with ill- defined humps between $2\theta = 6° - 8.5°$. Upon glycolation, the 14.7 Å shifted to 14.8 Å and shrinked down to

14.48Å on heating accompanied by the enhancement of the 10.27Å peak (Fig. 14.2). This was found within a crystal- and clastic- volcanic breccia with a tuffaceous matrix, the latter being moderately altered to a brownish clay giving interference colours near to illite. Temperature of occurrence is 130°C. For comparison it is worth noting that chlorite-smectite occurs in the thermal area, Otake, Japan, at a temperature range of 80- 200°C where it associated with neutral to weakly alkaline fluids (23).

Chlorite- vermiculite occurs in highly altered volcanic breccias with a tuffaceous matrix, the latter being mostly altered to clay. This could be the brownish green to dark green somewhat pleochroic clays with interference colours of yellow green. In air- dried samples, basal reflections are found at 14.67- 14.72Å which show little change when glycolated but heating causes the peak to shift to lower values with a corresponding increase in intensity. Upon heating the 10 Å peak generally becomes better defined (Fig. 14.3, 14.4). The temperature range of occurrence is from 100- 270°C. Mixed layer chlorite- vermiculite is reported from the Yugawara thermal area, in Japan, where it occurs at a temperature range of 40- 60°C. From the available literature, it seems that chlorite- vermiculite is a low temperature phenomena, originating from the low temperature alteration of ferromagnesians and is a component of some soils (17, 20, 44). However, experiments by Roy and Romo (1957) show that above 300°C, vermiculite may form into a pseudo- chlorite. Either the chlorite in Malitbog is being degraded to vermiculite or the vermiculite has been altered to chlorite. The first seems less likely since experiments by Roy and Romo (op.cit.) led them to conclude that vermiculite could not exist above 200°C.

Interlayered clays imply metastable conditions and in active geothermal areas mark a transition zone to clays with more stable and compact structures. The occurrence of mixed layered clays in the drillhole at such deep levels (1335 m) and high temperatures (270°C) implies disequilibrium conditions.

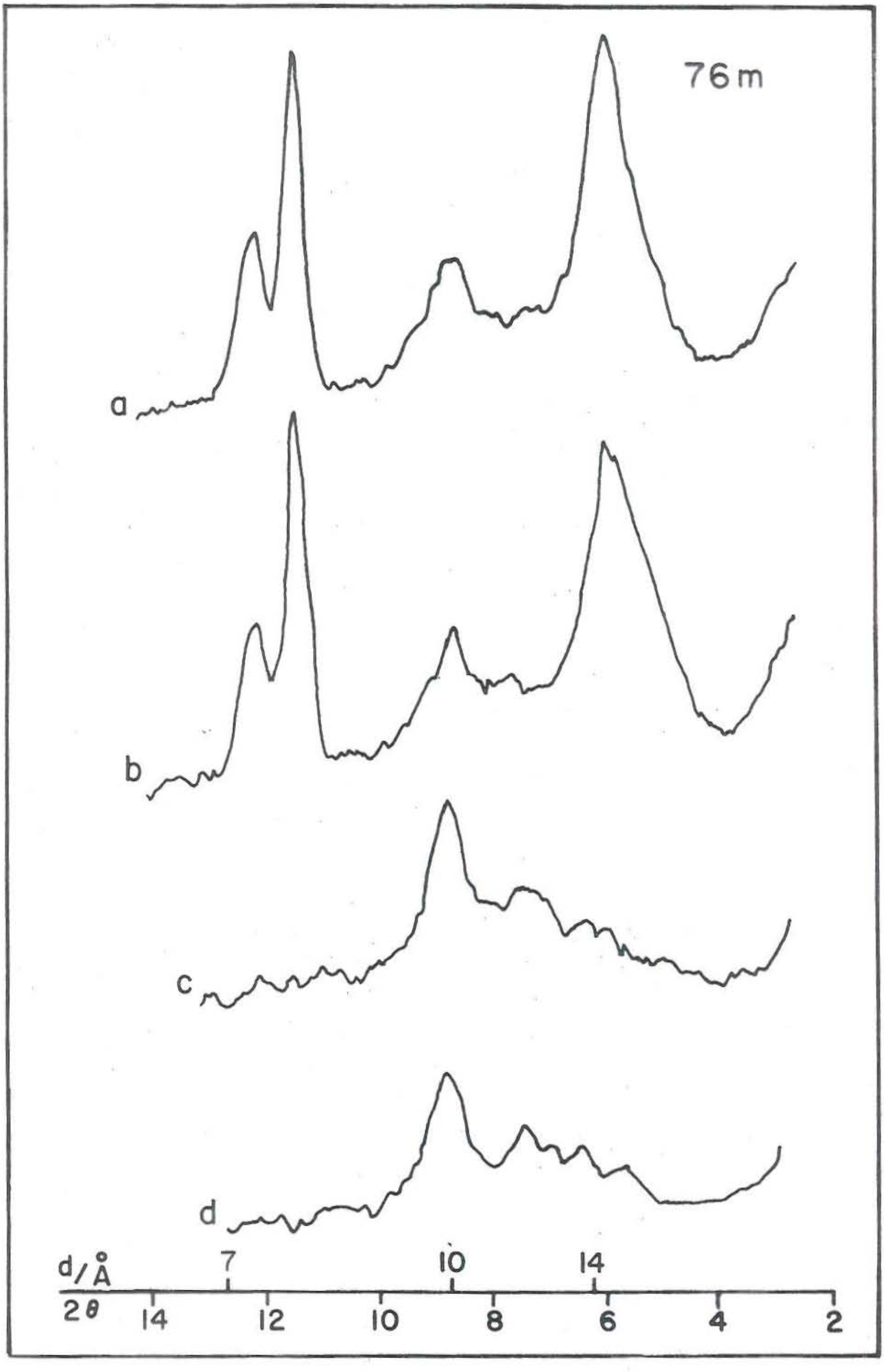


FIG **15** X- ray diffractogram of vermiculite with illite and gypsum. a. air- dried b. glycolated c. heated to 550°C for 2 hours d. heated for 1 hour at 700°C.

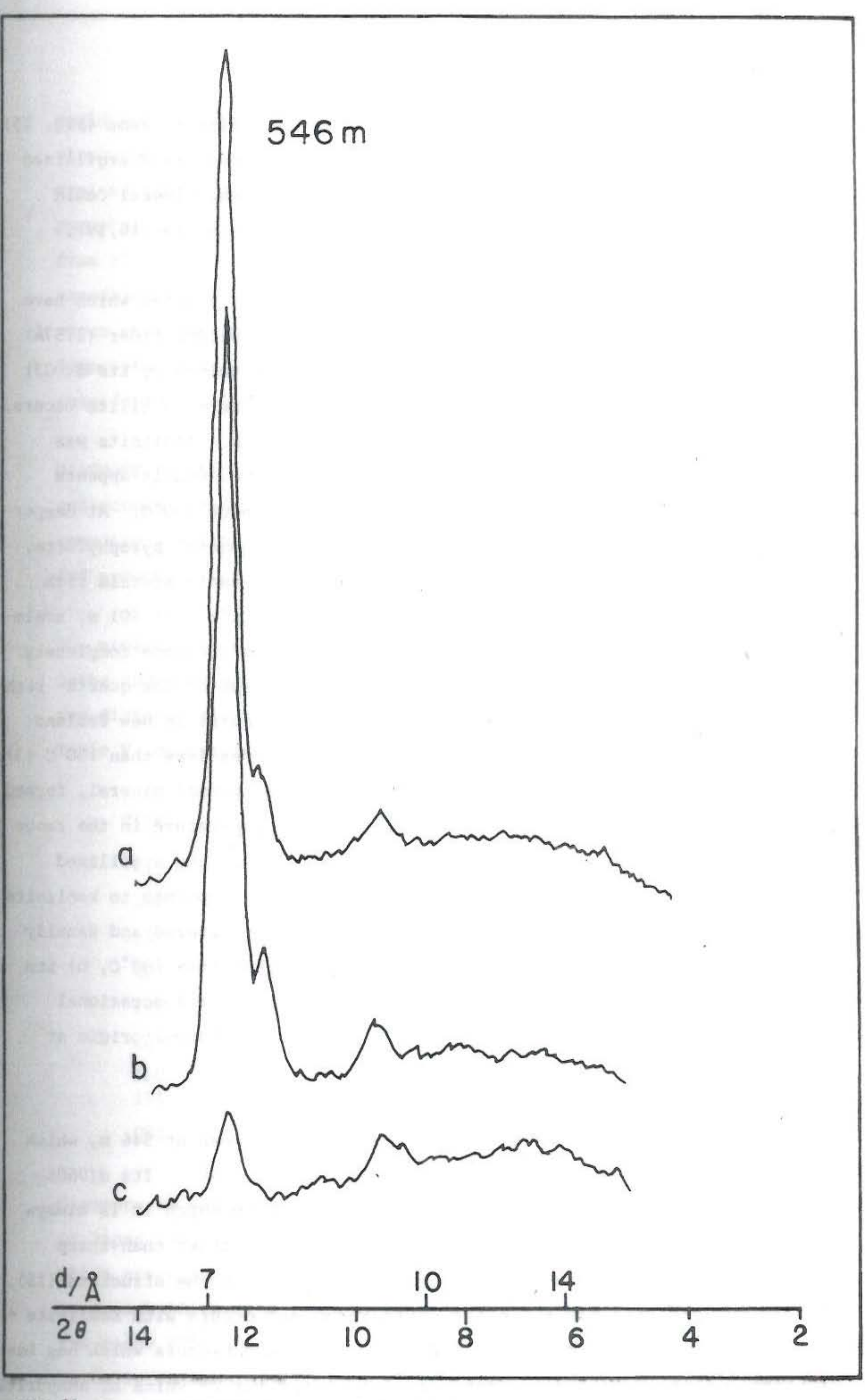


FIG. 16 X- ray diffractogram of kaolinite and pyrophyllite with gypsum.

VERMICULITE was identified at 76 m from X-ray diffractograms (Fig. 15) and IR spectra, in a highly bleached, intensely pyritized argillized volcanic rock. Since this is near the surface, the mineral could merely be a weathering product from chlorite or biotite (16,19).

KAOLINITE is usually associated with the Mg- Fe chlorites which have sharp peaks coincident to its first (7.16Å) and second order (3.57Å) reflections. The presence of kaolinite is ascertained by its d(003) reflection at 2.38Å. Some unoriented samples, where no illite occurs, were also run to find its 060 reflection at 1.49Å. Kaolinite was detected at 76 m where it occurs with vermiculite, and it appears sporadically down to 893 m where temperatures reach 230°C. At deeper levels, it is found associated with anhydrite, quartz, pyrophyllite, and diaspore. It is found in highly altered volcanic breccia rich in quartz, with little of its original texture left. At 801 m, scale-like aggregates of low refractive index and birefringence completely alter primary lath- shaped crystals and form wisps on the quartz- rich matrix. Kaolinite is considered a supergene mineral in New Zealand where it occurs at shallow levels and temperatures less than 100°C (3). In Otake, kaolinite is considered to be a hydrothermal mineral, formed in acidic conditions where pH= 2- 5, and the temperature in the range of 80- 200°C (22). The occurrence of kaolinite in the argillized andesites at shallow levels in the well Malitbog 1 points to kaolinite as supergenetic, but a) its occurrence in highly altered and usually silicified volcanoclastics at temperatures higher than 100°C, b) its intimate association with specific minerals and c) its occasional occurrence as crevice- fillings indicates a hydrothermal origin at deeper level.

PYROPHYLLITE was identified by its broad 9.22 Å peak at 546 m, which did not change with heating or glycolation (Fig. 16). Its d(060) could not be resolved from that of kaolinite with which it is always associated. Its tendency of having broad peaks rather than sharp reflections indicates a high degree of disorder in the structure (15). The pyrophyllite has a limited depth range and occurs with kaolinite + quartz + anhydrite from 537- 564 m in a bleached breccia which has been highly altered to a silicified mass and later cut by veins of anhydrite, anhydrite + coarse quartz mosaic and anhydrite + diaspore. Pyrophyllite could not be detected optically. It may, however, be the fine minute elongated crystals with yellow birefringence, associated with fine-grained quartz pseudomorphing after primary tabular crystals. The pyrophyllite- diaspore association implies a temperature of formation from 275- 405°C ( 16 ). The pyrophyllite- diaspore - kaolinite assemblage in Japan is considered relict since this is believed to occur at temperatures of about 310°C (16). This assemblage has a temperature range of 122- 134°C in the well Malitbog 1 and is here considered fossil.

DIASPORE is mainly found in highly altered tuff or volcanic breccia and occurs sporadically down to 1128 m. At 686 m and above, it is commonly associated with aluminum sheet silicates such as kaolinite and pyrophyllite, together with anhydrite and quartz.

The mineral is found in clusters or in veinlets as highly birefringent laths and distinguished from the associated anhydrite by having only one distinct cleavage. Unoriented samples were run on the XRD, and Table V enumerates the identified diaspore peaks.

| d(hkl) | d Å |
|---|---|
| 110 | 3.97 |
| 330 | 2.55 |
| 111 | 2.315 |
| 121 | 2.13 |
| 140 | 2.078 |
| 221 | 1.632 |
| 160<br>151 | 1.479 |
| 061 | 1.372 |

Table V . Peaks of diaspore occurring at 543 m.

Diaspore is not a common hydrothermal mineral and its occurrence, as in Japan (15, 24, 45), is usually accompanied by Al- rich silicates which are thought to be formed in acidic conditions. When accompanied by pyrophyllite, the temperatures of formation are believed to be in the range 275- 405°C (16). As the mineral occurs at much lower temperatures in Malitbog 1 (Table V ), it is believed to be relict from a past hydrothermal activity. Deer et al. (1966) mention that diaspore could form from the alteration of a buried alumina silica gel produced by weathering of silicates in the tropics, or that it could form as a hydrothermal product of pyrophyllite. Although no evidence could be found from microscopic analysis, some of the diaspore may possibly have formed from pyrophyllite, and this could explain the absence of this mineral with diaspore at deeper levels. Its occurrence in veins shows that some of the mineral has been precipitated from the fluids.

ANHYDRITE AND GYPSUM. Anhydrite is abundantly distributed throughout the drillhole, altering the volcanics, volcaniclastics, dykes and occurring as patches in the skarn. Anhydrite occurs mainly in clusters of colourless anhedral crystals with high refractive indices. Its high interference colours and rectangular cleavages distinguishes it from other minerals. Gypsum is usually found with anhydrite and is distinguished by having lower refractive indices and duller interference colours. In the XRD, gypsum has a distinct peak at 7.56 Å while anhydrite has a strong d(020) reflection at 3.49 Å. Calcium sulphate minerals alter both plagioclases and ferromagnesian minerals. They occur in veins commonly with associated quartz, and are also found as patches in the rock matrix. Their occurrence as fracture fills is most marked in the upper levels of the well where intense silicification is observed. Anhydrite was found associated with most of the secondary minerals encountered in the well. It is common to find anhydrite associated with two or more minerals in a vein or in the process of altering primary minerals. Gypsum is found with anhydrite to a depth where the temperature exceeds 280°C, which is far above the stability range of gypsum (19). Thin sections show patches of gypsum within anhydrite and islands of anhydrite within gypsum grains. It seems improbable that anhydrite is being hydrated to gypsum at such high temperatures, and the only explanation conceivable is that some of the anhydrite was hydrated to gypsum after it had been taken out of the hole. Samples from similar depths in Malitbog 1 were analyzed by C.P. Wood in 1978, but there is no mention of gypsum in his report.

EPIDOTE. The appearance of epidote in the nearby Mahiao field marks depths at which temperatures are 250°C and higher. However, epidote's initial appearance in MB-1 is at 329 m where the measured temperature is only 85°C. It appears sporadically to a depth of 375 m, where its existence becomes marked, and from there shows a general increase with depth and temperature. Intense epidotization gives a yellow-green colour to the rock mass. In thin section, epidote is recognized by its patchy yellow green colour and pleochroism, and its high interference colours. These alter ferromagnesians, plagioclases, the rock matrix and, indirectly, magnetite. Epidote is also found as vug- and fracture- fillings where it is associated with quartz, chlorite, anhydrite, calcite, garnet, actinolite, and pyrite in combinations that could number up to four individual mineral species. Steiner (1977) gives a comprehensive description of the transgression of magnetite to leucoxene to epidote in Wairakei, a phenomena similarly found in Malitbog but at lower temperatures. Since epidote has weak reflections in mixtures of many minerals, most of the identification is through the petrographic microscope. Samples were examined in the microprobe and the results are tabulated in Appendix IV. The epidote found at shallow depths is considered relict. And those epidote minerals occurring at high temperatures and deeper levels may not entirely be due to the present day activity. Examination of thin sections does not show any evidence that could be used to distinguish an earlier- formed epidote from a later one.

ACTINOLITE is a high temperature mineral that is found at 280°C and above in Iceland (31) and at 300°C and above in Mahiao (45). Its temperature of occurrence in Malitbog is 284°C. It is found in a propylitized volcanic breccia cored at 1655 m, where it is associated with epidote, alkali feldspars, calcite and anhydrite. The actinolite forms yellow green laths and is distinguished from epidote by its amphibole cleavage and lower birefringence. Actinolite is found in veinlets associated with calcite, quartz+calcite+adularia. It is seen to be formed from the alteration of hornblende, and also found to form clusters in the groundmass.

GARNET in Malitbog 1 could both be a contact metamorphic and a hydrothermal mineral. Its petrogenesis as a contact metamorphic mineral is well- defined in its occurrence as thick clusters in the skarn zone, but its existence though sporadic at such a wide depth range from 579 m to T.D., implies a hydrothermal origin of the garnet. Garnet is usually found in the well as clusters of anhedral to subhedral crystals in weakly to moderately altered volcanics, and is commonly found associated with Ca-bearing minerals such as calcite, anhydrite, epidote, and actinolite, as is evidenced in the bottom core. In a thin section of cuttings from 1079 m, euhedral garnet is found in a vein together with anhydrite, epidote, and chlorite and it looks as if it were growing from epidote and anhydrite. The garnets have high refractive indices and are completely isotropic, unlike the andradites from Okoy- 5 in Southern Negros (3). Three garnet types could be distinguished, based on their colours. The yellow- green garnet is most common in both the volcanics and the calc- silicate zone; crystals were picked from 689 m and run in the XRD, and these show peaks similar to that of andradite. Colourless and golden brown garnet is also found for example, in a vein at 1079 m. The garnets in the volcanics occur in a temperature range of 120°C- 284°C. Garnets are found in Mahiao at temperatures above 290°C, while hydrothermal garnets found in the Salton Sea exist at temperatures above 320°C (14, 11). Temperatures of as low as 170°C had been reported for metasomatic Ca- Fe garnets in the Indian Ocean Ridge (24).

CALCITE. Unlike occurrences in the Mahiao wells, the calcite abundance in Malitbog-1 does not show any marked decrease with the appearance of epidote, though at certain levels, epidote could be observed growing over calcite crystals. It is as ubiquitous as quartz, having a wide vertical range in the drillhole, indiscriminately altering the matrix, plagioclases, and the ferromagnesian minerals, filling up vugs and fractures and occurring as the main mineral in the skarn zone. It could be associated with one or more of the secondary minerals including actinolite. However, thin sections show that it seldom occurs with diaspore, Kaolinite and pyrophyllite. In the bulk samples run on the XRD, calcite is recognized by its peak at d/Å= 3.02.

SECONDARY QUARTZ. Quartz is pervasive throughout the hole. It occurs as coarse to fine mosaics altering the matrix, plagioclases, and ferromagnesians, and also occurs as vug- fills and fracture fills often associated with anhydrite. This is most marked in the upper levels of the well where anhydrite / quartz have completely sealed off openings together with secondary feldspars, pyrite, calcite epidote, pyrite, and sometimes, chalcopyrite. Quartz could also be found where circulation losses were encountered, as elongated euhedral six- sided crystals occupying vugs together with alkali feldspars.

SECONDARY ALKALI FELDSPARS. Browne (15) established secondary feldspars as permeability indicators, with adularia predominant in the aquifers. Wood suggested that similar occurrences in the Mahiao field could be correlated with permeable zones (11). In Malitbog 1, such a correlation is more difficult as both adularia and albite could be recognized in the impermeable, highly silicified zones above the production zones. This gives evidence of the high permeability of this level prior to self- sealing. Alkali feldspars were detected in the matrix and fills vugs together with quartz, as shallow as 576 m, in a silicified volcanic breccia. Identification of the alkali feldspars is mostly through examination of thin sections. Since they are usually tiny it is quite difficult to distinguish albite from adularia. Often neither exhibits any twinning, but occur as clear, colourless crystals interspersed with quartz. Adularia and albite from Core 5 taken at 1654 m were examined in the probe and the analyses showed that the adularia is nearly pure and the albite, which is found altering a plagioclase, has only a small percentage of the anorthite component (Appendix IV). Both albite and adularia are found in the production zone from 1420 m to the bottom, and according to Browne's findings, indicates a moderate permeability, but completion tests rated Malitbog's permeability as excellent (5). Finding alkali feldspars above the production zone indicates an old high permeability zone that has been sealed off by deposition of silica and feldspars. Based on the presence of alkali feldspars, similar fossil aquifers are also recognized at depths ranging from 570- 1052 m. The alkali feldspar is often encountered in volcanic breccias where the groundmass is largely altered to quartz and cut by veins of anhydrite, and it is sometimes also found associated with pyrite and chalcopyrite in veins.

IRON OXIDES. Hematite/limonite occur sporadically along the length of the hole and may mark former high oxidizing conditions in the upper levels of the hole and a probable inflow of water in the production zones. Unlike magnetite, which is usually found as disseminations, hematite was only found as reddish veinlets, whereas limonite occurs as orange stains in the rock matrix or concentrated on the margins of clasts.

LEUCOXENE. The term "leucoxene" is used to describe amorphous cottony material found in the matrix as discrete clusters, altering magnetite and it is also commonly found altering the rims of hornblendes. It is dull brown to white in reflected light. Leucoxene is a descriptive term rather than pertaining to a mineral with a specific composition, such as hydrous titanium oxide (27). Leucoxene is observed to incipiently crystallize to an epidote- like mineral with similar highly birefringent colours.

SULPHIDES. Besides pyrite, a few sporadic occurrences of chalcopyrite were observed from 128 m to the bottom of the hole. It is distinguished from pyrite by a golden tinge to its bronze colour, and sometimes by bluish, metallic "highlights" on its surface. It is found in silicified volcanics as disseminations and in veinlets. Pyrrhotite, galena, and sphalerite were reported from previous logs (1, 14) but were not observed in this study. Pyrite occurs from surface to bottom as fine disseminations, large cubic crystals in the groundmass, and as an alteration product of magnetite, ferromagnesians, and leucoxene. Megascopically pyrite is a distinct bronze coloured metal and in the XRD of bulk samples it is identified by its peak at d/Å= 1.63. The distribution of pyrite does not show any pattern with increased depth or magnetite content. Its presence is not only confined to zones of silicification. It is also found as fine disseminations in weakly altered volcanics.

The minerals of the calc silicate zone are discussed in brief below.

GARNETS occur as thick clusters on the calcite mosaic and can comprise about 25% of a rock chip. This is unlike the sporadic and sparse occurrences of garnets in the volcanics. Yellow green, golden brown and colourless garnets, similar to those in the volcanics are found in this zone.

WOLLASTONITE is not as common as garnet in this zone. It is found as elongated tabular crystals of relatively high refractive index. Interference colour is grey and the interference figure is biaxial negative.

Wollastonite forms from the contact metamorphism of an impure limestone or when Si is introduced during the metamorphism of a limestone. The formation of wollastonite from calcite and quartz is used as a geothermometer (16). At 1 kb it forms at about 580- 680°C and at 2 kb, temperature of formation ranges from 610- 750°C. The reduction of the partial pressure of $CO_2$ could lower the temperature of formation of wollastonite (33).

Idocrase has a high refractive index, parallel extinction and is uniaxial negative. According to Miyashiro (1973), the occurrence of idocrase with wollastonite in skarn zones in Oslo appears nearest to the intrusive. High temperature then, must have occurred during the formation of the calc- silicate zone.

CALCITE forms a coarse mosaic of equant grains that usually exhibit strain features such as 1) undulatory extinction, 2) curvature of lamellae, and 3) the presence of twinning lamellae which are often found in deformed marble (35).

### 2.4.2 Alteration of the Primary Rock Components

Malitbog 1 drilled through a thick sequence of intermediate volcanics interrupted by sedimentary horizons and a calc- silicate zone. Diorite dikes were encountered where massive circulation losses occurred. The andesites carry phenocrysts of plagioclase and hornblendes, and rarely, pyroxene. The groundmass is either glassy or feldspathic. Dacites are distinguished from andesites by the presence of interstitial quartz. The diorites are largely composed of plagioclase laths and minor hornblende. The sedimentary horizons invariably contain volcanic detritus such as plagioclase crystals and andesitic clasts.

The ferromagnesian minerals and glassy matrix are more susceptible to alteration than the plagioclases. Where rocks are weakly altered, the ferromagnesian minerals alter mostly to chlorite+calcite, and with increasing intensity of alteration they are found being altered to leucoxene, pyrite, anhydrite, quartz, epidote, and actinolite. When occurring in highly illitized tuff, the ferromagnesian minerals are found altered to a greenish illitic clay. The glassy matrix is reduced to chlorite, clay, quartz, alkali feldspars, with disseminations of leucoxene and pyrite.

Plagioclases change to a greater variety of alteration minerals than the ferromagnesians, e.g., chlorite, anhydrite, epidote, illite, quartz, calcite, and, where silicification is intense, to albite and adularia. With increasing degree of alteration, the plagioclase becomes cloudy with incipient alteration, zoning disappears, and twinning becomes blurred.

Magnetite alters to pyrite and leucoxene and exhibits a lesser degree of dependence on temperature for its alteration than the other primary minerals. It was found altered to pyrite and leucoxene in relatively weakly altered rocks but it can also be found in highly altered volcanics as abundant disseminations. The chemical environment in localized areas may dictate the stability of magnetite e.g., sulfur and oxygen fugacities.

## 2.5 Discussion of Results

### 2.5.1 Introduction

Several phases of hydrothermal metamorphism have affected the rock sequence in Malitbog 1 and large displacements have complicated the stratigraphy as well as the secondary mineralogy. Alteration minerals from previous hydrothermal events are juxtaposed over the assemblages due to the present hydrothermal regime. Comparison of data with the nearby Mahiao field (Table VI) and information from New Zealand and Japanese geothermal areas (15, 33) show that some of the assemblages are in disequilibrium with present conditions.

The calc-silicate zone is believed to be the axis of a large inactive fault which was intercepted by the well. The calc-silicate assemblage is confined to a narrow zone and it is postulated here that the magnitude of frictional heat generated at the time of movement may be reflected by the high temperature mineralogy such as wollastonite, idocrase and abundant garnet clusters. This is a typical assemblage of high grade contact metamorphism in limestone (33).

Hydrothermal activity is often thought of as a process in which geothermal parameters such as temperature, pressure and permeability are diffused away from the source and the reservoir. Mineral assemblages are formed accordingly and exhibit a sequence with respect to temperature and pressure for a given rock type and fluid chemistry.

With increasing temperature, a sequence of smectite to illite to predominantly chlorite had been established by C.P. Wood (1979) in the Mahiao field which is only 2.3 km away from Malitbog. Similar geological conditions prevail in Malitbog as in Mahiao. Furthermore, similar hydrothermal minerals occur in the Malitbog 1 as in the other wells in the Mahiao; the same sequence is observed in Malitbog 1 but the first occurrences are at shallower depths and lower temperatures.

The boundaries between the various temperature- dependent mineral assemblages are more diffuse (Fig. 18). At deeper levels, however, some of the assemblages in Malitbog grade into "equilibrium" conditions.

Localized zones of pyrophyllite and/or kaolinite and diaspore appearing down to a depth of 910 m are comparable to occurrences in the Japanese geothermal fields of Matsukawa and Otake. Studies by Hayashi (1974) and Sumi (1969) show that these preferably form in acidic conditions.

### 2.5.2 Types of Hydrothermal Alteration

The alteration minerals in Malitbog 1 are divided on the basis of their mode of occurrence:

1. Calc- silicate assemblage. This consists of garnets, wollastonite, idocrase and calcite. Though anhydrite is found associated with these minerals, it was not formed contemporaneously with the others and is believed to have been introduced to the zone during a later hydrothermal activity. The calc- silicate assemblage is believed to mark the axis of the big fault intercepted by well Malitbog 1.
2. Hydrothermal assemblages show a general trend of increasing grade with depth and temperature. The mineralogy consists of calcite, anhydrite, epidote, actinolite, quartz, alkali feldspars, chlorite, clays of the illite- smectite group, and possibly garnet. Sporadic and localized appearances of pyrophyllite, kaolinite, and diaspore were observed.

### 2.5.3 Summary and Interpretation of Results

The alteration in Malitbog 1 is not a continuous sequence of increasing intensity with depth. Instead, patches of high alteration may alternate with zones of weakly altered rocks. The intensity of alteration depends on the primary and secondary porosity and permeability of the formations.

The type of secondary mineral assemblages encountered at given depths in Malitbog 1 are governed by the original rock type, permeability, temperature and possibly, by differences in chemical conditions. The temperature and permeability dependence of the hydrothermal minerals is often masked by the complex history of faulting and hydrothermal surges that affected the area. Where temperatures in the hole are high, epidote, illite, and actinolite are found; and where permeability is good, alkali feldspars occur. Relict mineral assemblages implying high temperatures and permeable zones are found at shallower levels in the hole. Lithology of the rock seems to play an important role when alteration is low grade. But when alteration grades to high silicification, the lithology of the rock shows little influence on alteration.

Following studies from New Zealand and Japan (15, 33), the smectite-illite clays proved to be effective geothermometers in the much drilled Mahiao area, northwest of Malitbog 1. Three general temperature dependent zones were defined earlier on the basis of these clays; 1) the smectite zone occurs from the surface to a depth where the temperature is 130°C, 2) interlayered smectite - illite occurs from 130-250°C and 3) with increasing temperatures illite becomes dominant till 300°C where chlorite becomes the dominant sheet silicate in the rock (48). The same divisions could be made in the Malitbog 1 well but the transition from one zone to another is over a longer depth interval. It is possible that the geothermal gradient is lower in the Malitbog area than in Mahiao, as could be seen from Fig. 6 but the difference is not large enough to account for the broad boundaries of the clay zones (Fig. 18). Another possibility is a displacement in a fault, the same strata would be encountered again deeper in the hole, and thus give an apparent broadening of the transition zones.

The Malitbog 1 intercepted a fault with a displacement of about 500 m. Its locus is believed to be on the calc silicate zone. Just above the calc silicate zone are sedimentary horizons with a total thickness of 130 m, and these are topped by 89 m of pyroxene- bearing hornblende andesite. The same type of andesite is encountered 503 m below the same formation. Besides the good matches between the formations found at different depths, petrographic evidences suggest that a large fault caused the granulation and shearing observed in the rocks around the calc- silicate zone, strain features exhibited by calcite and plagioclases, and microfaults found in epidote and plagioclase crystals. The main proof of the intensity of the fault may be found in the calc-silicate zone wherein high temperature minerals such as wollastonite and idocrase occur along with garnet and calcite. A black isotropic material which occurs in streaks may be a kind of glass coming from the melting of the rock during deformation.

Cataclastic features are not only observed near the calc- silicate zone but also far down the hole, and in the permeable zone implying that; 1) either the hole was drilled through a fault plane which seems unlikely or several faults cut the rock sequence, though less in magnitude than the aforementioned fault, 2) one of the factors for the fracturing in the permeable zone is due to faulting.

Relict illite and mixed layer clays occur at shallow levels where temperatures are far below their "equilibrium" temperatures. Illite forms at about 230-250°C in Mahiao. Assuming temperatures following the boiling point curve an uplift of the area amounting to 100 m occurred.

Chlorite spans the whole length of the hole and sporadic appearances of chlorite interlayered with vermiculite, from near surface to depths of 1360 m where temperatures of 270°C are found. The anomalous extension of this mixed layer clay to such depths may be resolved by elevating the sequence by 500 m across the fault towards lower temperatures and shallower depths.

Apparently, pyrophyllite+ kaolinite+ diaspore+ quartz appear at two depth intervals: 518- 579 and below this till 910 m. Matching up the formations across the fault shows that the diaspore and pyrophyllite with associated kaolinite seems to be confined to a narrow zone in the sedimentary sequence.

Kaolinite is a supergenetic mineral near the surface but may be hydrothermal at depths where it is associated with pyrophyllite and diaspore.

The assemblage pyrophyllite + diaspore + kaolinite + quartz was possibly formed before the faulting.

Quartz and anhydrite are the most abundant vein materials, and together with alkali feldspars and some calcite probably sealed off former aquifers found in the upper regions of the well. The same group of minerals are also found at 1420 m to the bottom of the hole.

Garnets in the calc- silicate zone are found to comprise as much as 25% of a rock chip. Similar types of garnets are found in the other formations but are sparse, comprising less than 5% of the rock mass. Some of the garnets are believed to have a hydrothermal origin though relict.

Epidote at shallow levels where temperatures are lower than 250°C are considered relict but at depth, relict epidotes could not be distinguished from the epidotes presently being formed. Actinolite may be relict too.

The presence of base metal sulphides such as chalcopyrite indicates the presence of a regime whose fluids must have been saline enough as to be able to contain a large percentage of solids such as copper, perhaps quite similar to waters encountered in the Mahiao (Appendix II).

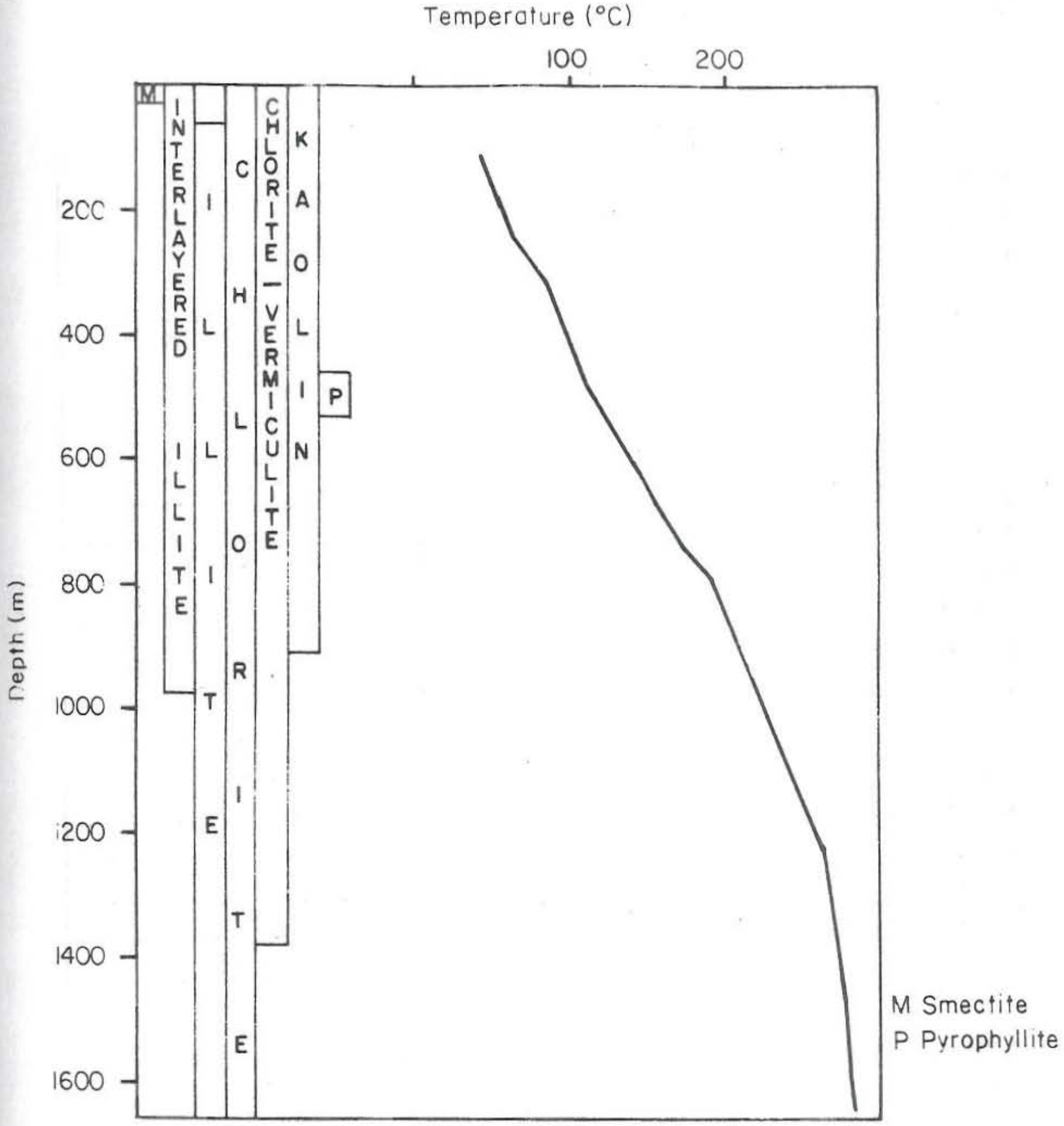


Fig. **17** Summary of clay mineral distribution with depth and temperature

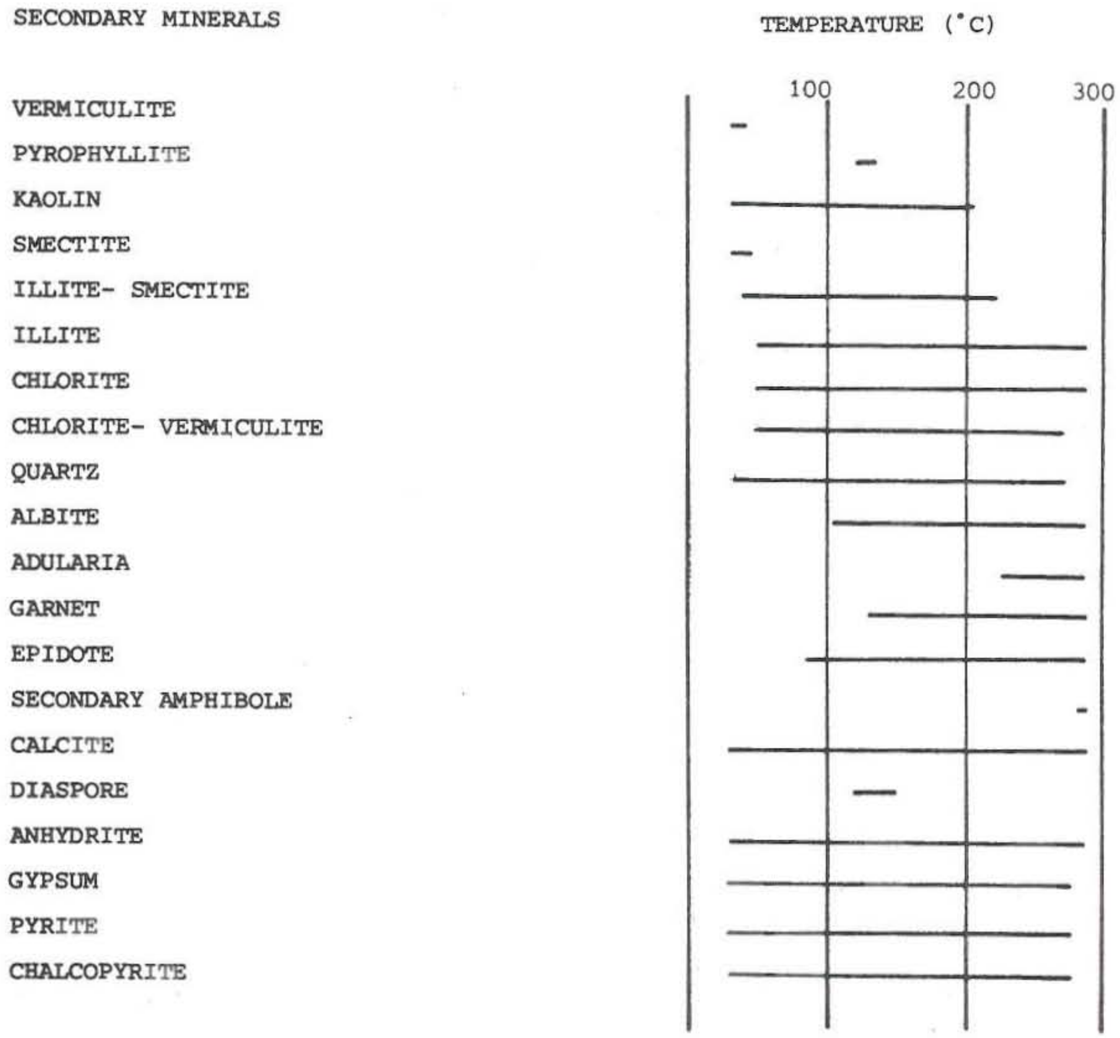


TABLE VI Summary of mineral distribution and associations with temperature.

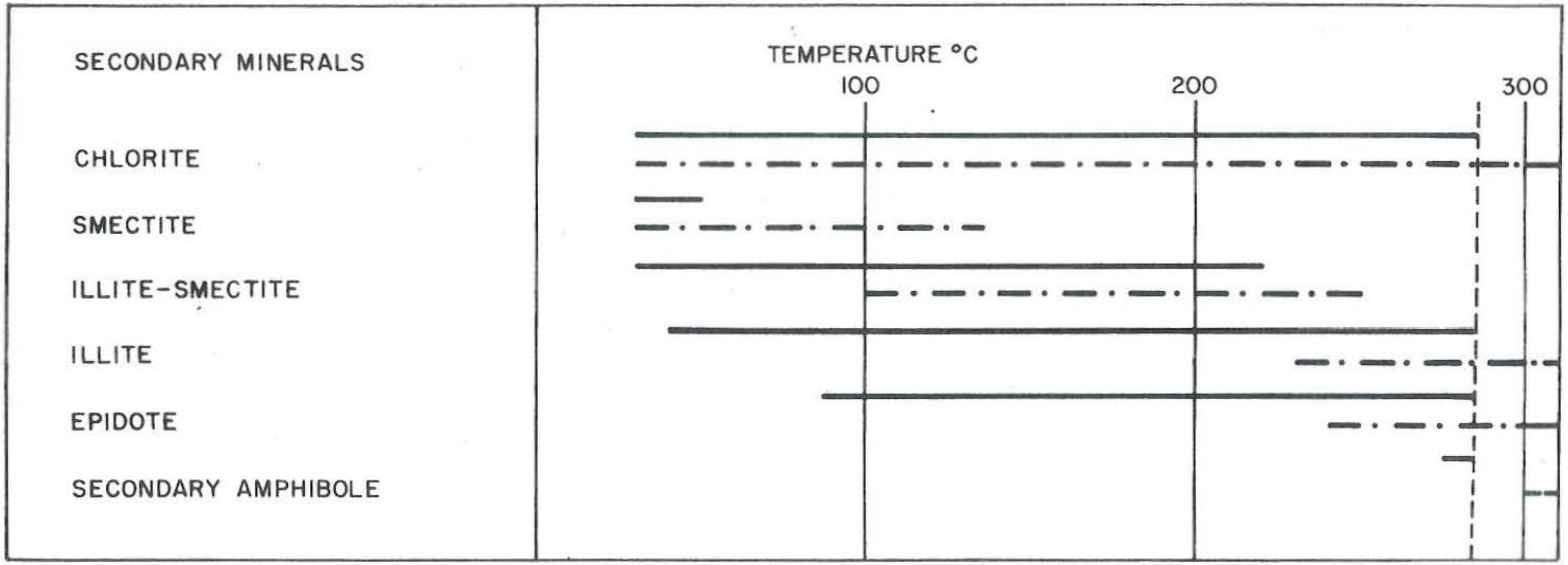


Table VII A comparison of mineral occurrences in Malitbog- 1 and in the Mahiao field in terms of temperature. —— Mineral distribution in Malitbog- 1, —·— Mineral distribution in a typical Mahiao well, -----·- Maximum temperature attained in Malitbog- 1 = 284°C.

## 3. CONCLUSIONS

1. The complex history of the Malitbog area includes faulting, upliftment, and several phases of hydrothermal activity. This is reflected in the observed overprinting of mineral assemblages in Malitbog 1.

2. Three clay zones are recognized in Malitbog 1 but the boundaries between zones cover a large depth interval and are relict at shallow depths:

a. Smectite zone. Occurs at shallow levels where the temperatures are less than 50°C. Though it does not extend to deeper levels, it is near equilibrium conditions near the surface.

b. Interlayered illite zone. Occurs near surface to a depth where measured temperature is 220°C. It is at equilibrium with present conditions from 400- 960 m where temperatures range from 100- 220°C. Its extension to near surface explains the narrowness of the smectite zone since the retrogression of interlayered illite to smectite would take a longer time than the alteration of fresh feldspars to smectite.

c. Illite zone. Illite is found at 150 m where the temperature is 50°C, and extends to the base of the hole where the temperature is 284°C. It is at equilibrium conditions from about 1025 m to the base of the hole where temperatures range from 230- 284°C.

3. A probable fault with a large displacement has its locus on the calc- silicate zone. Deformation was achieved rapidly at high temperatures in the presence of fluids, probably hydrothermal, to produce a skarn like assemblage characterized by wollastonite, garnets, and idocrase. The fault has a displacement of about 500 m and a repetition of the sedimentary and volcanic sequence had blurred the boundaries between temperature dependent clay zones and had given an apparent extension to higher temperatures of normally low temperature minerals.

The likely thermal history of the area in relation to this fault could be reconstructed:

a. Hydrothermal activity which produced propylitic alteration assemblages as well as a localized zone of pyrophyllite + diaspore + kaolinite.

b. Occurrence of the big fault, which upon the release of stress, provided new venues for the hydrothermal fluids.

c. Continued hydrothermal activity and the sealing off of the fault and fractures by anhydrite, quartz, alkali-feldspars, and calcite. Possible self-sealing of the hydrothermal system.

d. Continued hydrothermal activity but the heat source may be migrating to the northwest, parallel to the main tectonic trend, and activating the Mahiao field.

e. Faulting and uplift of area and consequent exposure of hydrothermal mineral assemblages to the surface.

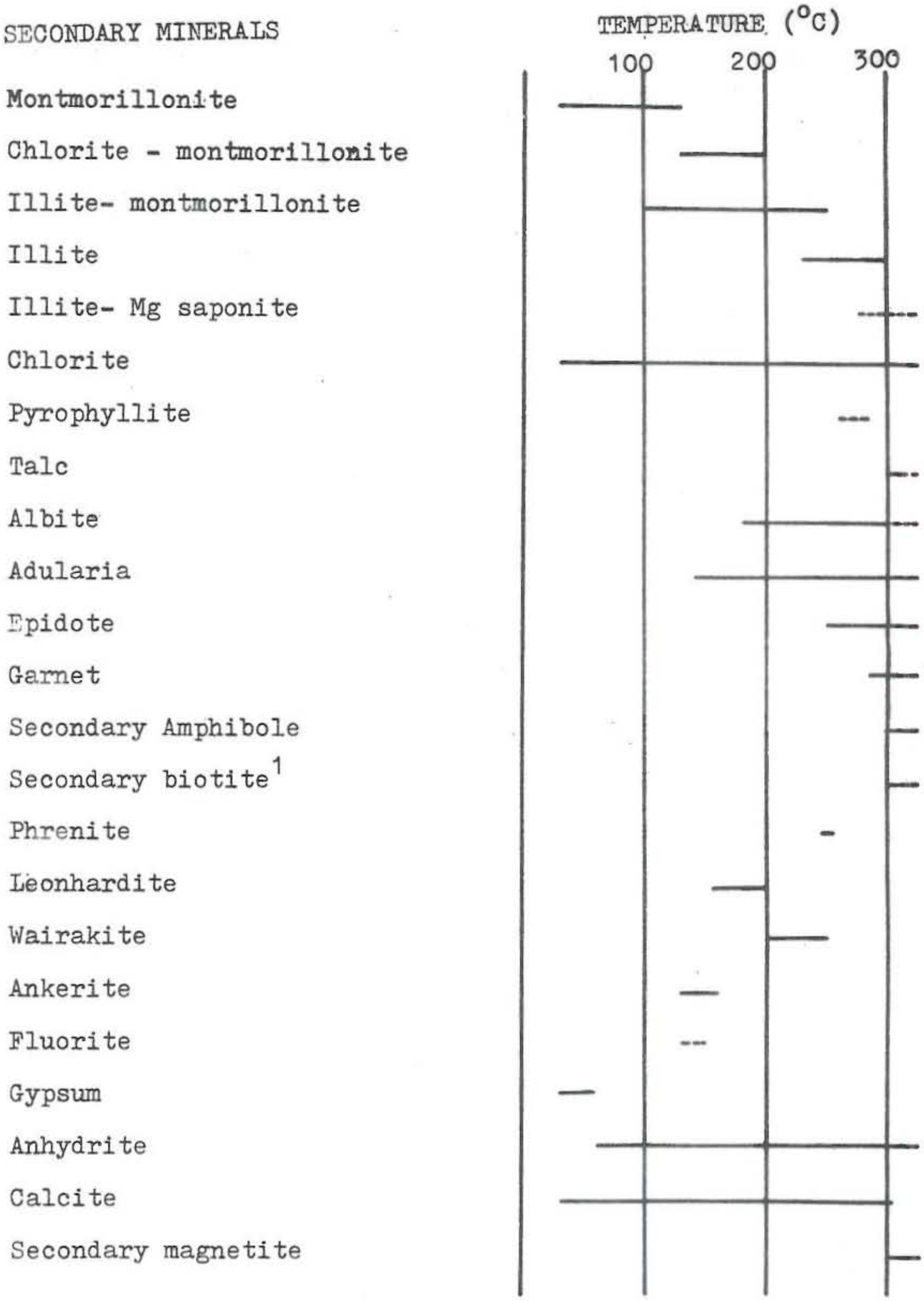
f. Further faulting but less in extent than the big fault. Intrusion of the diorite dikes may be as a consequence of these faults. The diorite dikes and associated faults plus later fracturing is believed to provide the permeability found in the present well.

# ACKNOWLEDGEMENTS

The writer is deeply honoured for having been awarded a UNU fellowship and wishes to thank the Icelandic UNU Geothermal Training Programme at the National Energy Authority of Iceland; in particular H. Franzson, I.B. Fridleifsson and H. Kristmannsdottir for their guidance, advice, the wealth of ideas which they offered to the writer and for examining this manuscript; to K. Grönvold and P. Imsland for their close supervision and lectures during the course on the microprobe; to S. Valdimarsdottir for typing the manuscript and to I. Sigurdardottir for drawing the figures.

## APPENDIX I

Hydrothermal alteration encountered in the Mahiao field, Tongonan, Leyte (data from C.P. Wood)



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[1] relict

## APPENDIX II

The Mahiao discharge chemistry is characterized by high chlorite (11600- 17750 ppm), neutral pH waters. The Malitbog- 1 well chemistry is quite similar but shows a depletion of some elements in comparison with Mahiao waters. Enumerated below is the discharge chemistry of wells Mahiao- 1 and Malitbog- 1. Concentration in ppm.

| | Mahiao- 1 | Malitbog- 1 |
|---|---|---|
| pH | 6.8 | 7.5 |
| As | 28 | 14 |
| $NH_3$ | 36.4 | - |
| B | 340 | 150 |
| Cs | 3.5 | 3.1 |
| Ca | 214 | 162 |
| Cl | 16100 | 8600 |
| $H_2S$ | 12 | 7 |
| Li | 40 | 21 |
| Mg | 0.3 | 0.2 |
| K | 2420 | 1240 |
| Rb | 13 | 7 |
| $SiO_2$ | 995 | 880 |
| Na | 7875 | 4300 |
| $SO_4$ | 32 | 18 |
| Na/K | 5.5 | 5.9 |
| Na/Li | 60 | 62 |
| Na/Ca | 64 | 46 |
| Ca/Mg | 435 | 490 |
| Cl/B | 14.4 | 17.5 |
| $Cl/SO_4$ | 1360 | 1295 |
| Cl/As | 1215 | 1300 |
| $CO_2/H_2$ | 26 | 27 |

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ORKUSTOFNUN JHD                     T O N G O N A N
1979-10-30 HS
================================APPENDIX III=====================================================================

MALITBOG-I TONGONAN LEYTE                                                              HITASTIG = KISILHITI

SOFNUNARTHRYSTINGUR    0.7  KG/SM2    KRITISKUR THRYSTINGUR   0.0 KG/SM2   FLATARMAL STUTS   0.000000 M2

EFNAGREINING VATNSSYNIS I PPM OG MMOL
    PH      SIO2      B        NA+      K+       CA++      MG++    CO2TOT     SO4--     H2S     CL-       F-     UPPL.E.
   7.50   880.00   150.00  4300.00  1240.00   162.00   0.2000    23.00     18.00     7.00  8600.00    0.00     0.00
   20.0  14.6471  13.8760 187.0378  31.7136   4.0419   0.0082   0.5226    0.1874   0.2054 242.5952  0.0000

EDLISVIDNAM    0.0  OHMM

EFNAGREINING GASSYNIS I PROSENTUM       H2S  CO2   H2   O2  CH4        GAS UPPLEYST I THETTIVATNI I PPM    H2S    CO2
                                        4.4 95.6  0.0  0.0  0.0                                            0.0    0.0
MED EINU KILOI AF THETTIVATNI KOMU   6.80  LITRAR AF GASI        HITI THETTIVATNS   24.GRADUR
UMREIKNINGSFAKTOR FYRIR GAS UT FRA LGAS/KGTHETTIV    2.78     BEINNI H2S MAELINGU   0.00     CO2 MAELINGU    0.00

GAS SAMSETNING I PPM OG MMOL  AKVORDUD UT FRA  1 GAS OG THETTIVATNSSYNI  2 BEINNI MAELINGU MED NAOH
   H2S 1    H2S 2    CO2 1     CO2 2     H2
   416.8      0.0  11695.4      0.0      0.0
  12.231    0.000  265.744    0.000    0.000

KISILHITI DJUPVATNS    269.4 GRADUR C      ENTHALPIA DJUPVATNS  (MAELD)   310.71 KCAL/KG      AFL HOLU  0.00  KG/SEK

NAKCAHITI  303.8 GRADUR C     NAKHITI 1  353.9 GRADUR C     NAKHITI 2  339.5 GRADUR C

GUFUHLUTFALL VID SKILJUTHRYSTING  36.96 PROSENT     GUFUMAGN      0.00  TONN A KLUKKUSTUND

    JONABALANS  I MILLIEQVIVALENTUM
KATJONIR       226.85168        ANJONIR       243.65063          MISMUNUR I PROSENT   -7.14

JONISKUR STYRKUR VID   PH HITA   0.239490     -ENDURREIKNAD GILDI  0.239490-

VIRKNISTUDLAR VID    PH HITA
    H+       H3SIO4-  NA+       K+        CA++      MG++      SO4--     CL-       F-       HCO3-     CO3--     HS-       S--
   0.791     0.706    0.706     0.680     0.311     0.367     0.265     0.680     0.693     0.706     0.265     0.693     0.281

DREIFISTUDLAR VID SUDU  115.0 GRADUR C   ACO2   2088.17  ( 0.89 AF TEOR. GILDI)   AH2S    206.57  ( 0.26 AF TEOR. GILDI)

LEIDRETTINGARFAKTOR DREIFISTUDLA  1.0

ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI    0.14685    KISILHITI  270.2    GUFUHLUTFALL   7.19    SUDUHLUTFALL  32.08
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ORKUSTOFNUN JHD                             T O N G O N A N
1979-10-30 HS
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KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
  H4SIO4   H2CO3   HCO3-     H2S     HS-   HSO4-      HF    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4
    9.21    7.89   11.42    7.65   14.84    5.60    5.63    0.46    0.23    1.63    2.58    4.04    4.25

   CACO3   MGCO3     H2O H3SIO4- NAH3SIO4  H3BO3   H2SO4 CAHCO3+ MGHCO3+   CAOH+   MGOH+   NH4OH
    6.67    5.25   11.02   11.61    1.28    9.15   -8.96    4.57    2.16    2.69    4.29    6.27

VIRKNISTUDLAR I DJUPVATNI
      H+ H3SIO4-     NA+      K+     CA++    MG++   SO4--     CL-      F-   HCO3-   CO3--
   0.669   0.555   0.555   0.522   0.137   0.180   0.105   0.522   0.539   0.555   0.105

     HS-     S--     OH-  H2BO3-    NH4+ H2SIO4-- CAHCO3+  CAOH+ MGHCO3+   MGOH+   HSO4-
   0.539   0.116   0.539   0.504   0.504   0.124   0.609   0.609   0.555   0.584   0.570

DJUPVATN SAMSETNING I PPM OG MMOL
    SIO2      NA+       K+      CA++      MG++    SO4--       CL-       F-   H2STOT   CO2TOT        H2  UPPL.E.
  597.71  2920.62   842.23   110.03      0.14    12.23  5841.24     0.00    61.33   819.63      0.00     0.00
  9.9485 127.0387  21.5403   2.7453    0.0056   0.1273 164.7740   0.0000   1.7996  18.6237    0.0000

DJUPGAS SAMSETNING I PPM OG MMOL
     H2S      CO2       H2
  1412.1  49728.3      0.0
  41.434 1129.932    0.000

PH I DJUPVATNI  5.95         (METIN AUKNING VID .1 MMOL AUKNINGU I HLEDSLU 0.089)

SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
  H4SIO4 H3SIO4-   H2CO3   HCO3-   CO3--     H2S     HS-     S--   HSO4-   SO4--      HF      F-     CL-
  955.31    0.93 1132.02   22.76    0.00   59.16    2.11    0.00    0.38    4.32    0.00    0.00 5292.81
   0.997  -2.009   1.261  -0.428  -5.184   0.240  -1.195  -9.420  -2.407  -1.347 -10.854 -10.268   2.174

OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4   CACO3   MGCO3     NA+      K+    CA++    MG++
  821.90  104.87    2.81    4.75    2.66    0.01    0.12    0.00 2596.74  785.85  109.20    0.13
   1.148   0.148  -1.627  -1.454  -1.709  -4.081  -2.918  -6.913   2.053   1.303   0.435  -2.259

JONABALANS I VATNI -7.87 PROSENT           HLEDSLUOSAMRAEMI I PH-JOFNU  -11.346 MMOL
ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.14696       -0.00010  LAEGRI EN ADUR

EFNAHITAMAELAR (GRADUR C)

KISILHITI   270.2     NAKCAHITI   299.1 (374.6)     NAKHITI 1   364.7     NAKHITI 2   348.9
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ORKUSTOFNUN JHD                    T O N G O N A N
1979-10-30 HS
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DJUPVATN SODID VID 100.0  GRADUR.  GUFUHLUTFALL  39.09    SUDUHLUTFALL  34.37    JONISKUR STYRKUR SODINS VATNS 0.223918

KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
 H4SIO4    H2CO3    HCO3-      H2S      HS-    HSO4-       HF     NACL      KCL   NASO4-    KSO4-    CASO4    MGSO4
   9.13     6.40    10.13     6.59    16.08     2.99     3.84    -0.66    -1.06     0.63     1.30     2.50     3.06

  CACO3    MGCO3      H2O H3SIO4- NAH3SIO4    H3BO3    H2SO4  CAHCO3+  MGHCO3+    CAOH+    MGOH+    NH4OH
   3.99     3.46    12.26    10.99     1.35     8.94    -8.08     2.00     1.33     1.58     2.59     4.86

VIRKNISTUDLAR I DJUPVATNI
     H+ H3SIO4-      NA+       K+     CA++     MG++    SO4--      CL-       F-    HCO3-    CO3--
  0.767    0.673    0.673    0.645    0.266    0.321    0.221    0.645    0.660    0.673    0.221

    HS-      S--      OH-   H2BO3-     NH4+ H2SIO4--  CAHCO3+    CAOH+  MGHCO3+    MGOH+    HSO4-
  0.660    0.237    0.660    0.629    0.629    0.249    0.718    0.718    0.673    0.698    0.686

DREIFISTUDLAR    H2S  1462.1   CO2  3328.9          LEIDRETTINGARFAKTOR  1.0

PH I DJUPVATNI  7.03

DJUPVATN SAMSETNING I PPM OG MMOL
    SIO2      NA+       K+     CA++     MG++    SO4--      CL-       F-   H2STOT   CO2TOT       H2 UPPL.E.
  910.72  4450.12  1283.29   167.66     0.21    18.63  8900.25     0.00     1.44    24.38     0.00     0.00
 15.1585 193.5677  32.8207   4.1830   0.0085   0.1939 251.0647   0.0000   0.0423   0.5540   0.0000

DJUPGAS SAMSETNING I PPM OG MMOL
     H2S      CO2       H2
   403.2  11058.3      0.0
  11.831  251.267    0.000

SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
 H4SIO4 H3SIO4-    H2CO3    HCO3-    CO3--      H2S      HS-      S--    HSO4-    SO4--       HF       F-      CL-
1440.03   16.83     4.66    28.99     0.07     0.28     1.13     0.00     0.00    13.27     0.00     0.00  8732.50
  1.176  -0.752   -1.124   -0.323   -2.939   -2.092   -1.466  -10.067   -5.379   -0.860  -13.362   -9.985    2.392

OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
   NACL      KCL   NASO4-    KSO4-    CASO4    MGSO4    CACO3    MGCO3      NA+       K+     CA++     MG++
 259.65    21.53     3.03     2.63     1.47     0.01     0.28     0.00  4347.39  1271.24   167.11     0.20
  0.648   -0.539   -1.595   -1.711   -1.966   -4.020   -2.559   -5.698    2.277    1.512    0.620   -2.075

JONABALANS I VATNI -7.27 PROSENT           HLEDSLUOSAMRAEMI I PH-JOFNU  -17.346 MMOL
ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.24295       -0.01904  LAEGRI EN ADUR
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ORKUSTOFNUN JHD                         T O N G O N A N
1979-10-30 HS
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MALITBOG-I TONGONAN LEYTE                                                                  HITASTIG = KISILHITI

SOFNUNARTHRYSTINGUR    0.7  KG/SM2    KRITISKUR THRYSTINGUR   0.0 KG/SM2   FLATARMAL STUTS   0.000000 M2

EFNAGREINING VATNSSYNIS I PPM OG MMOL
     PH      SIO2       B       NA+       K+       CA++      MG++   CO2TOT     SO4--      H2S      CL-        F-    UPPL.E.
     7.50   880.00   150.00  4300.00  1240.00   162.00   0.2000    23.00     18.00      7.00  8600.00     0.00      0.00
     20.0  14.6471  13.8760 187.0378  31.7136   4.0419   0.0082   0.5226    0.1874    0.2054 242.5952   0.0000

EDLISVIDNAM     0.0  OHMM

EFNAGREINING GASSYNIS I PROSENTUM      H2S  CO2   H2   O2  CH4         GAS UPPLEYST I THETTIVATNI I PPM    H2S    CO2
                                       4.4 95.6  0.0  0.0  0.0                                             0.0    0.0
MED EINU KILOI AF THETTIVATNI KOMU    6.80  LITRAR AF GASI        HITI THETTIVATNS   24.GRADUR
UMREIKNINGSFAKTOR FYRIR GAS UT FRA LGAS/KGTHETTIV    2.78     BEINNI H2S MAELINGU    0.00     CO2 MAELINGU    0.00

GAS SAMSETNING I PPM OG MMOL  AKVORDUD UT FRA  1 GAS OG THETTIVATNSSYNI  2 BEINNI MAELINGU MED NAOH
    H2S 1    H2S 2    CO2 1    CO2 2      H2
    416.8      0.0  11695.4      0.0     0.0
   12.231    0.000  265.744    0.000   0.000

KISILHITI DJUPVATNS    269.4 GRADUR C      ENTHALPIA DJUPVATNS (REIKNUD)  282.28 KCAL/KG      AFL HOLU  0.00  KG/SEK

NAKCAHITI  303.8 GRADUR C     NAKHITI 1  353.9 GRADUR C     NAKHITI 2  339.5 GRADUR C

GUFUHLUTFALL VID SKILJUTHRYSTING  31.59 PROSENT     GUFUMAGN      0.00  TONN A KLUKKUSTUND

     JONABALANS  I MILLIEQVIVALENTUM
KATJONIR      226.85168       ANJONIR       243.65063          MISMUNUR I PROSENT   -7.14

 JONISKUR STYRKUR VID   PH HITA   0.239490     -ENDURREIKNAD GILDI  0.239490-

VIRKNISTUDLAR VID    PH HITA
    H+       H3SIO4-  NA+       K+        CA++      MG++      SO4--    CL-       F-        HCO3-    CO3--    HS-      S--
   0.791    0.706    0.706    0.680    0.311    0.367    0.265    0.680    0.693    0.706    0.265    0.693    0.281

DREIFISTUDLAR VID SUDU  115.0 GRADUR C   ACO2   2088.17  ( 0.89 AF TEOR. GILDI)   AH2S    206.57  ( 0.26 AF TEOR. GILDI)

LEIDRETTINGARFAKTOR DREIFISTUDLA  1.0

ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI    0.14685    KISILHITI  270.8    GUFUHLUTFALL   0.00    SUDUHLUTFALL  31.91

DJUPVATN SAMSETNING I PPM OG MMOL
    SIO2      NA+       K+     CA++      MG++    SO4--      CL-       F-   H2STOT   CO2TOT       H2  UPPL.E.
  599.22  2927.98   844.35   110.31     0.14    12.26  5855.97     0.00   137.77  3747.35     0.00     0.00
  9.9736 127.3590  21.5946   2.7522   0.0056   0.1276 165.1895   0.0000   4.0424  85.1477   0.0000
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ORKUSTOFNUN JHD                     T O N G O N A N
1979-10-30 HS
==========================================================================================================

KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
  H4SI04   H2C03   HC03-     H2S     HS-   HS04-      HF    NACL     KCL  NAS04-   KS04-   CAS04   MGS04
    9.21    7.90   11.43    7.66   14.84    5.61    5.64    0.47    0.24    1.64    2.59    4.05    4.25

   CAC03   MGC03     H20 H3SI04- NAH3SI04  H3B03   H2S04 CAHC03+ MGHC03+   CAOH+   MGOH+   NH4OH
    6.68    5.26   11.02   11.61    1.28    9.15   -8.97    4.58    2.17    2.69    4.30    6.28

VIRKNISTUDLAR I DJUPVATNI
      H+ H3SI04-     NA+      K+    CA++    MG++   S04--     CL-      F-   HC03-   C03--
   0.668   0.554   0.554   0.521   0.137   0.179   0.105   0.521   0.538   0.554   0.105

     HS-     S--     OH-  H2B03-    NH4+ H2SI04-- CAHC03+  CAOH+ MGHC03+   MGOH+   HS04-
   0.538   0.115   0.538   0.503   0.503   0.124   0.608   0.608   0.554   0.583   0.569

PH I DJUPVATNI  5.34           (METIN AUKNING VID .1 MMOL AUKNINGU I HLEDSLU 0.089)

SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
  H4SI04 H3SI04-   H2C03   HC03-   C03--     H2S     HS-     S--   HS04-   S04--      HF      F-     CL-
  958.43    0.23 5255.55   25.72    0.00  136.54    1.18    0.00    1.43    3.93    0.00    0.00 5297.52
   0.999  -2.618   1.928  -0.375  -5.743   0.603  -1.446 -10.273  -1.833  -1.388 -10.454 -10.482   2.174

OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
    NACL     KCL  NAS04-   KS04-   CAS04   MGS04   CAC03   MGC03     NA+      K+    CA++    MG++
  837.22  106.41    2.57    4.38    2.44    0.01    0.03    0.00 2598.13  787.28  109.58    0.13
   1.156   0.154  -1.666  -1.489  -1.747  -4.121  -3.470  -7.468   2.053   1.304   0.437  -2.258

JONABALANS I VATNI -7.87 PROSENT          HLEDSLUOSAMRAEMI I PH-JOFNU  -11.356 MMOL
ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.14708       -0.00024  LAEGRI EN ADUR

EFNAHITAMAELAR (GRADUR C)

KISILHITI   270.8     NAKCAHITI   299.2 (374.5)     NAKHITI 1   365.0     NAKHITI 2   349.1
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ORKUSTOFNUN JHD                        T O N G O N A N
1979-10-30 HS
========================================================================================================================

DJUPVATN SODID VID 250.0  GRADUR.  GUFUHLUTFALL   6.05   SUDUHLUTFALL   6.05   JONISKUR STYRKUR SODINS VATNS 0.156559

KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
  H4SI04   H2C03   HC03-     H2S     HS-   HS04-      HF    NACL     KCL  NAS04-   KS04-   CAS04   MGS04
    9.06    7.65   11.20    7.41   14.94    5.27    5.40    0.21    0.03    1.50    2.37    3.84    4.14

   CAC03   MGC03     H20 H3SI04- NAH3SI04  H3B03   H2S04 CAHC03+ MGHC03+   CAOH+   MGOH+   NH4OH
    6.30    5.00   11.05   11.44    1.22    9.09   -8.76    4.23    2.05    2.54    3.97    6.01

VIRKNISTUDLAR I DJUPVATNI
      H+ H3SI04-     NA+      K+    CA++    MG++   S04--     CL-      F-   HC03-   C03--
   0.687   0.576   0.576   0.544   0.156   0.201   0.121   0.544   0.561   0.576   0.121

     HS-     S--     OH-  H2B03-    NH4+ H2SI04-- CAHC03+  CAOH+ MGHC03+   MGOH+   HS04-
   0.561   0.133   0.561   0.526   0.526   0.142   0.628   0.628   0.576   0.604   0.590

DREIFISTUDLAR    H2S    34.6   C02    99.3          LEIDRETTINGARFAKTOR  1.0

PH I DJUPVATNI  5.92

DJUPVATN SAMSETNING I PPM OG MMOL
     SI02       NA+        K+      CA++      MG++     S04--       CL-        F-    H2STOT    C02TOT        H2   UPPL.E.
   637.82   3116.61    898.74    117.42      0.14     13.05   6233.21      0.00     47.22    554.27      0.00      0.00
  10.6161 135.5636   22.9857    2.9295    0.0060    0.1358 175.8311    0.0000    1.3855   12.5943    0.0000

DJUPGAS SAMSETNING I PPM OG MMOL
     H2S       C02        H2
  1543.3   53313.5       0.0
  45.286  1211.394     0.000

SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
  H4SI04 H3SI04-   H2C03   HC03-   C03--     H2S     HS-     S--   HS04-   S04--      HF      F-     CL-
 1019.14    1.27  756.92   23.84    0.00   44.65    2.49    0.00    0.25    5.16    0.00    0.00 5822.18
   1.025  -1.876   1.086  -0.408  -5.008   0.117  -1.124  -9.522  -2.583  -1.270 -10.976 -10.208   2.215

OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
    NACL     KCL  NAS04-   KS04-   CAS04   MGS04   CAC03   MGC03     NA+      K+    CA++    MG++
  610.70   85.34    3.18    4.35    2.79    0.01    0.11    0.00 2875.74  852.73  116.55    0.14
   1.019   0.059  -1.573  -1.493  -1.688  -3.975  -2.968  -6.857   2.097   1.339   0.464  -2.232

JONABALANS I VATNI -7.63 PROSENT            HLEDSLUOSAMRAEMI I PH-JOFNU  -12.114 MMOL
ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.16175       -0.00519  LAEGRI EN ADUR
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ORKUSTOFNUN JHD                          T O N G O N A N
1979-10-30 HS
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DJUPVATN SODID VID 200.0  GRADUR.  GUFUHLUTFALL  17.36    SUDUHLUTFALL  17.36    JONISKUR STYRKUR SODINS VATNS 0.177971

KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
  H4SIO4   H2CO3   HCO3-     H2S     HS-   HSO4-      HF    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4
    8.84    7.12   10.70    6.94   15.24    4.48    4.86   -0.15   -0.38    1.20    1.95    3.36    3.84

   CACO3   MGCO3     H2O H3SIO4- NAH3SIO4  H3BO3   H2SO4 CAHCO3+ MGHCO3+   CAOH+   MGOH+   NH4OH
    5.44    4.41   11.25   11.11    1.12    8.98   -8.37    3.44    1.78    2.18    3.34    5.49

VIRKNISTUDLAR I DJUPVATNI
      H+ H3SIO4-     NA+      K+    CA++    MG++   SO4--     CL-      F-   HCO3-   CO3--
   0.719   0.614   0.614   0.583   0.194   0.243   0.155   0.583   0.599   0.614   0.155

     HS-     S--     OH-  H2BO3-     NH4+ H2SIO4-- CAHCO3+  CAOH+ MGHCO3+   MGOH+   HSO4-
   0.599   0.168   0.599   0.566   0.566   0.179   0.664   0.664   0.614   0.641   0.628

DREIFISTUDLAR    H2S    90.9   CO2   320.1          LEIDRETTINGARFAKTOR  1.0

PH I DJUPVATNI  6.32

DJUPVATN SAMSETNING I PPM OG MMOL
     SIO2      NA+       K+     CA++     MG++    SO4--      CL-       F-   H2STOT   CO2TOT       H2  UPPL.E.
   725.05  3542.85  1021.66   133.47     0.16    14.83  7085.70     0.00    11.37    83.10     0.00     0.00
  12.0681 154.1040  26.1294   3.3302   0.0068   0.1544 199.8788   0.0000   0.3335   1.8882   0.0000

DJUPGAS SAMSETNING I PPM OG MMOL
     H2S      CO2       H2
   739.7  21196.4      0.0
  21.704  481.627    0.000

SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
  H4SIO4 H3SIO4-   H2CO3   HCO3-   CO3--     H2S     HS-     S--   HSO4-   SO4--      HF      F-     CL-
 1154.31    5.61   93.24   23.38    0.00    8.14    3.13    0.00    0.03    7.63    0.00    0.00 6806.51
   1.080  -1.229   0.177  -0.417  -4.202  -0.622  -1.023  -9.397  -3.523  -1.100 -11.775 -10.093   2.283

OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4   CACO3   MGCO3     NA+      K+    CA++    MG++
  419.79   51.63    3.49    3.66    2.46    0.02    0.17    0.00 3377.03  993.52  132.68    0.16
   0.856  -0.160  -1.533  -1.567  -1.743  -3.862  -2.764  -6.394   2.167   1.405   0.520  -2.178

JONABALANS I VATNI -7.42 PROSENT           HLEDSLUOSAMRAEMI I PH-JOFNU  -13.787 MMOL
ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.18922       -0.01125  LAEGRI EN ADUR
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ORKUSTOFNUN JHD                        T O N G O N A N
1979-10-30 HS
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DJUPVATN SODID VID 150.0  GRADUR.  GUFUHLUTFALL  26.36    SUDUHLUTFALL  26.36    JONISKUR STYRKUR SODINS VATNS 0.199725

KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
  H4SIO4   H2CO3   HCO3-     H2S     HS-   HSO4-      HF    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4
    8.84    6.69   10.33    6.65   15.61    3.72    4.33   -0.34   -0.73    0.91    1.61    2.91    3.48

   CACO3   MGCO3     H2O H3SIO4- NAH3SIO4  H3BO3   H2SO4 CAHCO3+ MGHCO3+   CAOH+   MGOH+   NH4OH
    4.67    3.90   11.64   10.94    1.15    8.92   -8.13    2.70    1.54    1.86    2.90    5.12

VIRKNISTUDLAR I DJUPVATNI
      H+ H3SIO4-     NA+      K+    CA++    MG++   SO4--     CL-      F-   HCO3-   CO3--
   0.744   0.645   0.645   0.615   0.230   0.282   0.187   0.615   0.630   0.645   0.187

     HS-     S--     OH-  H2BO3-    NH4+ H2SIO4-- CAHCO3+  CAOH+ MGHCO3+   MGOH+   HSO4-
   0.630   0.202   0.630   0.598   0.598   0.213   0.692   0.692   0.645   0.670   0.658

DREIFISTUDLAR    H2S   279.0   CO2  1032.3          LEIDRETTINGARFAKTOR  1.0

PH I DJUPVATNI  6.62

DJUPVATN SAMSETNING I PPM OG MMOL
     SIO2      NA+       K+     CA++     MG++    SO4--      CL-       F-   H2STOT   CO2TOT       H2  UPPL.E.
   813.67  3975.90  1146.54   149.79     0.18    16.64  7951.81     0.00     4.50    31.58     0.00     0.00
  13.5432 172.9406  29.3233   3.7373   0.0076   0.1733 224.3105   0.0000   0.1320   0.7176   0.0000

DJUPGAS SAMSETNING I PPM OG MMOL
     H2S      CO2       H2
   510.1  14129.6      0.0
  14.968  321.053    0.000

SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
  H4SIO4 H3SIO4-   H2CO3   HCO3-   CO3--     H2S     HS-     S--   HSO4-   SO4--      HF      F-     CL-
 1289.87   11.77   19.24   24.72    0.02    1.83    2.59    0.00    0.00   10.37    0.00    0.00 7703.60
   1.128  -0.907  -0.508  -0.392  -3.567  -1.270  -1.106  -9.604  -4.395  -0.967 -12.521 -10.035   2.337

OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4   CACO3   MGCO3     NA+      K+    CA++    MG++
  383.51   32.73    3.33    3.13    1.90    0.02    0.20    0.00 3824.39 1128.47  149.15    0.18
   0.817  -0.358  -1.553  -1.635  -1.855  -3.886  -2.693  -6.074   2.221   1.460   0.571  -2.126

JONABALANS I VATNI -7.36 PROSENT          HLEDSLUOSAMRAEMI I PH-JOFNU  -15.486 MMOL
ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.21425      -0.01452  LAEGRI EN ADUR
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      ORKUSTOFNUN JHD                      T O N G O N A N
      1979-10-30 HS
===== ================================================================================================================

9725  DJUPVATN SODID VID 100.0  GRADUR.  GUFUHLUTFALL  34.12    SUDUHLUTFALL  34.12    JONISKUR STYRKUR SODINS VATNS 0.223269

      KLEYFNISTUDLAR I DJUPVATNI SEM -LOG K
       H4SIO4   H2CO3   HCO3-     H2S     HS-   HSO4-      HF    NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4
         9.13    6.40   10.13    6.59   16.08    2.99    3.84   -0.66   -1.06    0.63    1.30    2.50    3.06

        CACO3   MGCO3     H2O H3SIO4- NAH3SIO4  H3BO3   H2SO4 CAHCO3+ MGHCO3+   CAOH+   MGOH+   NH4OH
         3.99    3.46   12.26   10.99    1.35    8.94   -8.08    2.00    1.33    1.58    2.59    4.86

      VIRKNISTUDLAR I DJUPVATNI
           H+ H3SIO4-     NA+      K+    CA++    MG++   SO4--     CL-      F-   HCO3-   CO3--
        0.757   0.673   0.673   0.645   0.267   0.321   0.222   0.645   0.660   0.673   0.222

          HS-     S--     OH-  H2BO3-     NH4+ H2SIO4-- CAHCO3+  CAOH+ MGHCO3+   MGOH+   HSO4-
        0.660   0.237   0.660   0.629   0.629   0.249   0.719   0.719   0.673   0.698   0.686

      DREIFISTUDLAR    H2S  1462.1   CO2  3328.9          LEIDRETTINGARFAKTOR  1.0

      PH I DJUPVATNI  7.04

      DJUPVATN SAMSETNING I PPM OG MMOL
         SIO2      NA+      K+     CA++    MG++    SO4--     CL-      F-  H2STOT   CO2TOT       H2  UPPL.E.
       909.59  4444.59 1281.70  167.45    0.21    18.61  8889.18   0.00    1.44    24.26     0.00     0.00
      15.1397 193.3272 32.7800  4.1778  0.0085   0.1937 250.7527 0.0000  0.0423   0.5512   0.0000

      DJUPGAS SAMSETNING I PPM OG MMOL
          H2S     CO2      H2
        401.0 10935.2     0.0
       11.765 248.471   0.000

      SYRUR OG TILSVARANDI ANJONIR I DJUPVATNI I PPM OG LOG MMOL
       H4SIO4 H3SIO4-   H2CO3   HCO3-   CO3--     H2S     HS-     S--   HSO4-   SO4--      HF      F-     CL-
      1438.12   16.92    4.61   28.86    0.07    0.27    1.13    0.00    0.00   13.25    0.00    0.00 8721.73
        1.175  -0.750  -1.129  -0.325  -2.938  -2.094  -1.466 -10.063  -5.383  -0.860 -13.365  -9.986   2.391

      OKLOFNAR SAMEINDIR OG TILSVARANDI KATJONIR I DJUPVATNI I PPM OG LOG MMOL
         NACL     KCL  NASO4-   KSO4-   CASO4   MGSO4   CACO3   MGCO3     NA+      K+    CA++    MG++
       259.21   21.50    3.02    2.63    1.47    0.01    0.28    0.00 4342.04 1269.66  166.90    0.20
        0.647  -0.540  -1.595  -1.711  -1.966  -4.020  -2.557  -5.697   2.276   1.512   0.620  -2.075

      JONABALANS I VATNI -7.27 PROSENT          HLEDSLUOSAMRAEMI I PH-JOFNU  -17.325 MMOL
      ENDURREIKNADUR JONISKUR STYRKUR I DJUPVATNI   0.24265       -0.01939  LAEGRI EN ADUR
```

## APPENDIX IV MICROPROBE RESULTS

Albite

| | |
|---|---|
| $SiO_2$ | 65.56 |
| $TiO_2$ | 0 |
| $Al_2O_3$ | 18.10 |
| $FeO_T$ | 0.49 |
| MgO | 0.24 |
| CaO | 1.30 |
| $Na_2O$ | 7.27 |
| $K_2O$ | 0.98 |
| $P_2O_5$ | 0.01 |
| | 100.30% |

FORMULA

| | |
|---|---|
| Si | 12.18 |
| Al | 3.94 |
| $Fe_T$ | .074 |
| Mg | .064 |
| Ca | 0.48 |
| Na | 2.624 |
| K | .224 |

| | | |
|---|---|---|
| Mol% | Or | 7.6% |
| | Ab | 89% |
| | An | 3.4% |

Albite from Core 5 altering primary plagioclase

Chlorite

| | |
|---|---|
| $SiO_2$ | 28.15 |
| $Al_2O_3$ | 18.43 |
| $FeO_T$ | 21.33 |
| MnO | .86 |
| MgO | 18.80 |
| Na | 0.02 |
| | 88.90% |

FORMULA

| | | |
|---|---|---|
| Si | 5.81 | 8.0 |
| Al | 2.19 | |
| Al | 2.29 | |
| Fe | 3.68 | 11.9 |
| Mn | .15 | |
| Mg | 5.78 | |

Chlorite from Core 5

Epidote

| | |
|---|---|
| $SiO_2$ | 38.41 |
| $TiO_2$ | 0.10 |
| $Al_2O_3$ | 20.10 |
| $Cr_2O_3$ | 0.03 |
| $FeO_1$ | 14.16 |
| MnO | 0.12 |
| MgO | 1.92 |
| CaO | 22.21 |
| $Na_2O$ | 0.23 |
| $K_2O$ | 0.87 |
| $P_2O_5$ | 0.09 |
| | 99.14% |

| | | |
|---|---|---|
| Si | 3.28 | 3.28 |
| Al | 2.02 | 3.022 |
| Cr | .002 | |
| Fe | 1.01 | |
| Mn | .009 | |
| Mg | .24 | |
| Ca | 2.03 | 2.415 |
| Na | .04 | |
| K | .09 | |
| P | .006 | |

Epidote from Core 5

(next page)

Adularia

| | |
|---|---|
| $SiO_2$ | 64.32 |
| $TiO_2$ | 0.06 |
| $Al_2O_3$ | 18.73 |
| $Cr_2O_3$ | 0.01 |
| $FeO_T$ | 0.07 |
| MgO | 0.02 |
| CaO | 0.08 |
| $Na_2O$ | 0.35 |
| $K_26$ | 13.77 |
| | 97.32% |

FORMULA

| | |
|---|---|
| Si | 12.03 |
| Ti | .008 |
| Al | 4.12 |
| Fe | .01 |
| Mg | .005 |
| Na | .112 |
| K | 3.27 |

| | | |
|---|---|---|
| Mol% | Or | 96.7% |
| | Na | 3.3% |
| | Ca | 0% |

Adularia from Core 5

ILLITIC CLAY

| | |
|---|---|
| $SiO_2$ | 49.21 |
| $TiO_2$ | 0.15 |
| $Al_2O_3$ | 32.73 |
| $Cr_2O_3$ | 0.02 |
| $FeO_T$ | 1.87 |
| MnO | 0.10 |
| MgO | 0.58 |
| CaO | 0.17 |
| $Na_2O$ | 0.13 |
| $K_2O$ | 7.34 |
| $P_2O_5$ | 0.01 |
| | 92.30 |

FORMULA

| | | |
|---|---|---|
| Si | 6.54 | 8 |
| $Al^{IV}$ | 1.46 | |
| $Al^{VI}$ | 4.172 | |
| Ti | 0.18 | |
| Cr | .001 | |
| Fe | .228 | 4.572 |
| Mn | .009 | |
| Mg | .12 | |
| Ca | .024 | |
| Na | .035 | 1.41 |
| K | 1.376 | |

Green pleochroic clay with yellow green interference colours

## APPENDIX V PETROGRAPHIC ANALYSES OF CUTTINGS AND CORES

DEPTHS ARE IN FEET

### CUTTINGS

9134 (880)

Highly altered. Matrix recrystallized nearly completely to medium grained quartz mosaic. Some incompletely altered feldspars present. Matrix altered to medium grained quartz mosaic + small patches of anhydrite + patches of calcite. Ferromagnesians are completely altered to chlorite. Chlorite + pyrite + clay, pyrite + leucoxene. Major rock alteration is quartz, seconded by calcite with minor clay (XRD : chlorite and interlayered illite).

9135 (1560)

Moderately to weakly altered hornblende- rich dacite
Plagioclase : andesine to sodic labradorite zoned and twinned.
Plagioclase incompletely altered to calcite + clay, epidote + calcite. Hornblende is more altered than plagioclase. Hornblende may be completely altered to pyrite + clay + quartz, or incompletely altered to calcite + chlorite + incipient epidote + leucoxene, chlorite + calcite + epidote + pyrite, calcite + chlorite + quartz, chlorite + anhydrite + quartz + calcite.
Magnetite alters to pyrite.
Matrix is altered partly to quartz + epidote + calcite + pyrite + chlorite + anhydrite.
Cataclastic rock showing marked granulation and shearing with quartz crystals showing parallelism of long axes and preferred crystallographic orientation.

9136 (1690) Sedimentary rock

Moderately to highly altered fine- grained rock in which fragmental plagioclase are still visible. Plagioclases still show twinning and zoning but the ferromagnesian minerals are completely altered. Plagioclases are altered to calcite. Ferromagnesian minerals are altered to calcite and pyrite. Matrix is altered to a fine quartz mosaic + illitic clay + chlorite + anhydrite + minor pyrite disseminations.

9139 (1990)

Highly altered andesite. Shadows of primary plagioclases discerned
Plg → fine illite fibers + patches of anhydrite, calcite + quartz.
Abundant illitic clay.
Matrix medium grained Q crystals + patches of calcite + microveinlets of Ah + Py diss + I in veinlets.
Calcite vein shows undulatory extinction.

9140 (2100)

Highly altered volcanic breccia.
Shadows of clasts and primary minerals. Shape of primary minerals defined by differences in intensity and type of mineral associations compared to the matrix. Alteration minerals consist of green chlorite (dark blue in crossed nichols), calcite, brown to greenish clay, minor quartz, pyrite disseminations, hydromuscovite.
Alkali feldspars as vug fills.

A few fragments are highly altered with no original textures visible. Marked lineation evinced by parallelism of different types of alternating alteration minerals: fine quartz mosaic- anhydrite- diaspore arranged in a line- anhydrite- quartz mosaic. Alkali feldspars in matrix and as vug-fills.

9141 (2230)

Weakly altered siltstone with very fine- grained dark matrix upon which fragmental plagioclases and ferromagnesians are scattered. Plagioclases clean of secondary mineralogy. Highly altered volcanic breccia reminiscent of breccia in 9140 (2100).

9142 (2260)

Calc silicate zone.
Equant grains of calcite with abundant garnets (about 25% of some rock chips), minor wollastonite, diaspore, anhydrite.
Some calcite shows undulatory extinction, in others, bent lamellae could be observed, while several grains show rich development twinning.

Wollastonite crystals show preferred crystallographic orientation in a given chip.
Black mineral may be glass and in some chips is observed to define a kind of lineation in the rock.
Mylonite present. Pulverized rock with lineation defined by parallel iron oxide.

9144 (2480)

Weakly to moderately altered andesite porphyry. No ferromagnesians observed. Fluidal texture on groundmass defined by plagioclase laths. Openings are filled with chlorite with medium grained quartz mosaic, anhydrite scattered in chlorite or associated with quartz, rimming the openings.
Pyrite present.
Plagioclase calcite, calcite + anhydrite, chlorite + calcite, illite, quartz.
Ferromagnesians + leucoxene (?) + pyrite + anhydrite, magnetite.

9147 (2830)

Moderately altered andesite porphyry.
Veinlets of epidote are common. Ferromagnesians are altered to calcite + pyrite + epidote, garnet occurs with calcite.
Plagioclase alters to micaceous clay, chlorite + epidote.
In some cuttings, matrix + primary minerals are altered to quartz + micaceous clay + epidote.
Some cuttings have their matrix altered to medium- grained quartz mosaic scattered with micaceous clay + minor anhedral anhydrite.
K- feldspar present.
(XRD detects chlorite, quartz, illite, plagioclase)

9148 (2930)

Weakly to moderately altered andesite porphyry with felted groundmass. In some, Px weakly altered and some brown pleochroic hornblende incipiently altered.

Ferromagnesians → calcite + chlorite + pyrite, chlorite + epidote, leux + py (leux → py).
Plagioclase → calcite, illite, epidote.
Some cuttings are quartzofeldspathic streaked with I with Mt + leux.
Granulated plagioclase crystals showing lineation. (XRD : I, Ch, Gyp, Q, Plg, Ah)

9149 (3100)

Moderately to highly altered volcanic breccia. Fine grained matrix altered to a fine grained mosaic of quartz and feldspar with fine fibers of illite. Fmags ( hb, a few px) altered to magnetite and leucoxene, to chlorite.
Plagioclase altered to calcite, illite.
In some cuttings are weakly altered trachytic andesite with plagioclase altering to illite, illite + anhydrite, calcite, calcite + chlorite + anhydrite + illite. Fmags are altered to chlorite + anhydrite. Matrix of flow banded feldspar laths with alteration minerals of illite, chlorite, leucoxene, clay. No pyrite observed but magnetite is abundant.
Albite and adularia present.

9151 (3350)

Moderately to highly altered porphyritic andesite + lesser volcanic breccia. Phenocrysts of plagioclase partly altered to epidote, matrix to medium grained quartz matrix. Matrix dotted by leucoxene with cubic magnetite present.
Plagioclase → ch + ep, I + ah
Leux → incipient epidote
matrix → I + Q
mt → leux
Fmags → ch + ep + leux
Granulated and sheared andesite present. Lineation further defined by hematic stains.

9152 (3440)

Highly altered andesite + tuff ?. Highly illitic.
Rock mass completely altered to micaceous clay + quartz + leux.
A few volcanic fragments are altered to calcite + illite + anhydrite + leux + magnetite .
Plagioclase altered to chlorite + epidote + leux + anhydrite.
Some fragments with albite, pyrite diss., and clots of fine quartz mosaic. Veins of anhydrite + adularia + gypsum + quartz observed.

9153 (3540)

Highly altered fine- grained volcanic with shadows of plagioclase left. Fractures are filled with epidote + anhydrite + honey brown garnet + chlorite. Vugs are filled with chlorite bordered by fine quartz mosaic. Illite present. Matrix is altered to a fine- grained mosaic with pyrite disseminations and leucoxene incipiently altering to epidote. Ferromagnesian shadows are defined by chlorite + leucoxene + pyrite.
Other cuttings are fine- grained rocks completely altered to illite + pyrite + anhydrite + fine quartz mosaic. These are cut by anhydrite veinlets.
Some volcanic breccia present whose matrix is altered to fine quartzofeldspathic maosaic with veinlets of quartz + anhydrite studded with large pyrites. Alteration includes illite + quartz + K- feldspars + garnets + chlorite + pyrite + leucoxene + epidote + albite.
Cataclasite : granulated and sheared andesite observed.
(XRD detected chlorite + illite + gypsum + albite + quartz + anhydrite + pyrite).

9154 (3680)

Volcanic breccia, highly altered. Intense alteration had obliterated original texture into a mass composed of illite + fine quartz mosaic + patches of dark green clay (yellow green in cross- nichols) + pyrite disseminations + green chlorite. Some fragments are moderately to weakly altered porphyritic andesite with plagioclase still showing twinning but cracked and slightly corroded. Cut by quartz veinlet, and some chlorite veinlets. Ferromagnesians are altered to calcite + chlorite + leucoxene, chlorite + leucoxene, chlorite + anhydrite + pyrite, fibrous amphibole (?) + anhydrite + chlorite + pyrite.

Plagioclase is altered to epidote, anhydrite, chlorite.
(XRD detects chlorite dominating over illite + gypsum + quartz + plagioclase).

9156 (3850)

Weakly to moderately altered porphyritic andesite. Phenocrysts are completely altered to quartz. Matrix altered to medium- grained quartz mosaic + calcite + epidote with magnetite disseminations. Also found in matrix are clusters of honey brown garnets associated with chlorite and epidote. Matrix seems not so altered as the phenocrysts. Ferromagnesians are altered to leucoxene + chlorite + calcite + anhydrite.
(XRD detected chlorite, illite, plagioclase, calcite, gypsum, and pyrite).

9157 (4050)

Moderately to highly altered porphyritic andesite. Relict porphyritic texture with secondary minerals pseudomorphing after tabular crystals. Alteration consists of: Matrix alters to medium- grained mosaic of illite + anhydrite + calcite + minor albite. Primary minerals alter to quartz + anhydrite + calcite + chlorite. Veinlet of quartz + minor anhydrite with pyrite. Other fragments have matrix altered to quartz mosaic with illite and some a greenish pleochroic clay which has interference colours of micaceous clay in cross nichols. Plagioclases are incompletely altered.
Leucoxene incipiently alters to epidote. Crushed rock showing marked lineation in a vein of epidote. Cataclastic rock with lineation made more marked by hematitic lines.

9159 (4310)

Cuttings are in the vicinity of the permeable zone.

1. Volcanic breccia, weakly to highly altered. Matrix altered to chlorite, anhydrite, calcite, quartz mosaic and disseminated with magnetite.
2. Holocrystalline hornblende andesite, quite fresh with hornblende still unaltered. Minor patches of leucoxene and minor epidote on the matrix, minor quartz.

3. Highly to moderately altered porphyritic andesite. Plagioclase usually completely altered to coarse quartz mosaic while matrix retains some primary flow banding. Matrix partly alters to illite + quartz with disseminations of magnetite some of which are found altering to pyrite.
4. Sedimentary rock. Fine- grained matrix altered largely to illite, and fine quartz mosaic. Rock is cut by veinlets of anhydrite + minor gypsum. Fragmental plagioclase altered to illite. Leucoxene and magnetite are found on the matrix.
5. Strongly silicified porphyritic andesite. Medium- grained quartz mosaic + chlorite + anhydrite + magnetite + epidote + leucoxene + alkali feldspars.
6. Sheared fine- grained rock observed.

9160 (4360)

Highly altered porphyritic andesite.
Plg → Ep, fine mosaic of Q, I
Magnetite and pyrite dot the matrix. Anhedral Ah in matrix, quartz too is present.
Cataclastic rocks are common. Mylonitized rock with primary plagioclase crushed and showing some kind of rotation. Other mylonites are crushed but illitic clay shows marked lineation.

9162 (4650)

Moderately altered diorite. Coarse interlocking crystals of plagioclase with minor amounts of ferromagnesians. Ferromagnesians are completely altered to chlorite. Alteration minerals in diorite are : chlorite, anhydrite, epidote, pyrite and calcite.
Some fragments are very highly altered, with no traces of original texture discernible. Rock mass is now composed of medium- grained quartzo- feldspathic mosaic with anhydrite patches and pyrite disseminations.
A fragment shows contact between intrusive which is less altered and a very altered rock with banded texture and consists of epidote, quartz, calcite, anhydrite, chlorite, and k- feldspar.

9163 (4850) In vicinity of permeable zone

1. Moderately to highly altered andesite porphyry characterized by large plagioclase phenocrysts laid on a matrix scattered with smaller laths of plagioclase, exhibiting rough alignment where moderately altered. Original texture discernible. Plagioclase incompletely altered to illite and anhydrite. Ferromagnesians are completely altered to chlorite + leucoxene. Leucoxene shows incipient alteration to epidote. Matrix still with distinct flow texture. Leucoxene altering from magnetite present in the matrix, so is chlorite.
2. In other altered cuttings : Plagioclase alters to epidote patches with clay. Vein material/ vug fills consist of epidote, epidote + chlorite, chlorite, anhydrite and minor gypsum + calcite, anhydrite + quartz, anhydrite and minor gypsum + pyrite + coarse quartz + chlorite + illite. Epidote occurs in tight interlocking clusters in veins. Plagioclases are altered to calcite, anhydrite.
3. Highly altered andesites.

a. Matrix had been altered to a medium to coarse grained mosaic consisting of quartz, albite, K- feldspar, anhydrite with illite and leucoxene.

Plagioclase phenocrysts are incompletely altered to calcite + chlorite + quartz, epidote + chlorite.

b. Original texture obliterated; only shadows of primary laths discerned. Rock now is a mass of illite + chlorite + leucoxene + minor quartz.

c. Highly epidotized rock.

Fibrous thin unidentified mineral usually found in veinlets/ vugs associated with anhydrite + quartz, chlorite + anhydrite. Suspected secondary amphibole associated with epidote vein. Lineation marked by closely parallel veinlets of illitic clay in a rock crushed and sheared beyond recognition. Sheared and crushed rock common in cuttings.

9164 (4870)

Essentially the same as 9163 (4850) but with garnet on calcite found on a moderately altered andesite porphyry with epidote, chlorite, quartz, pyrite and secondary amphibole. Sheared rock present. Albite and adularia observed.

9165 (4950)

1. Moderately to highly altered quartz diorite intrusive (composes about 40% of the cuttings). Interlocking laths of plagioclase blemished by alteration. Alteration includes chlorite occurring in the interstices as alteration of ferromagnesians and partial alteration of plagioclases. Probable ferromagnesians completely altered to chlorite + epidote. Blemished plagioclase incompletely altered to epidote + illite + chlorite. Veinlets of epidote present. Pyrite disseminations present.

2. Highly altered porphyritic andesite, matrix is quartzo-feldspathic (feldspars are albite and adularia).

Plagioclase alters to chlorite, illite.

Ferromagnesians alter to a green pleochroic clay which is olive green in cross nichols) + anhydrite. For the olive green clay, XRD shows chlorite with some vermiculitic interlayers.

9166 (5010)

Highly altered porphyritic andesite with original textures as mere shadows defined by secondary alteration.

Groundmass alteration : anhydrite interspersed with coarse quartz crystals. Anhydrite observed altering partly to gypsum. Illite occurs in patches. Pyrite is disseminated. Secondary albite on matrix. Adularia is associated with quartz + anhydrite in patches. Vein materials : chlorite + pyrite + anhydrite, anhydrite + quartz + adularia + pyrite, quartz + chlorite. Clusters of epidote + yellow garnet. Disseminations of leucoxene on the matrix altering to epidote.

9167 (5070)

Moderately to highly altered andesitic microbreccia with porphyritic andesite. In microbreccia, plg are fragmental and are laid on a fine-grained altered matrix.

Epidote ubiquitous occurring as veins, as alteration of feldspars and ferromagnesians, as clusters on matrix in all cases well-crystalline.

In veins occur ep + q, ep + ch.

Epidote observed "eating up" calcite. Py diss.

Fmags completely altered to Ch + Ep + Py, Ep.

Plg incompletely altered to Ep + I, I, secondary albite.

Matrix altered to Q + Ab + I + Ch + Ep + Ct and disseminated with Py. (XRD : I, Ch , Q, Ab , Gypsum, Ah)

## CORES

### CORE 1 (2210- 2215)

Top. Volcanic breccia highly altered to fine- grained mosaic of quartz with fibers of chlorite, leucoxene (from pyroxene), pyrite, anhydrite patches. Quartz occurs in coarse patches pseudomorphing after plagioclases.

### CORE 1 (2210- 2215)

Bottom. Medium to fine- grained quartz mosaic dominant on volcanic breccia. Fine- grained matrix partly altered to quartz, anhydrite in patches and fractures, epidote + pyrite in veins associated with anhydrite. Diaspore ? in veinlets associated with anhydrite. Calcite is present on the altered groundmass too.

s.

### CORE 3 (4042- 4049)

Moderately altered porphyritic andesite. Original plagioclase still discernible but usually riddled by incipient alteration. Plagioclases alter to calcite + illite + quartz, illite, calcite + quartz + K- feldspar + chlorite. Ferromagnesians completely altered to chlorite + quartz + anhydrite and lined by leucoxene on its edges. Vein material consist of anhydrite + pyrite, quartz + anhydrite + chlorite. On matrix are large patches of quartz or quartz + anhydrite + chlorite + K- feldspar. Secondary albite alters primary plagioclase. Epidote present. (XRD : chlorite, illite, quartz, plagioclase, anhydrite).

### CORE 5 (5425- 5430)

Moderately altered sedimentary rock. Fragmental plagioclases are laid on a fine- grained altered matrix. Some hornblende still incompletely altered to calcite + chlorite. Plagioclases are incipiently to partially altered. Alteration of plagioclases consist of epidote, chlorite, calcite, actinolite, adularia. Matrix is partially altered to quartz, calcite, well- crystalline actinolite, with epidote, chlorite, pyrite, leucoxene, albite. Actinolite occurs as the alteration of primary minerals, as patches of euhedral to subhedral crystals, in veinlets sometimes associated with quartz + adularia + calcite.

## APPENDIX VI

## DESCRIPTION OF METHODS USED

XRD analyses were run on a Phillips PW 1050/25 wide range goniometer connected to a PW 1130/00 X- ray generator. Cu- radiation was used in all cases. The diffraction pattern was recorded by a chart recorder. Idientification of minerals was done by close checking with the NEA laboratory's standard collection of XRD patterns and by the use of the ASTM Search Manual and diffraction data references. For clay- mineral interpretation, selected papers and handbooks were also used.

Two types of sample preparation for the XRD were used:

Sample preparation for the XRD samples:
1. The sample is powderized to a recommended value of about 5- 10 µm. To prevent the powder being blown off during grinding, it has been found convenient to use acetone as a binder. When grinding a very hard and brittle mineral, it can be convenient to cover it with a sheet of weighing paper. The sample holder consists of a square disc with a rectangular hole with a microscope glass as a base. In order to prevent the scattering of X-rays, the upper surface of the powder put in the glass is made smooth by gently pressing a microscope glass on the sample. If the quantity of powder is too small to fill the aforementioned sample holders, a microscope slide is used as specimen holder, on which thin evenly distributed grease such as vaseline has been applied on.

2. For clays, oriented samples were run and prepared thus :
A few drops of the clay suspension from the cuttings are allowed to dry out slowly. Samples were put in a dessicator, then glycolated, then heated to 550°C for two hours. Others were heated to 700°C for one hour.

IR spectra were recorded in pressed KBr pellets (sample dilution 1:100) on a grating Perkin Elmer infra- red spectrometer.

The micro- probe analyses were done on an ARL automatic micro- analyzer. Polished thin sections of core samples and cuttings were prepared and carefully examined before the probe.

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