SUBSURFACE HYDROTHERMAL ALTERATION IN THE ULUMBU GEOTHERMAL FIELD, FLORES, INDONESIA

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ABSTRACT

Three wells drilled from the same pad at the Ulumbu geothermal field, Flores Island, encountered temperatures up to 240°C. Quaternary andesite lavas and pyroclastic rocks occur down to about 840 m with Tertiary sediments, dominantly limestones below, to at least 1900 m.

The volcanic rocks have been pervasively altered by neutral pH, alkali chloride waters to produce a suite of hydrothermal minerals which occur both in veins and as replacement products. These include quartz, albite, titanite, calcite and calc-silicate minerals whose distributions are thermally sensitive, ie. laumontite occurs at depths where the temperatures are between 160 and 230°C, pumpellyite from 185 to 200°C, wairakite above 190°C, prehnite above 205°C and epidote above 200°C.

There is a regular zoning of the clay minerals with depth whereby smectite is stable from ambient temperature to 120°C, smectite plus chlorite from 120 to 200°C, interlayered chlorite-smectite from 160 to 200°C and discrete chlorite plus illite above 200°C.

The homogenisation temperatures of fluid inclusions mostly match both the measured well temperatures and those deduced from the distribution of the thermally sensitive minerals.

Permeable zones occur at depths of 500 and 800 m and are characterised by euhedral quartz and adularia and the intense alteration of the host rocks.

INTRODUCTION

The Ulumbu geothermal field is located in the western part of Flores Island, Indonesia. This is the first geothermal field drilled in the Nusa Tenggara Timur Province of Eastern Indonesia. Preliminary scientific work was mostly conducted by the Volcanological Survey of Indonesia (eg. Muchsin, 1975; Kartokusumo & Somad, 1978; Muharjo et al., 1983; Setiawan & Suparto, 1984, and Simanjuntak, 1987). Exploration/production drilling was carried out by PT PLN (Persero) with assistance from GENZL and the New Zealand Ministry of Foreign Affairs and Trade. Tests suggest that at least 15 MWe could be generated by the three wells,

Flores Island forms part of the Banda Island arc system that comprises Upper Cenozoic volcanic rocks with volcanogenic and carbonate sediments (Hamilton, 1979). The volcanic rocks are dominantly of mafic and intermediate calc-alkaline composition and are unconformably underlain by Tertiary sediments. The oldest rocks exposed are of Middle Miocene age (Koesoemadinata et al., 1981).

This paper describes cuttings and cores recovered from 3 wells and interprets their alteration mineralogy.

GEOLOGY AND THERMAL MANIFESTATIONS

The Ulumbu field occurs on the southern flank of the Poco Leok volcanic complex and is about 650 m above sea level (KRTA/MERT, 1989). The youngest rocks in the area, however, outcrop approximately 7 km north of Poco Leok. These are andesites, basaltic andesites, silicic andesites and dacite domes that overlie rocks of the Poco Rii volcano which erupted lavas and breccias, dominated by andesitic to basaltic andesite lithologies. The most recent volcanic event in the region was the 1987 eruption of a dome of silicic andesite - dacite (Anak Ranakah), about 10 km north east of Poco Leok (Sjarifudin & Rakimin, 1988).

Most thermal features in the Ulumbu geothermal field occur over an area of about 28 km^2 within the crater and on the western and southwestern flanks of the Poco Leok complex. Features include hot springs, fumaroles, mud pots and steaming ground. The springs are mostly characterised by high concentrations of sulphate, very low chloride and low pH (~3), but some are of neutral pH - bicarbonate type. No chloride waters discharge at the surface.

SUBSURFACE GEOL

Three wells have been drilled from the same drill pad, one is vertical and the others deviated. The measured downhole temperatures are up to 240°C. The deepest well (ULB-01) encountered Quaternary volcanics to a depth of 838 m with Tertiary sediments below this to the well bottom, at 1887 m. The subsurface stratigraphy is summarised in Table 1.

SUBSURFACE HYDROTHERMAL ALTERATION

The primary minerals present in the Quaternary Volcanics are mainly plagioclase (andesine to bytownite), orthopyroxene, clinopyroxene and volcanic glass. The rocks have been pervasively altered by neutral pH, alkali chloride waters to produce a suite of hydrothermal minerals which occur both in veins and as replacement products. The distribution of the secondary minerals with respect to depth and the measured downhole temperatures in the three wells are shown on Fig. 1. The hydrothermal minerals are:

Quartz. Quartz is generally abundant and both replaces primary minerals and the groundmass and also fills veins.

Albite. Albite is present only as a replacement of primary plagioclase; it usually has a dusty appearance due to myriad inclusions.

Adularia. Adularia mostly fills cracks in plagioclase phenocrysts and occurs as euhedral crystals within permeable zones.

Titanite. Titanite commonly replaces the groundmass but some replaces crystal fragments or fills veins. It is usually cloudy or semi-opaque, but some samples from greater depth are clearer.

Epidote. Epidote replaces the groundmass and larger crystals (ie. plagioclase and pyroxene) and also fills veins. It is most abundant at 878 m drilled depth in ULB-02.

Prehnite and Pumpellyite. Neither mineral is widespread but both fill veins and some partly replaces plagioclase.

Zeolites. Zeolites are widely distributed; both laumontite and scolecite are present at shallower depths than wairakite (fig. 1). Laumontite occurs below 320 m, mostly as vein filling and replacing plagioclase. Wairakite occurs below 450 m, both in vesicles and replacing plagioclase.

Calcite. Calcite is the most abundant secondary mineral present and occurs from below 60 m to the bottom of the wells. It replaces primary minerals and forms veins.

Anhydrite. Anhydrite mostly occurs above 800 m. It is present as both a replacement of plagioclase and as vein fill, together with calcite, epidote and titanite.

Thickness (m)	Rock Unit	Lithology	Permeability	Age
~263	Quaternary Volcanics, Upper (QVU)	Predominantly volcanic breccias up to 50 m thick: andesite and basaltic andesite lavas less than 15 m thick and tuff.	low - moderate	Quaternary
365-386	Quaternary Volcanics, Middle (QVM)	Uniform volcanic breccias	moderate	
~210	Quaternary Volcanics, Lower (QVL)	Volcanic breccias: andesite and basaltic andesite lavas up to 25 m thick, and tuff	high	
~252	Sandstone	Altered volcanogenic and calcareous sandstones	moderate	Tertiary
~65	Mudstone-Limestone (ML)	Calcareous volcanogenic sandstone, mudstone and limestone	moderate	
~221	Limestone (Lm)	Compact limestone; thinly bedded siltstone and mudstone	low-moderate	
~350	Limestone-Sandstone-Lava (LSL)	Limestone: volcanogenic sandstone and porphyritic basalt lava	moderate	
>161	Limestone-Mudstone-Lava (LML)	Limestone, dark grey mudstone and basalt lava	moderate, but low in the deepest part	

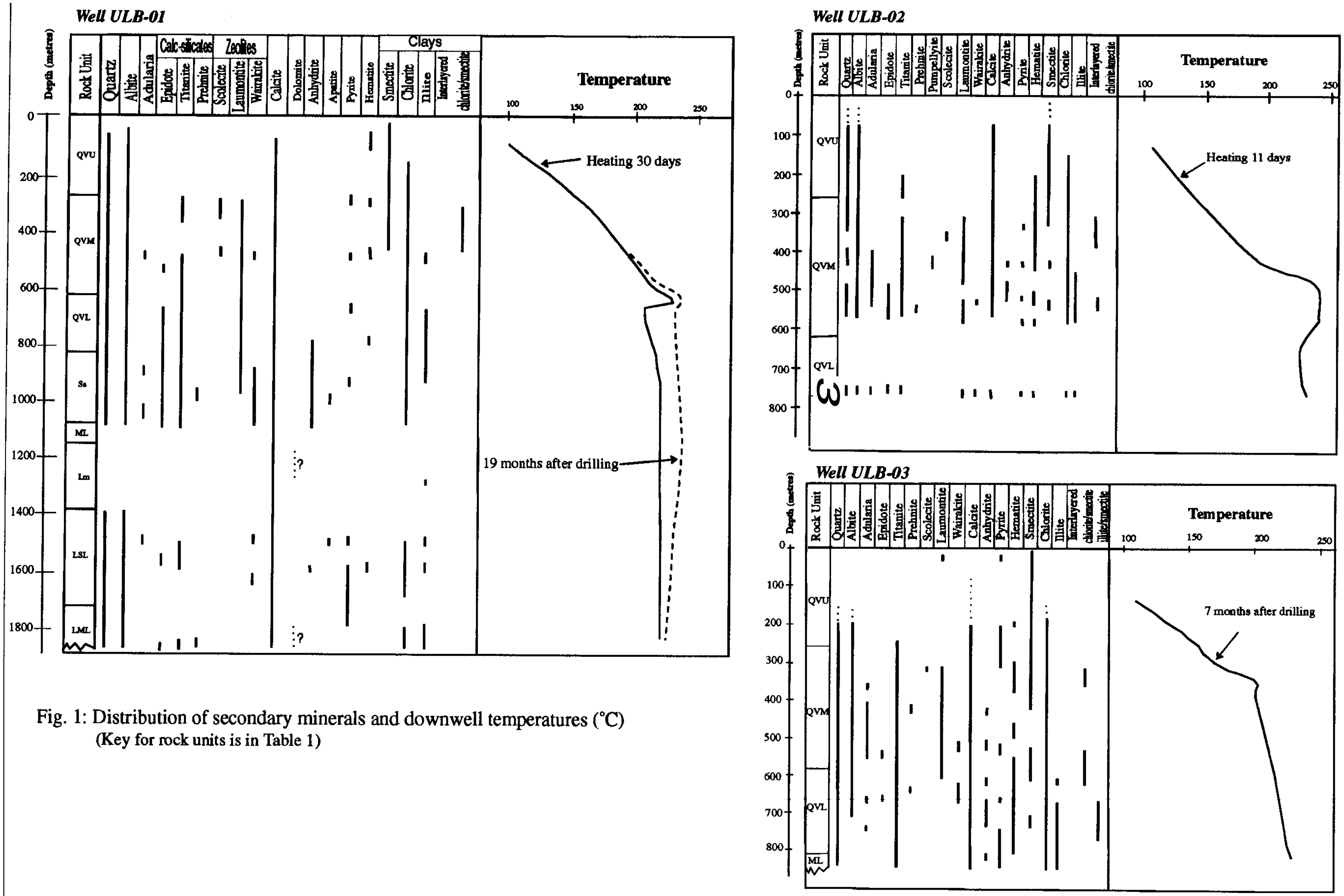


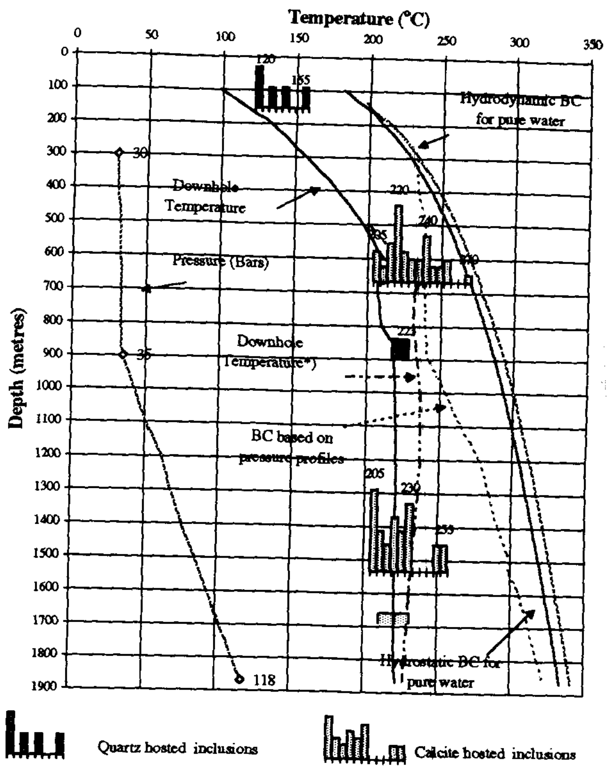
Fig. 1: Distribution of secondary minerals and downwell temperatures (°C)
(Key for rock units is in Table 1)

Clays. Clay minerals were mostly identified by X-ray diffraction (Table 2). Their energy dispersive X-ray spectra (EDX) indicate that the smectite is the calcium type. There are two types of chlorite: chlorite 1 (swells slightly upon glycol treatment) and chlorite 2 (nonswelling). Microprobe analyses show that both types have total FeO contents that are mostly in the range 15-27 wt% and MgO contents from 12 to 18wt%. Illite changes little on glycol treatment and has d(001) spacings from about 9.89 to 10.73A.

FLUID INCLUSION GEOTHERMOMETRY

To assess the thermal history of the Ulumbu reservoir, a number of fluid inclusions in samples from different depths were examined. Most inclusions are secondary but some are pseudosecondary; primary inclusions were very difficult to recognise. The inclusions occur in calcite and quartz crystals, however, calcite hosts many more inclusions than does quartz. Generally, the inclusions are liquid rich with vapour /liquid ratios of about 20%.

The homogenisation temperatures are plotted as a function of depth on Fig. 2. This figure also shows the downhole temperatures and pressures, boiling curves (BC) for pure water in both hydrodynamic and hydrostatic conditions, and a BC calculated from the measured downhole pressures. The ighest homogenisation temperatures (Ths) mostly all above the measured downhole temperatures but elow the BC, ie. only liquids were trapped, except n one inclusion, from 680-683 m, which homogenised at 270°C, that may have trapped two phases. However the modes at 240°C on the relevant histogram also closely match the BC calculated from the downhole pressure profiles,



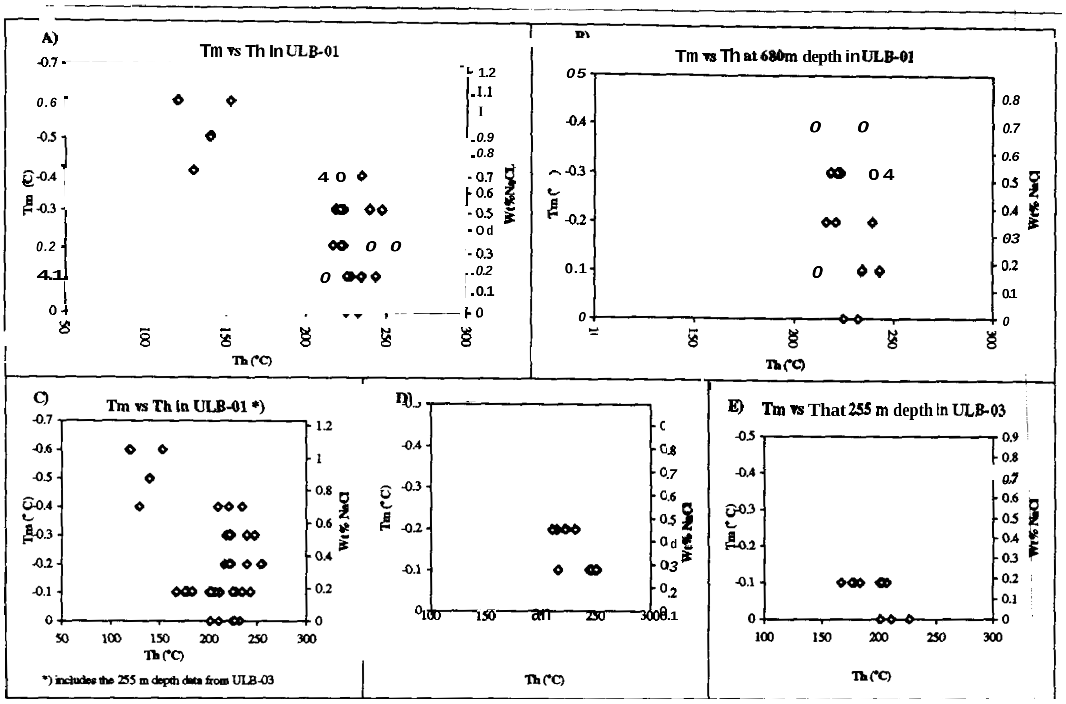
*) Downhole temperature measured on 27-04-1996

Fig. 2: Homogenisation temperatures of fluid inclusions and measured downhole temperatures as a function of depth in cores from well ULB-01

'able 2: X-ray diffraction charactersitics of of clay minerals in cores and cuttings from Ulumbu vells.

Mineral	Air-dried	Glycolated	Heated to 550°C	Powder
	d (001) in Å	**d(001) in Å**	**d (001) in Å**	**d (060) in Å**
Smectite A1	14.52 - 15.62	17.19 - 18.3	9.85 - 11.51	1.539-1.542
Smectite A2	14.95 - 15.72	17.48 - 18.03	~ 10	not detected
Smectite B	12.36 - 12.5	17.37 - 17.97	10.53 - 12.55	1.541
Chlorite 1	14.18 - 14.76	14.44 - 14.86	13.76 - 14.5	
Chlorite 2	14.05 - 14.37	14.01 - 14.35	14.01 - 14.3	
Illite	9.89 - 10.73	9.52 - 9.99	9.9 - 10.27	
	d (001*) in Å	**d (001*) in Å**	**d (001*) in Å**	
Interlayered chlorite/smectite 1	27.31 - 29.18	30.12 - 31.98	collapsed or 25.79 - 25.91	
Interlayered chlorite/smectite 2	25.94 - 26.89	28.87 - 29.24	collapsed or 24.31 - 26.69	
Interlayered illite/smectite	25.02-26.77	27.3 - 27.96	9.97 - 10.03 or 21.02	

note: *superstructure basal reflection



'ig. **3:** Homogenisation **and** ice melting temperatures of fluid inclusions

ıggesting that the trapped fluids were at mperatures close to boiling. Most Ths closely ıatch the present temperatures. This suggest ither that the system has been thermally stable, at :ast in the area drilled (ie. ULB-01), or that the iclusions are all young.

'he ice melting temperatures (Tm) are mostly in ıe range 0.0 to -0.4°C (Fig. **3).** This corresponds) an apparent salinity of 0 to 0.70wt% NaCl.

ʌY MINERAL ZONATION (Fig. 4

here is a regular zoning of the clay minerals with :spect to depth. The smectite only zone is in the ıallowest part; below this are chlorite plus nectite and interlayered chlorite/smectite zones, ıen a chlorite with or without illite zone in the eepest part. Methylene blue treatment indicates ıat the amounts of smectite present in the mectite only zone is up to 52% but it is much less bundant in the deeper samples.

'he clay mineral zones correlates both with the neasured downhole and the homogenisation emperatures (Table 3). The clay mineral zones at Jlumbu are very similar to those in the Philippine ields. which also occur in calc-alkaline rocks.

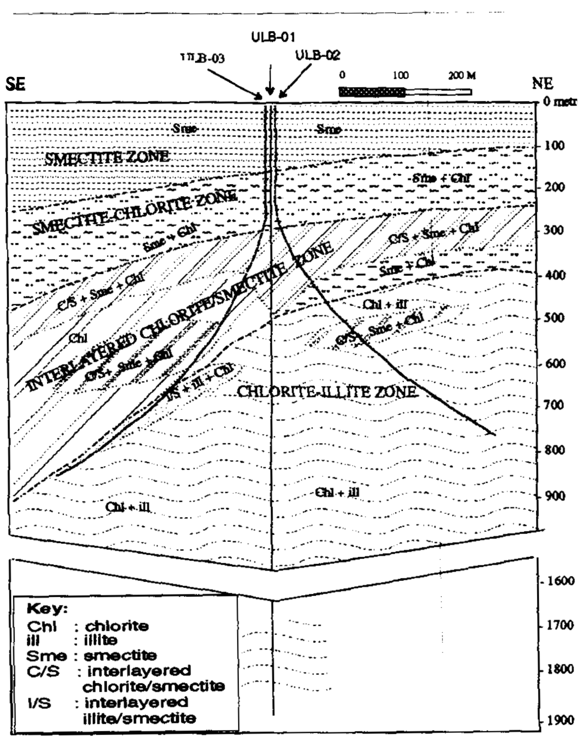


Fig. **4:** Clay mineral Zones

TEMPERATURES DEDUCED FROM THE OCCURRENCES OF CALC-SILICATE MINERALS

Minerals that contain in their structures either (OH) or n-H_2O, such as clays and calc-silicates, can usually provide temperature information. The thermal ranges of the calc-silicate minerals with respect to the measured temperatures in the field are summarised in Table 4 and are here compared with the Philippine and Icelandic fields. The temperatures of the shallowest appearance of the calc-silicates (except for laumontite) at Ulumbu are lower than those in the Philippines, however the zeolites at Ulumbu occur at temperatures higher than they do in the Icelandic fields. These differences are probably due to the different rock types present, which are mostly andesite, basaltic andesite and basalt in the Philippines, Ulumbu and Icelandic fields, respectively.

PERMEABILITY

The Quaternary volcanics exhibit generally moderate to high permeability (Table 1). However, the lowest permeability occurs at shallowest depths, where most rocks have been intensively altered to smectite, causing sealing within the upper unit (QVU) and down to the middle unit (QVM). The highest permeability occurs in the lower unit (QVL), ie. at depths of 500 to 800 m. Rocks here are characterised by the presence of euhedral quartz and adularia and intense alteration; circulation losses occurred here during drilling.

CONCLUSIONS

Reservoir rocks at the Ulumbu geothermal field have been hydrothermally altered by pervasive chloride waters of neutral pH. This produced a suite of hydrothermal minerals which occur both in veins and as pseudomorphs including quartz, albite, adularia, titanite, epidote, prehnite, pumpellyite, laumontite, scolecite , wairakite and calcite. However, anhydrite, deposited from sulphate rich fluid, occurs mostly above 800 m.

Both calc-silicate and clay minerals present are thermally sensitive. The lowest thermal stability ranges of the calc-silicates at Ulumbu are generally 30 to 50°C lower than they are in the Philippines, but higher than in the Icelandic fields.

Clay mineral zones	Range of measured temperatures ("C)	Range of the lowest Ths (°C)	Range of the modes of Ths (°C)	Philippine fields*) (°C)
Smectite	–120	–120	–120	–120
Smectite+Chlorite	120-200	120-190	120-210	120-180
Interlayered Chlorite/Smectite	160-200	160-190	180-210	180-210**)
Chlorite+illite	>190	>190	>210	>210

Table 4: Distribution of thermally sensitive calc-silicate minerals

Mineral	Ulumbu ("C)	Iceland (°C)*	Philippines (°C)**
Laumontite	160-230	100-230	120-220
Scolecite	160-190	70-100	
Wairakite	>190	170-300	220-310
Prehnite	>205		250-310
Pumpellyte	185-200		
Epidote	>200		250-340
Titanite	>140		200-340

** taken from Fig. 7 in Reyes, 1990.

Clay mineral zones are an excellent temperature indicator at Ulumbu and can probably be used as temperature guides in future geothermal exploration in eastern Indonesia.

Highly permeable zones are generally characterised by the presence of euhedral quartz and adularia and the intense alteration of the host rocks.

ACKNOWLEDGMENTS

We thank the management of PT PLN (Persero) of Indonesia and MFAT of New Zealand for permission to publish this paper.

REFERENCES

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

Direktorat Vulkanologi (1989), "Pemetaan geologi G. Api Anak Ranakah, Flores", In Laporan Tahunan Direktorat Vulkanologi Tahun 1988/ 1989 (Volcanological Survey of Indonesia Annual Report 1988/ 1989) 108 - 135

GENZL (1994), "Geological log of well ULB-01, Ulumbu geothermal field, Flores, Indonesia", Unpublished report Ulumbu mini geothermal power project.

GENZL, (1995), "Geological log of well ULB-02, Ulumbu geothermal field, Flores, Indonesia", Unpublished report Ulumbu mini geothermal power project.

GENZL (1996), "Geological log of well ULB-03, Ulumbu geothermal field, Flores, Indonesia", Unpublished report Ulumbu mini geothermal power project.

Hamilton, W.B. (1979), "Tectonics of the Indonesia region", USGS Professional Paper 1078.

Kartokusumo, W.S., and Somad, A. (1983), "Laporan penyelidikan geokimia panasbumi daerah Ulumbu, Ruteng, Flores, Nusa Tenggara Timur", Unpublished report, Direktorat Vulkanologi, Departemen Pertambangan dan Energi.

Koesoemadinata, K. , Noya, Y., and Kadarisman, D. (1981), "Preliminary geological map of the Ruteng quadrangle, Flores, Nusa Tenggara, Indonesia", GRDC, Bandung.

Kristmannsdottir,H., and Tomasson, J. (1978), "Zeolite zones in geothermal areas in Iceland; Natural Zeolites Occurrence, Properties, Use", Pergamon Press, Oxford, 277-288.

KRTA/MERT (1989), "Flores mini-geothermal project, Ulumbu geothermal field, Flores, Indonesia. Feasibility study report", Unpublished report, New Zealand Ministry of External Relation and Trade.

Moore, D.M., and Reynolds, Jr, R,C. (1989), "X-ray diffraction and the identification and analysis of clay minerals", Oxford Univ. Press. 332 pp.

Muharjo, Erfan, R.D., Setiawan, T., Nahlohi, F., and Yuhan (1983), "Laporan Penyelidikan geologi daerah panasbumi Poco Leok, Kabupaten Manggarai, Flores", Unpublished report, Direktorat Vulkanologi, Indonesia.

Muchsin, M.C. (1975), "Inventarisasi dan penyelidikan pendahuluan terhadap gejala-gejala panasbumi di daerah Flores", Unpiblished report, Direktorat Geologi, Bandung, Indonesia.

Reyes, A.G. (1990), "Petrology of Philippine geothermal systems and the application of alteration mineralogy to their assessment", J. Volcanol. Geotherm. Res.,43, 279-309.

Roedder,E. (1984), "Fluid inclusions", Mineralogical Society of America, Reviews in Mineralogy, V. 12, 644 pp.

Setiawan, T., and Suparto (1984), "The geology of the Ulumbu geothermal area, Flores, Indonesia", Unpublished report, Direktorat Vulkanologi, Bandung.

Simanjuntak, J. (1982), "Laporan-studi geofisika tahanan jenis lapangan panasbumi Ulumbu dan sekitarnya, Ruteng, Kabupaten Manggarai, Flores Barat", Unpublished VSI report.

Simanjuntak, J. (1985), "Laporan-studi geofisika tahanan jenis lapangan panasbumi Ulumbu dan sekitarnya, Ruteng, Kabupaten Manggarai, Flores Barat", Unpublished VSI report.

Sjarifudin, M.Z., and Rakimin II (1988), "Petrokimia batuan kompleks Mandasawu", (Letusan Anak Ranakah 28-12-1987 s/d 19-1-1988), Flores, Nusa Tenggara Timur, Direktorat Vulkanologi, Bandung.