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THE GEOLOGY AND ALTERATION MINERALOGY OF WELL OKOY-5, S.NEGROS, PHILIPPINES

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ABSTRACT

Analyses on the alteration mineralogy of well Okoy-5 in the Palimpinon field, S. Negros, Philippines, show a definite zonation of alteration minerals related to the increased downhole temperatures, which in turn are related to the production zone lying at a depth of 1085 to 1500 m. The progressively changing clay mineral assemblages are used to define three major alteration zones: Zone I - Montmorillonite, Zone II - Montmorillonite - Illite, and Zone III - Illite. A possible fourth zone, mainly composed of Fe - rich chlorite, is also suggested. Other significant alteration minerals such as epidote, quartz, anhydrite, pyrite, garnet etc., have likewise contributed in defining the present state of the well. The temperatures measured correspond fairly well with the known stability ranges for the various minerals reported from other geothermal fields. This suggests that the geothermal system at the location of well Okoy-5 is presently near equilibrium with regard to temperature and rock alteration.

1. INTRODUCTION

1.1 Scope of work and analytical methods used.

The author of this report was awarded a UNU Fellowship to attend the 1979 UNU Geothermal Training Programme held at the National Energy Authority in Iceland. After about three weeks of lecture courses the author received specialized training in borehole geology. This included theoretical and practical aspects of X-ray analyses (3 weeks), mineral separation techniques (1 week), analytical methods of clay minerals (3 weeks), theoretical aspects of electron miçroprobe analyses (2 days), field and magnetostratigraphic mapping (1 week) and practical introduction to various geophysical logging methods (1 week). This report is an outcome of the research project carried out mainly during the last eight weeks of the training. The analytical methods acquired during the specialized training were applied to samples from a drillhole in the Southern Negros Geothermal Field in the Philippines.

The normal routine megascopic identification of the common minerals was made on all available cores and drillcuttings, but some selected samples were impregnated, thin sectioned and analysed under the petrographic microscope. The clay minerals were mostly identified by X-ray diffraction methods, but in some cases, where results obtained were doubtful, infrared spectrometry was used. Some selected minerals of significance were on the other hand subjected to electron microprobe analysis, which gave fairly reliable and detailed results of their composition.

1.2 Regional geological setting.

The Philippine archipelago is an island arc system situated along the Circum-Pacific belt of high heat flow and seismicity (Fig. 1). This island arc system consists of two reversely fronting arcs that are concordant to two oceanic trenches located along its northwestern and eastern margins (Fig. 2).

Related to this arc-trench system is the Philippine fault, a major left lateral transcurrent tectonic structure which traverses the whole country from north to south.

Also concordant to the arcs is a broad belt of Plio-Quaternary andesitic volcanoes which is found distributed throughout the islands (Fig. 2).

Presently there are about 71 known thermal areas in the Philippines, most of which have been identified with andesitic volcanic centers (Alcaraz et al. 1977). Four of these fields are proven as exploitable for power production and are now in various stages of exploration and development. These are Tiwi in Albay, Makiling - Banahaw in Laguna, Tongonan in Leyte, and Southern Negros in Negros island. (Fig. 3).

2. THE SOUTHERN NEGROS GEOTHERMAL FIELD

2.1 Location of thermal areas.

The Southern Negros Geothermal Field (SNGF) is situated close to two dormant andesitic volcanoes, namely Cuernos de Negros and Balinsasayao (Fig. 4). These volcanoes may be related to the Northeast - trending conjugate segment of the Philippine Fault which dissects the area (Fig. 1). The SNGF consists of two promising geothermal areas: the Magaso de Dauin, which is situated on the ring plain southeast of Cuernos de Negros on the one hand, and the Palimpinon thermal area on the other (Fig. 5). The latter, which is located on the eastern sector of the Okoy valley, is at a relatively advanced stage of exploration. However, borehole geology and alteration studies have not yet been given much attention, thus rendering it difficult to correlate the subsurface geology of Okoy-5 to other drillholes in the area.

Two shallow exploratory wells (Negros 1 and 2) and six deep ones (Negros 3, Okoy 1-5) have at present been completed. Three of the deep wells are producing, giving estimated total output of about 14 MWe. When completed the field is expected to contribute about 100 MWe to the Visayan power grid.

2.2 Tectonic setting.

The Palimpinon thermal area is located within a narrow localized graben that forms the Okoy valley, where the slopes of the two aforementioned volcanoes coalesce. The thermal area is marked on the surface by hot springs, fumaroles and altered ground. The surface manifestations have been found to be related to three major fault patterns (Tolentino and Loo, 1974) (Fig. 6):

1) NW-NNW trending right lateral faults.
2) Northeasterly trending left lateral faults.
3) A system of step-faults trending WNW, NW and NE.

The first two fault patterns are marked by distinct offsets along the Okoy-river, and have been attributed to the regional second degree almost east-west compressive forces sympathetic to the main Philippine fault. The third pattern has been attributed to a failure caused by local coupling stresses that have arisen from the lateral movements along shear planes.

By comparing the top of the oldest formation (siltstone) encountered in the wells, there appears to be a downward displacement of some 500 m between well Okoy-3 in the NE to wells Okoy-4 and Okoy-5 in the SW (Fig. 7). The wells concerned form a line almost parallel with the regional strike and thus the most likely cause of the displacement is either localized tilting towards the Cuernos de Negros volcano or faulting. A likely fault has not yet been located by surface mapping. In fact, a major E-W trending fault forms an escarpment between the wells, but its downfaulting has been interpreted as northerly, or opposite to the displacement suggested by the top of the siltstone in the wells.

2.3 Lithology and stratigraphy.

The stratigraphy of the area gathered from surface mapping and well logging is summarized in Table 1. The oldest known rock formation is the upper Miocene siltstone. This rock is calcareous, impervious and black in colour, and is in places highly fossiliferous and pyritic. Four of the deep exploratory wells (Okoy 1,3,4 and 5) penetrated down into this formation to a maximum depth of 762 m (Okoy-1) without breaking through its base. The producing horizons encountered in wells hitherto have all been in formations above the siltstone. The depth to the top of the impervious siltone, relative to sea level, is -200 m in well Okoy-1, -300 m in Okoy-3, and -900 m in wells Okoy-4 and Okoy-5 (Fig. 7). Due to this and the regional topography, the thickness of the volcanics overlying the siltstone thus increases from about 800 m in Okoy-1 furthest NE to about 1500 m in Okoy-5 furthest SW and closest to the Cuernos de Negros. The thickness of the potential geothermal reservoir rock (above the siltstone) thus increases significantly towards the volcano. This can be partly caused by southerly downfaulting, as was discussed in the previous chapter. The impervious nature of the siltstone and in particular the positive thermal gradient encountered in that formation may possibly imply a deeper separate geothermal reservoir to which this siltstone acts as a cap rock.

The siltstone is overlain by younger volcaniclastics of upper Miocene to Pliocene age known as the Southern Negros Formation (SNF). The SNF consists dominantly of hydrothermally altered conglomerates commonly including andesitic clasts. It was the only known hydrothermally altered formation prior to drilling and as such was one of the determining factors in well siting at the beginning of exploratory drilling.

The SNF is unconformably overlain by a thick lava succession derived essentially from the two volcanoes of Balinsasayao and Cuernos de Negros. The succession is composed of andesite lavas (hornblende - andesite, andesite, pyroxene-andesite), hornblende - dacitic lavas and hornblende - rich dacite lavas in order of decreasing age. A fourth rock type, which may be the oldest among this sequence, is exemplified by a moderately altered porphyritic pyroxene andesite lava identified in well Okoy-5 (core 3) at a depth of 1352-1354 m (Appendix 1). A similar rock type, but highly altered, was reported to occur at about 1400 m depth in Okoy-4, a well 800 m northeast of Okoy-5. Similarly, Castro et al. (1979), identified some pyroxene-hornblende-andesite lava flows unconformably overlying the SNF at Tibanglan and in some other parts of the Okoy valley. In view of the above observations the porphyritic pyroxene andesite is considered a separate unit in the stratigraphic sequence.

The youngest formation in the column, however, is a sequence of Quaternary sediments composed of a Pleistocene reef limestone, outcropping northeast of Balinsasayao and Palimpinon, and unconsolidated beach gravel and thermal deposits seen within the thermal areas towards the coast.

2.4 Geochemistry.

Studies have been made on the geochemistry of the thermal springs. Glover (1975) divided the springs into two spatially and chemically distinct groups:

a) A spring area downstream of Okoy river, which issues waters of high chloride content but neutral pH. This water is attributed to a direct leakage from the deep aquifers.

b) A spring area upstream from Ticala to Lagunao issuing waters of low chloride but high sulphate content. This water is thought to represent a mixing at a shallow level of cold groundwater and steam, the latter being flashed from a nearby geothermal reservoir.

Deep wells drilled in the upstream and downstream areas, however, tap water of similar salinity. Thus, well N-1 in the downstream area has about 4400 ppm Cl^- in the discharge and well Okoy-5 in the upstream area has about 4700 ppm Cl^- (Table 2). The Na/K ratios are, however, different indicating a temperature of about 290°C and 250°C in the upstream (Okoy-5) and the downstream (N-1) areas respectively, suggesting an upflow under the upstream area and lateral transport at depth towards the downstream area.

2.5 Geophysics.

Dipole - dipole resistivity surveys conducted by Vazques and Abear (1973) revealed the presence of low resistivity anomalies associated with the surface thermal manifestations of the Palimpinon area. Similarly a Schlumberger resistivity survey with electrode spacings of AB/2 equals 250 and 500 m detected four distinct anomalies (Fig. 5), all converging towards Cuernos de Negros. This configuration may suggest a common heat source most likely to be associated with that volcanic center.

2.6 Drilling history

The Palimpinon resistivity anomaly (Fig. 8) trends E-W along the main axis of the Okoy-valley. Two shallow wells (N-1, N-2) of 605 m and 610 m depths respectively were drilled within this anomaly. Both wells showed temperature reversals at depth, but N-1 which is located west of N-2, exhibited a higher temperature implying that the holes intersected a flow path system which originated upstream (i.e. from west to east). On basis of this a third well (N-3) was drilled further to the southwest. This well (975 m) encountered a similar flow path pattern and recorded as expected the highest temperature of the three drillholes. Subsequently wells Okoy 1 and 3 drilled to the northwest of N-1 and N-3, showed similar results. At that stage it was becoming clear, that an upflow zone was likely to be situated at the southwestern end of the low resistivity lobe. Three deep wells (Okoy - 2,4 and 5) were drilled in this direction. As Okoy-2 was terminated earlier than programmed, the flow path situation was not detected in this well, but a significant increase was found in the temperature of its production zone, or from 226°C (N-3) to 257 °C (Okoy-2). These findings in Okoy-2 led to the drilling of Okoy-4 and 5 further to the southwest and outside the main resistivity anomaly. Both wells showed maximum temperature at depth with no distinct reversals, but the water levels were observed to be much depressed in the wells. Okoy-5 was successfully discharged only after a number of stimulation attempts by using a compact boiler injecting steam into the drillhole. The rated capacity of Okoy-5 is 7,5 MWe with a total mass flow of 24,7 kg sec^{-1} and enthalpy of 1850 KJ kg^{-1} . The same stimulation technique was applied to Okoy-4 but the well collapsed after a few hours of discharge.

3. WELL OKOY-5, SOUTHERN NEGROS

3.1 Location.

Okoy-5, the 8th well to be drilled in Southern Negros, was sited, as previously mentioned, outside the 20 Ωm apparent resistivity anomaly that terminates within the neighbourhood of Okoy-2 (Fig. 8). Its location has the coordinates 518050 E, 1027300 N. It is at an elevation of 932,5 m a.s.l., and reached a total depth of 1975 m.

Encouraged with the results realized from the drilling of Okoy-4 (also a step-out exploratory well south of Okoy-2,) it was decided to drill further towards the southwest, in order to test a possible extension of the thermal anomaly towards an inferred ultimate heat source in the roots of the Cuernos de Negros volcano.

3.2 Well stratigraphy.

The stratigraphy of the rocks penetrated in Okoy-5 is shown in Table 3. The strata in the uppermost 1100m of the drillhole consist mainly of variably altered hornblende-andesite lavas and porphyritic andesite lavas. Due to a total loss of circulation fluid the only stratigraphic data between 1100 m and the bottom of the hole (1975 m) is represented by four 3,1 m cores (cores 2,3,4 and 5) at the depths of 1161,1352,1822 and 1971 m respectively. These cores are generally composed of volcanic breccia (core-2), porphyritic pyroxene andesite lava (core 3) and volcaniclastics, mainly composed of andesitic fragments set in a calcareous siltstone matrix (core 4 and 5). A description of the rock types is presented in Table 4.

3.3 Alteration mineralogy.

The degree of alteration of the rocks encountered in the well is quite variable, and this may reflect differences in rock permeabilities. However, the alteration intensity appears in general to increase with depth, towards the production zone.

Tables 3 and 5 show the general distribution of the alteration minerals found in the well, and the summary of the methods applied in their identification are listed in Table 6. The temperatures plotted in Fig. 3 and 5 are based on predischarge measurements made about 3 months after completion of drilling, and are assumed to represent the stabilized temperature of the rock formations.

As there is very limited data available on other wells in the area no attempt will be made to compare the secondary mineralogy of Okoy-5 with the other wells. In the following section the clay minerals will first be discussed followed by the common alteration minerals including the rare garnets.

3.3.1 Clay minerals.

The XRD patterns of the 21 samples analysed are shown in Fig. 9. The results of the XRD analyses are compiled in Appendix II.

Kaolinite. Mere traces of this mineral are found at 55-60 m depth, where the temperature is $<40^\circ$C. It occurs together with montmorillonite and chlorite. Due either to its paucity in occurrence or its imperfect crystallinity, only two distinct basal reflections were detected by XRD d(001) =7,19Å and 2,34 Å. Both disappear upon heating to 550°C, as expected for kaolinite. Furthermore, a strong d(060) reflection at 1,49 Å, confirms its presence. Similarly confirmative, weak but distinct kaolinite absorption bands appeared in the IR spectra.

Montmorillonite. Smectite and smectite/illite mixed-layer minerals are found down to a depth of about 800 m. The smectite is of montmorillonite type according to the d(060) spacing. Montmorillonite and mixed-layer montmorillonite/illite rich in the Montmorillonite component are the dominant clay minerals in the uppermost 400 m. This appears in a sequence of weakly to moderately altered andesite lavas where low temperatures (less than 100°C) prevail. It occurs in association with chlorite and mixed-layer minerals of various kinds. The XRD patterns are often obscured by overprinting of patterns due to chlorite and other mixed-layer minerals.

Vermiculite. A tentative occurrence of vermiculite coincides with the complete disappearance of montmorillonite at a depth of about 800 m and at about 185°C. A change from a Mg-rich chlorite to a Fe-rich chlorite also seems to coincide approximately with this level. The existence of the vermiculite is only reported here as tentative, as the distinctive peaks of this mineral were not indicated in the XRD analyses. Its existence is only indicated from the IR spectra, which gave an absorption band of 2840, 2910 and 3380 cm^{-1}.

Illite starts to appear as a component in mixed-layer minerals at about 420 m along with smectite and chlorite, where intense pyritization has occurred and a temperature of about 100°C is recorded (Tables 3 and 5). With increasing temperature and depth, the mixed-layer minerals change from a high d(001) spacing towards lower d(001), i.e. the illite component in the minerals increases. However, this trend is not a very gradual or regular one. At deeper levels (around 840 m depth) illite becomes the dominant clay mineral.

Chlorite. The chlorite minerals can be distinguished mainly by two methods i.e. x-ray diffraction and petrographic examination. Under the microscope, the chlorites appear as light brownish-green or dark-green pleochroic minerals, normally in thin scales and as minute radiating aggregates. They are often associated with quartz, calcite, epidote and anhydrite and replace ferrromagnesia minerals in andesites. In XRD analysis, chlorite species are recognized by the sequence of basal 00.l reflections from the (001) cleavage plane, and especially by the d(001) spacing of 14,0-14,3 Å (Brindley, 1961).

As shown in Tables 10 and 11 two distinct groups of chlorite appear in the section. According to the XRD results one is Mg-rich, the other is Fe-rich. In the former group the relative intensities of 001 and 003 are in general stronger than its 002 and 004 reflections. In the Fe-rich variety, on the other hand, the opposite relative strengths of intensities were observed. Only one sample of chlorite was analysed on the microprobe. This is a sample from core 4 (depth 1822 m) of a chlorite characterized by XRD-analysis as a Fe-rich variety. This is an analysis of a single point and may therefore not be altogether representative for the Fe-rich chlorite in the lower section of the well. According to Hey's classification (Hey, 1954) the analysed chlorite is a ripidolite with a calculated formulae of $Mg_{6.1}Al_{2.3}Fe_{3.5}$ $(Si_{5.5}Al_{2.5})$.

Other clay minerals. Besides the common types of sheet silicates, there were observed in some samples, irregularly mixed-layer minerals of illite/chlorite and illite/smectite/chlorite. "Swelling chlorite" and some poorly defined (by XRD) 14Å minerals were also found. Those minerals are most common in the upper 800 m of the section, but are found down to about 1000 m depth.

3.3.2 Other common alteration minerals.

Calcite is the most widely distributed alteration mineral found in this well. It is most commonly found as a alteration product of plagioclase, pyroxene and groundmass of andesite lavas and siltstones. It also occupies vugs and fractures in cores 3 and 4 (1352 m and 1822 m) and is furthermore observed to replace microforaminiferas in the siltstone. It is usually found associated with quartz, anhydrite and gypsum, and is also seen to co-exist with epidote and chlorite in cores 4 and 5 (1822 m and 1971 m). However, calcite is notably absent in core 2 (1161 m) where epidote is found in relative abundance. The abundance of calcite is generally low to moderate in the upper 1500 m, but is observed to increase in the siltstone. An electron microprobe analysis of calcite is included in Table 7.

Anhydrite and gypsum. The anhydrite (d_{020}=3,49Å) and its hydrous counterpart gypsum (d_{020}=7,56Å) are the only sulphates so far identified in this drillhole. They are usually found as vugs and fracture fillings, and are commonly associated with quartz, pyrite and calcite. They are also found in veins and matrices of andesites together with epidote and chlorite. They are found to be particularly abundant in cores 1 and 2 (913 m and 1161 m) within the production zone.

Hydrothermal quartz is like calcite also widespread in the hole. It often forms a mosaic pattern within the matrix of andesites, is observed to replace primary plagioclase phenocrysts, and is also a common vein constituent. Minerals commonly found associated with the quartz are calcite, anhydrite, albite, pyrite and chlorite. It is particularly abundant in the intensely pyritized volcanic breccias in core 2 (1161 m).

Pyrite occurs intermittently throughout the hole. It appears as euhedral cubic crystals with brassy yellow lustre in reflected light. It is commonly found as disseminations in the upper 1000 m of the drillhole, but as vein and fracture fillings below 1100 m. Boxwork structures and stringers are also occasionally noted. It is often seen associated with quartz, magnetite and hematite, but rarely with epidote and chlorite. It usually replaces ferromagnesian minerals like hornblende and pyroxenes and is occasionally seen altering plagioclase phenocrysts. XRD data of pyrite in core 2 (1161 m) are shown in Table 7, where typical reflections and relative peak intensities serve to distinguish it from other minerals.

Magnetite - ilmenite - hematite - leucoxene: The occurrence of magnetite is relatively restricted to the hornblende andesitic rocks of the upper 1000 m, where the temperature is less than about 200°C. In thin section, the magnetite grains are euhedral, opaque, cubic crystals with metallic lustre under reflected light. Although some magnetites are reported below 1000 m, they have probably been exsolved to ilmenite which in turn has usually been altered to leucoxene. Leucoxene is here defined as a substance occurring as a white cotton-like mineral in reflected light. The magnetite is usually associated with pyrite and hematite. It often occurs as pseudomorphs after hornblende crystals and as an alteration product of pyroxenes. It is also being oxidized to hematite along its rims.

Epidote occurs below 850 m and is a significant alteration mineral in the two lowest alteration zones, i.e. zone III, (illite zone 885-1354 m), and zone IV (mainly Fe-chlorite, 1500-1974 m). In zone III, in the temperature ranges 200-250°C, the epidote appears in a discontinuous manner, though with the notable exception of core 2 (1161 m) where it occurs in abundance along with pyrite and illite, but with the apparent absence og chlorite. In zone IV, where the temperature is about 300°C, the epidote is found crystallizing along with Fe-chlorite, where there are no clays present. The epidote crystals range in size from incipient, minute granules to well formed radial aggregates. They are common vein constituents frequently associated with hydrothermal quartz, anhydrite/gypsum and pyrite. Except in core 2 (1161 m) chlorite and calcite are also often associated with it. The epidote is found replacing plagioclase in core 2 and probably altering andradite garnets in cores 4 and 5 (1822 m and 1971 m). A microprobe analysis of the epidote is given in Table 7.

<u>Garnet</u> is a very rare alteration mineral in the well. It is only found in cores 4 and 5 (1822 m and 1971 m) where temperatures exceed 300°C. A microprobe analysis is given in Table 7. The analysis shows that they are pure andradite garnets. The garnets are colourless in thin section, show a high relief, and have distinct rough surfaces. They usually occur in minute octahedral crystal chains lining up walls of veins, vugs and fractures. They are intimately associated with calcite and epidote together with chlorite and in places anhydrite. Most crystals are isotropic but others, which display fine granular birefringence similar to epidote, are just nearly isotropic to weakly anisotropic. Furthermore, a kind of a reaction rim or a faint zoning probably due to some compositional variation, are observed around some of the nearly isotropic crystals (Table 9). A replacement by epidote of the core of some garnets is also observed (Table 9).

3.4 <u>Discussion of results.</u>

3.4.1. <u>Zonation of the clay minerals</u>

There appears to be a sequence of clay mineral assemblages within Okoy-5, where at least three and possibly four distinct zones can be roughly established. The zones are as follows:

Clay zone	measured temp. (C°)	depth (m)
I. Montmorillonite	< 100	400
II. Montmorillonite-illite	< 200	400 - 800
III. Illite	200-250	800 - approx. 1500
IV. Chlorite	> 300	below approx. 1500

As there are only available four cores from the depth range 1100-1974 m, the boundaries between the zones have to be regarded as tentative only.

I. Montmorillonite zone.

The characteristic clay mineral of this zone is,as the name implies, montmorillonite. It is associated with poorly defined mixed-layer minerals or swelling chlorites with minor occurrences of other clay minerals such as chlorite and kaolinite.

A temperature of approximately 100°C marks the boundary with the next zone (zone II) in which a gradual transformation to illite takes place in an irregular manner. In Wairakei, Steiner (1953) showed montmorillonite to be formed at temperatures ranging from 100-122°C. In Iceland, Kristmannsdottir (1978) likewise reported the formation of such clay minerals within this order of temperatures in mudpots and even in near-surface acid leaching zones in high temperature areas.

II. Montmorillonite-illite zone.

The appearance of illite at about 400 m depth (approx. 100°C) and the disappearance of the montmorillonite component at about 800 m depth, where a temperature of about 190°C was measured, marks the boundaries in this zone. Muffler and White (1969) reported that montmorillonite is converted to an illite-montmorillonite assemblage at temperatures above 100°C in the sediments of the high temperature areas of the Imperial and the Mexicali Valleys. Similarly, Ellis and Mahon (1977, p.98) have reported that the assemblage illite-montmorillonite is formed at about 100°C at the Salton Sea geothermal field. Wood (1977) implied a similar change towards illite-montmorillonite at slightly higher temperatures of about 140°C. The temperatures measured at this clay zone boundary in Okoy-5, where illite starts to appear at about 100°C,are thus quite comparable with data from other geothermal fields.

Lower boundary of zone II, at 800 m, where smectite ceases to exist (i.e. having been completely transformed to illite) the temperature was measured to be around 190-200°C. This boundary has been well defined in some other areas where temperatures are believed to be in equilibrium with the mineral assemblages. Thus, in the Salton Sea geothermal field a conversion at about 210° was reported by Ellis and Mahon (op. cit.). At the Broadlands geothermal field illite was reported to occur at lower temperatures in association with quartz or from 270°C down to 160°C (Eslinger and Savin, 1973). Studies of the alteration mineralogy of six high temperature areas in Iceland showed that smectite disappears at temperatures surpassing 200°C (Kristmannsdottir, 1979).

III. Illite zone.

The upper boundary of this zone at 800 m in the well is defined by the total transformation of smectite into pure illite at temperatures around 200°C. Here, the clay assemblage consists of two components, those of illite and chlorite.

During drilling of Okoy-5 a total circulation loss was experienced below about 1100 m which resulted in non-recovery of cuttings to the bottom of the drillhole (1974 m). The mineralogical data available below 1100 m are therefore limited to only 4 three meter long cores at the depths of 1161 m, 1352 m, 1822 m and 1971 m.

Although the relationship between illite and chlorite is complex the following systematic changes may be inferred to occur:

In the depth range from 800 m down to about 1100 m (where total circulation loss occurred) illite is the dominant component over chlorite. XRD-analyses further indicate an overall downward enrichment of the illite component within this depth range. Two samples at depths of 885 m and 916 m suggest an interlayering state of the illite and chlorite. The core taken at 1161 m is heavily altered with the dominant alteration mineral assemblage of pyrite, quartz, epidote and anhydrite. Here illite occurred as the sole clay constituent. The apparent increase in the illite component down to 1100 m depth at the cost of chlorite, and the pure illite in the absence of chlorite in core 2 (1161 m), may imply the continuity of such an enrichment to that depth. In core 3 (1354 m), however, an interlayered illite-chlorite, similar to those found between 885-916 m was identified.

Below 1354 m, no mineralogical data are available until at 1822 m (core 4) and 1974 m (core 5). These cores indicate a change in lithology from the dominant lava succession above 1354 m to a relatively impervious volcaniclastic/siltstone sequence. The boundary between these formations is not known. It is, however, plausible that the sudden change towards a relatively steep thermal gradient occurring from 1500 m to the bottom of the hole may imply the transition from the high permeability experienced in the production zone, where andesite lavas predominate, to the impervious sequence of the volcaniclastics/siltstone. The base of the illite zone is therefore tentatively put at the depth of 1500 m.

IV. Chlorite zone.

A possible fourth zone is inferred where illite and the other clays have ceased to exist. This zone is found in the core samples from 1822 m and 1974 m, where temperatures in excess of 300°C were recorded. The zone is characterized by a chlorite rich in iron (Fig. 9 no. 20 and 21, Appendix I). Similar occurences have been reported at Salton Sea, where temperatures in excess of 300°C prevail (Ellis and Mahon, 1977). In Iceland, Fe-rich chlorite has also been reported to be the dominant sheet silicate at rock temperatures exceeding 240°C and,where all other clays have disappeared (Kristmannsdottir, 1978). Similarly, chlorites of unknown composition have been reported in the Tongonan geothermal field in Leyte, Philippines, where temperatures of up to 325°C prevail (Reyes, 1979). Although relatively little is known about the relationship between illite and chlorite, the transformation of illite to chlorite is considered unlikely. This is mainly due to considerable differences in crystal structures as well as chemistry (illite is a K-Al-silicate whereas chlorite is a Mg-Fe-Al-silicate). It is perhaps more plausible to connect this change in mineralogy to a change in the chemical composition of the host rocks, as the drillhole logs indicate the predominance of lavas above the estimated depth of 1500 m, whereas the rocks below that are of volcaniclastics richly intercalated by siltstone. A further contributory factor may be the drastic differences in permeabilities. Thus the apparent progressive increase in illite towards the production zone may perhaps be related to the amount of a chemical composition of the hydrothermal fluid of the production zone. On the other hand, the rocks below are impervious and show in general less alteration (e.g. the plagioclases are found to be relatively fresh) and in addition it is conceiveable that the composition of the fluid in these rocks is different.

3.4.2 Other significant minerals.

Although the clays constitute the basis of the subdivision of the hydrothermal alteration zone, other hydrothermal alteration minerals, described earlier in this chapter, play an important role in the alteration history recorded in the drillhole.

Anhydrite. It is mostly confined to cores 1 and 2 (913 m and 1164 m) where it is found in abundance in at least two generations of veining. The analysis of the deep water from the drillhole indicates a relatively high Ca^{2+} and SO_4^{2-} concentrations and activity calculations show it to be oversaturated with respect to $CaSO_4$ (Fig. 10) at the temperatures measured, thus encouraging precipitation. The occurrence of anhydrite conforms therefore with the present state of the hydrothermal system.

Epidote. The first occurrence of epidote is at about 913 m where it is found as intermittent incipient streaks to approximately 1100 m. It is relatively abundant at 1161 m (core 2) in the absence of calcite, where temperature is about 240°C. It disappears at 1354 m (core 3), where calcite is abundant. The epidote is fairly common as well crystalline radial aggregates at 1822 m and 1971 m (cores 4 and 5), where temperatures exceed 300°C.

The temperature at which epidote starts to form is fairly well recorded to lie in the region of 235-260°C (Reed, 1976; Kristmanns-dottir, 1975, 1979). Occurrences of epidote have, however, been recorded at lower temperatures at conditions og high SiO_2 activity (Steiner, 1977). High oxygen fugacity, high H_2O activity, low CO_2 concentration and high concentration of dissolved solids may also encourage the growth of epidote at relatively low temperatures (Ellis, 1969). The iron-rich epidote (microprobe analysis, Table 7) at 1800 m depth (core 4) complies well with other reported occurrences of such epidotes above 300°C (Kristmanns-dottir, 1978). Furthermore, Liou (1972) stated that epidote is most iron-rich at a high oxygen fugacity. The occurrences of epidote at the measured temperatures in Okoy-5, in relation to its known temperature stability in other areas, and the probable conditions mentioned above, may suggest a near equilibrium condition with the hydrothermal fluid.

Calcite is the most common mineral in the drillhole and is found over a wide temperature range to over 300°C in Okoy-5. Although noticably absent in core 2 (1161 m), where epidote is abundant, calcite is found as thick vein fillings in core 3 (1354 m) and appears to increase towards the bottom as approaching the calcareous siltstone. The wide vertical range of the calcite may indicate variations in temperature and pressure. The presence of calcite at temperatures exceeding 300°C may be due to a Ca-rich water being derived from the calcareous siltstone. Its coexistence with anhydrite implies neutral water, though relatively high in sulphate, while its absence in core 2 (1161 m) maybe due to low CO_2 pressure, which in turn facilitates the formation of epidote.

Hydrothermal quartz, although common at various temperatures, is particularly abundant within the inferred production zone and persisted up to the highest temperatures recorded. Adularia was not identified with the quartz, as is found to be the case in e.g. the Broadlands geothermal field. The occurrence of hydrothermal quartz in Okoy-5 concords well with the findings of Browne (1970), who showed that it is in general abundant within production zones.

Pyrite. Browne (1970) and Steiner (1977) have suggested that the occurrences of pyrite may in some cases be correlated with zones of relatively high permeabilities where high P_{H_2S}/P_{H_2} prevail, whereas pyrrhotite would preferentially form where permeability is low and at a low P_{H_2S}/P_{H_2} ratio. This interpretation may comply to a certain extent with the occurrence of pyrite in Okoy-5, as it is particularly abundant in core 2 (1161 m) (upper part of the production zone). High P_{H_2S}/P_{H_2} ratio in geothermal fluids are in some cases associated with relatively low CO_2 values, and this in turn complies with the abundant epidote and the absence of calcite in core 2, as discussed above.

Garnet. Andradite garnets occur in skarn type assemblages in cores 4 and 5 (1822 and 1971 m) where temperature exceed 300°C. Andradite garnets of probable hydrothermal origin have been reported at temperatures exceeding 340°C (Browne,1977). In the Krafla geothermal area in Iceland (Kristmannsdottir, 1979)andradite garnet is certainly of contact metamorphic origin and not directly related to the present hydrothermal activity. Andradite garnet is a common contact metamorphic mineral in calcareous rocks. (Miyashiro, 1973) A hydrothermal origin of andradite in well Okoy-5 is considered unlikely, as the prevailing temperatures are at and below 310°C. This is supported by a partial replacement of some garnets by epidote. The occurrences of garnet may therefore imply the proximity of intrusion(s) near or below the Okoy-5 drillhole.

Other alteration minerals such as magnetite, hematite and ilmenite may also have played a minor part in the alteration history.

4. CONCLUSIONS

1. The secondary alteration mineralogy of well Okoy-5 can be devided into four major clay assemblage zones. These are: Zone I- Montmorillonite (<100°C), Zone II-Montmorillonite-Illite (<200°C), Zone III-Illite (200°C-250°C), and Zone IV-mainly composed of Chlorite (>300°C).

2. The temperatures measured in the well correspond closely with the temperatures indicated by the alteration mineralogy, the latter being confirmed by comparison with data from various other geothermal fields around the world where studies regarding mineral stabilities have been conducted.

3. There are no apparent signs of retrograde mineralization in the well, which suggests that the present geothermal system is near equilibrium.

4. The apparent increase or downward enrichment of illite towards the production zone is not a coincidence and is considered a sign of active hydrothermal circulation through that rockformation.

Acknowledgements

The author is much indebted to the organizers of the 1979 UNU Geothermal Training Programme in Iceland, to the unlimited patient assistance extended by H. Franzson, I.B. Fridleifsson and H. Kristmannsdottir; their helpful comments and constructive criticism were much appreciated. Sincere thanks are due to K. Gronvold of the Nordic Volcanological Institute for instructions on the electron microprobe, B. Baldursdottir for making the thin sections, to all the lecturers in the training and to all the people of Orkustofnun (National Energy Authority of Iceland) who have contributed to this undertaking. Special thanks are also due to Ms. Solveig Jonsdottir for typing the manuscript and to Ms. I. Sigurdardottir for preparing the figures.

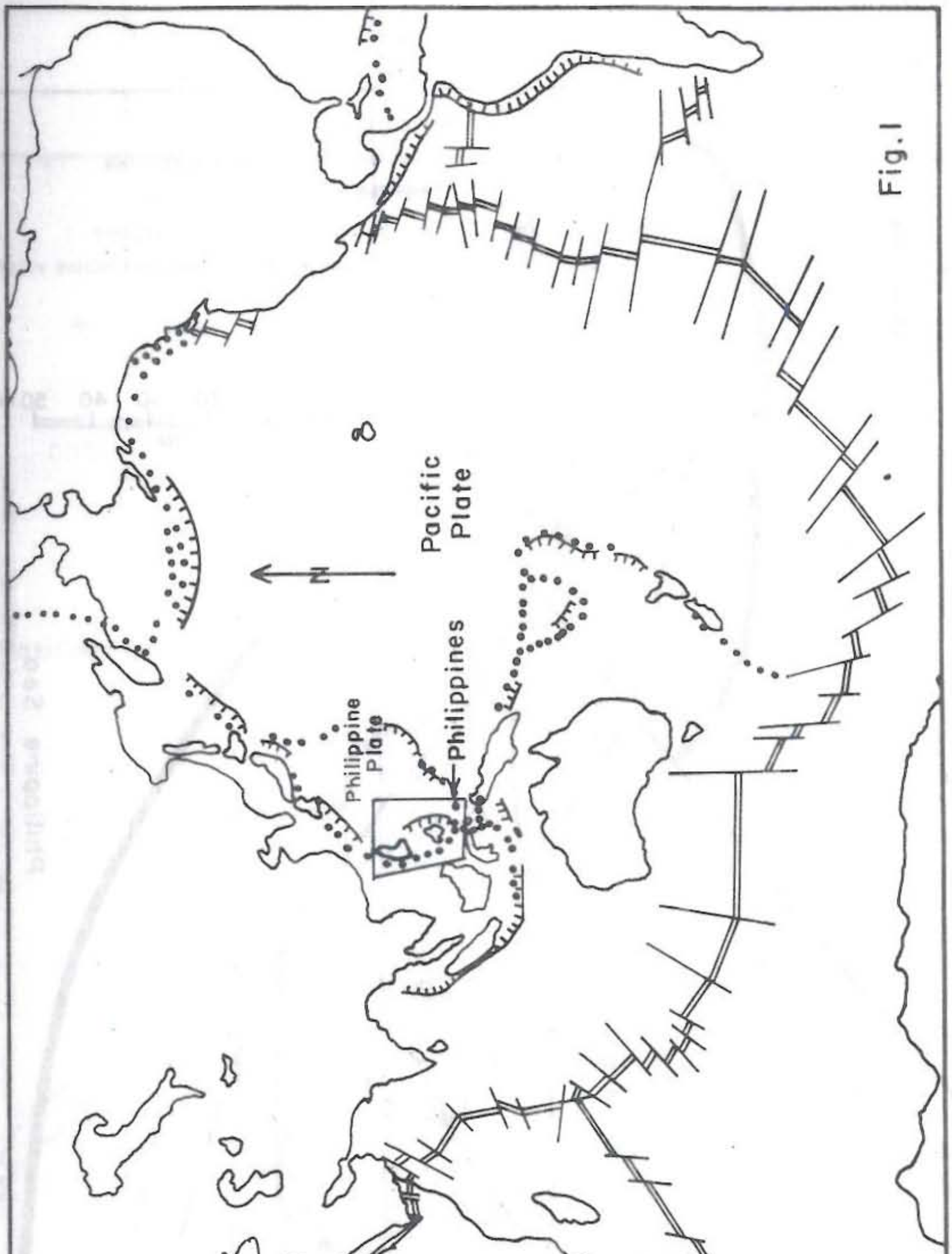


Fig.I

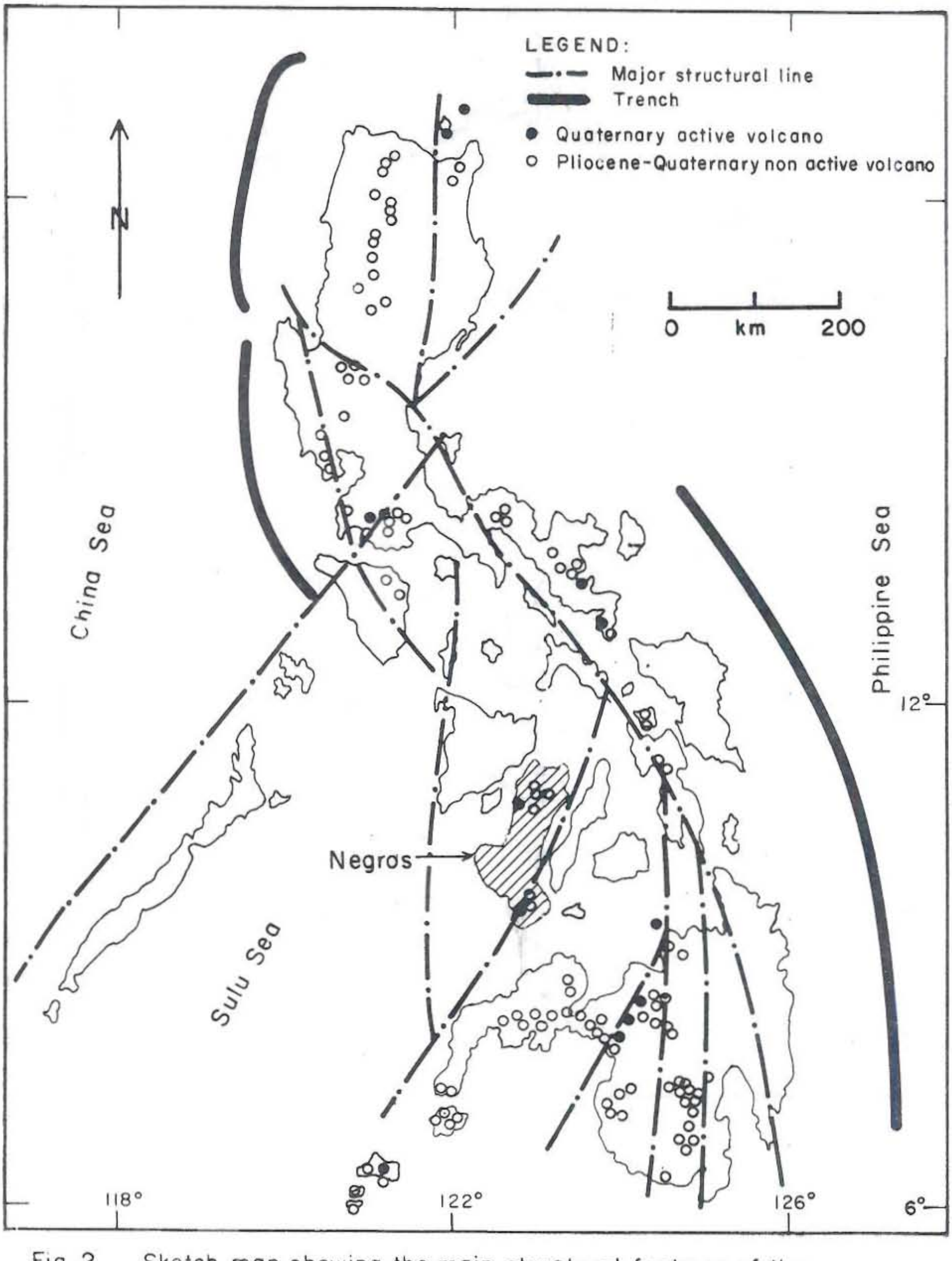


Fig. 2 Sketch map showing the main structural features of the Philippines and the locations of volcanoes.

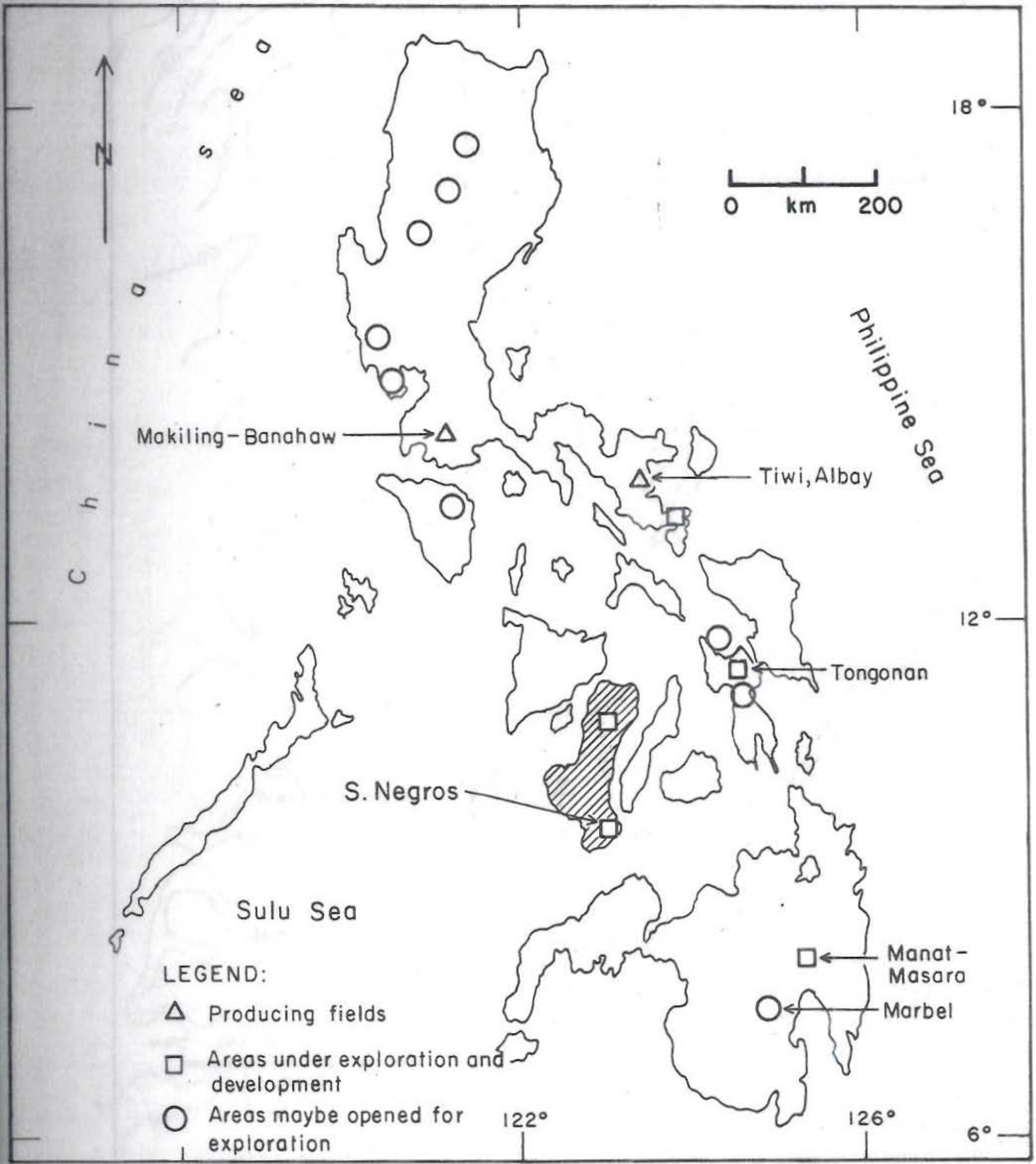


Fig. 3 Philippine geothermal areas

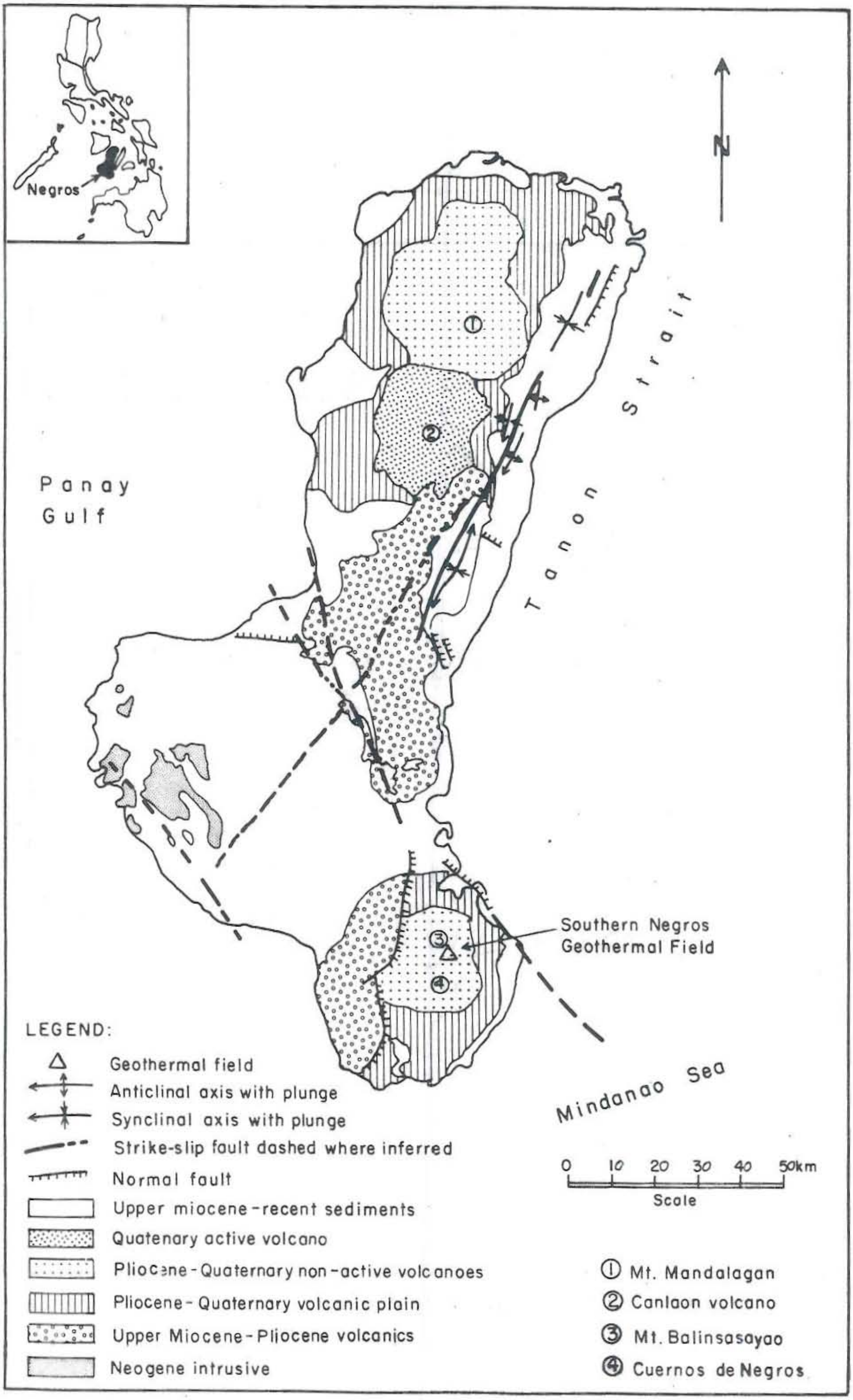


Fig. 4 General geological map of Negros showing main structural and volcanic features.

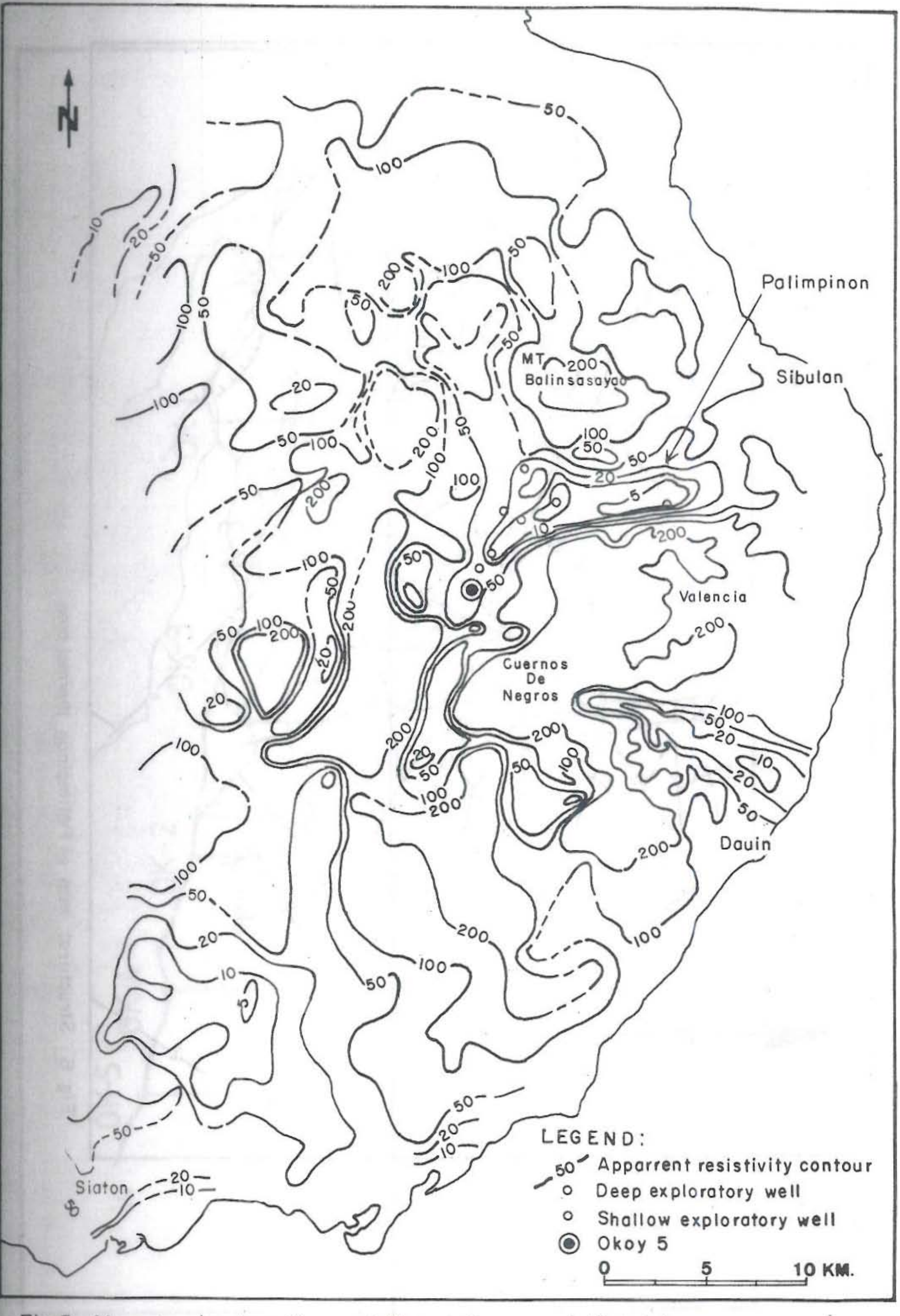


Fig.5 Map showing locations of thermal areas defined by apparent resistivity anomalies AB/2 = 500 m.

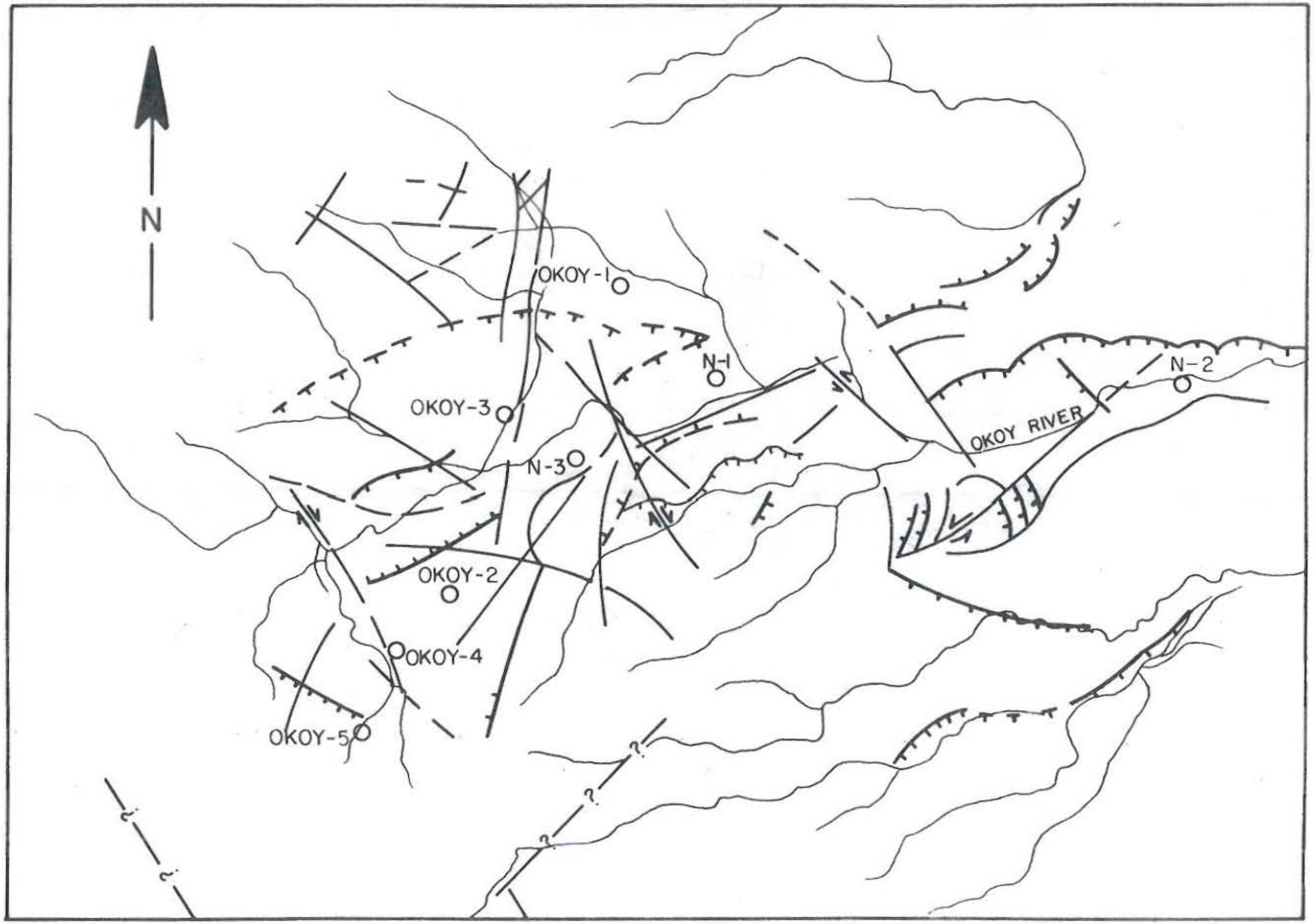


Fig. 6 Structural map of Palimpinon thermal area

Fig. 6 Structural map of Palimpinon thermal area

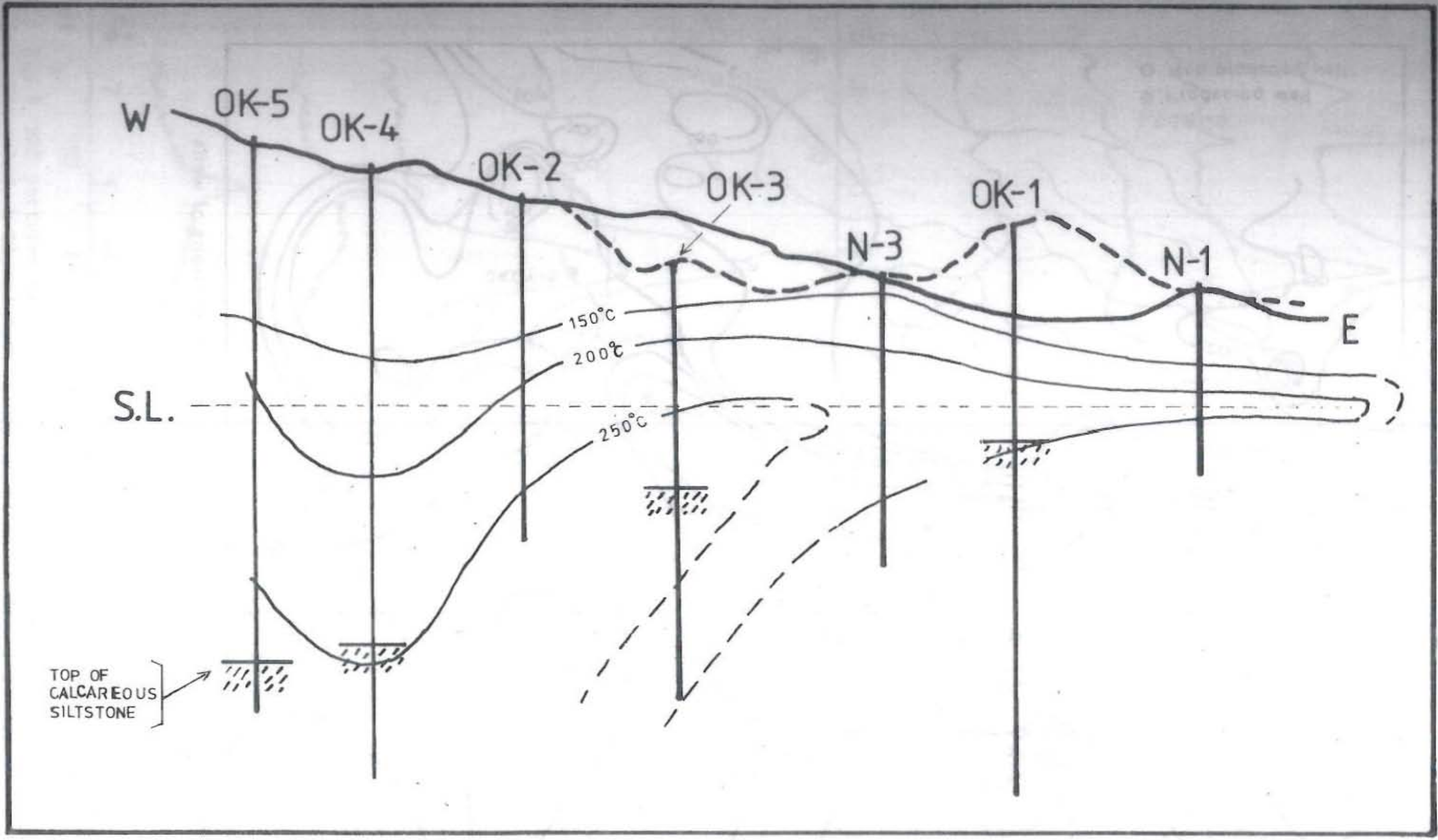


Fig. 7 A simplified E-W projection of the subsurface isothermal lines in the Palimpinon thermal area. Top of the calcareous siltstone is indicated where encountered.

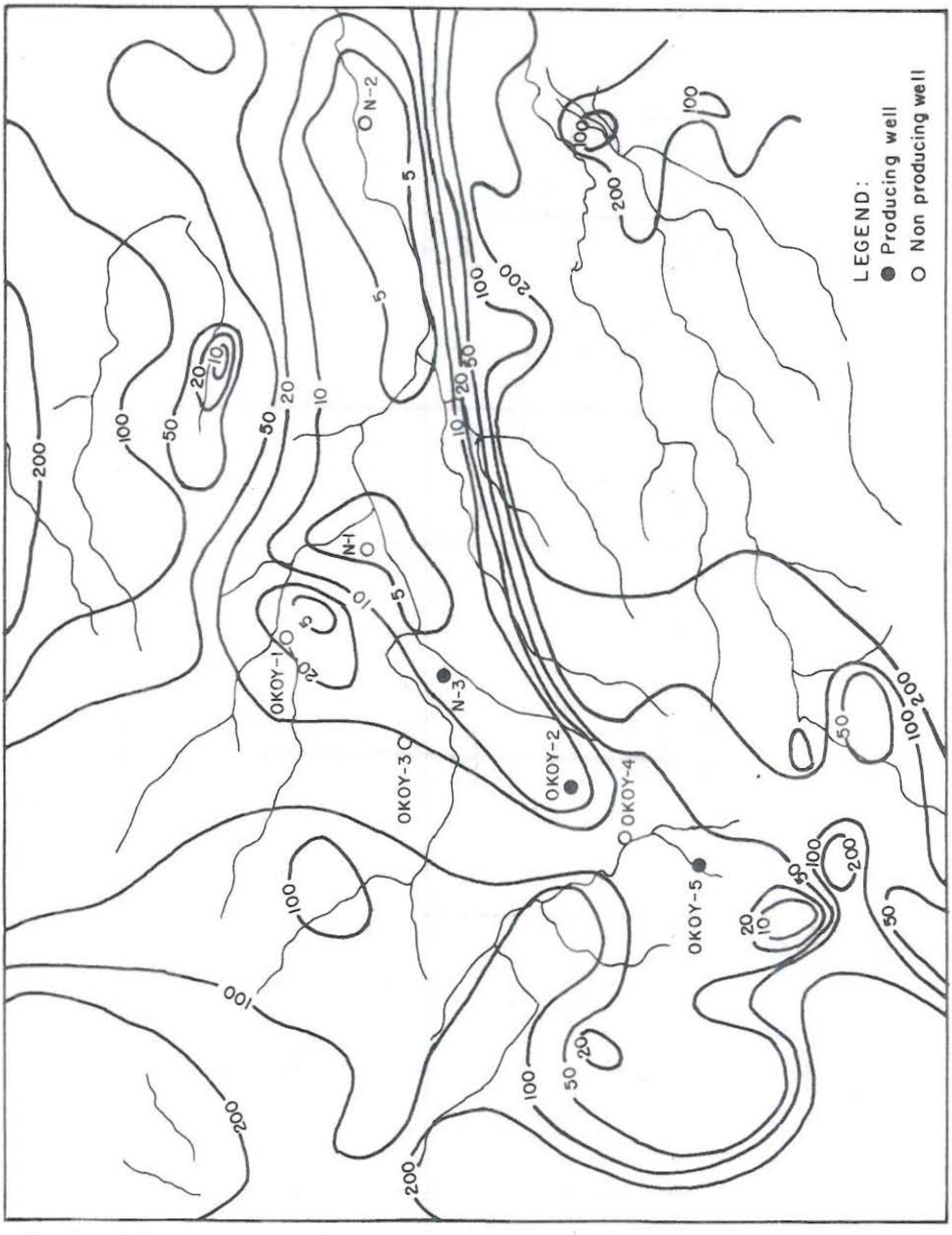


Fig. 8 Palimpinon resistivity anomaly showing relative locations of wells

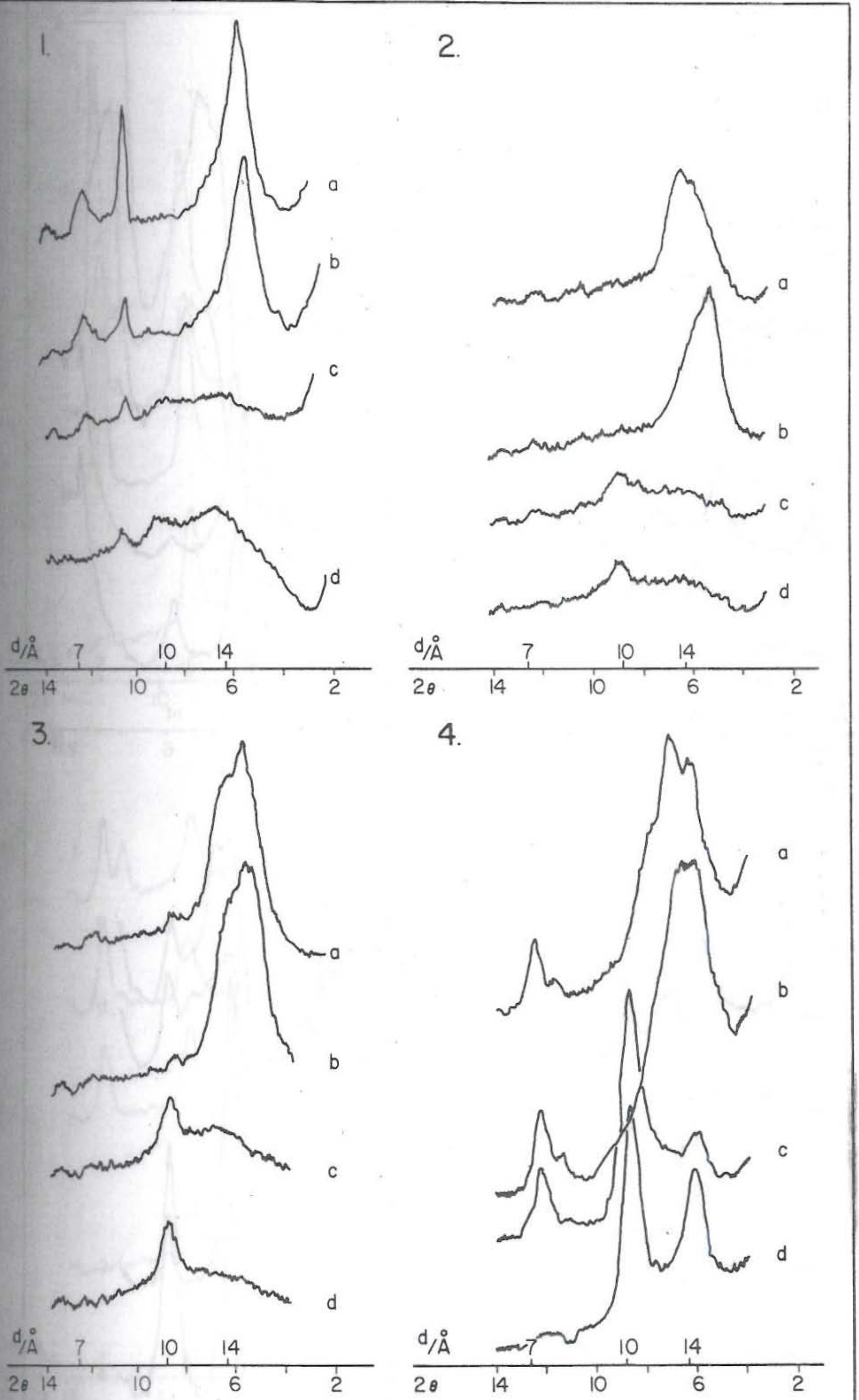
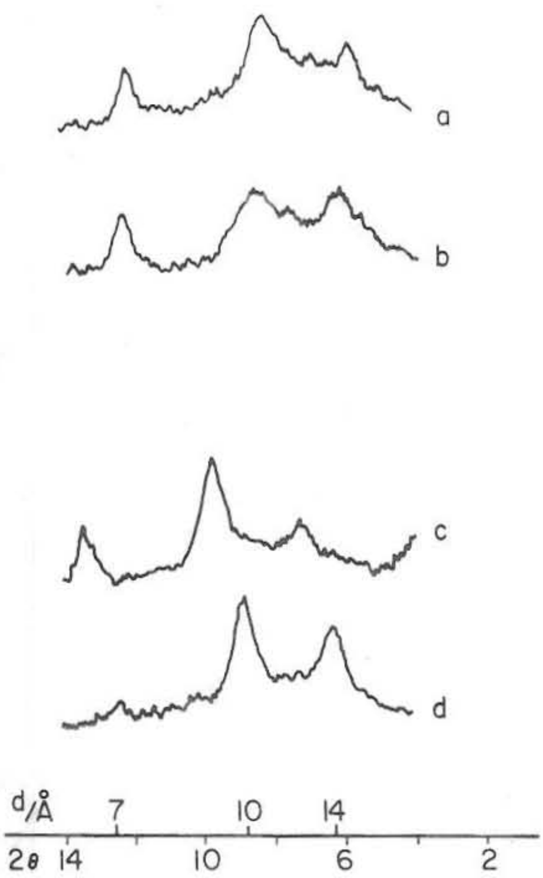
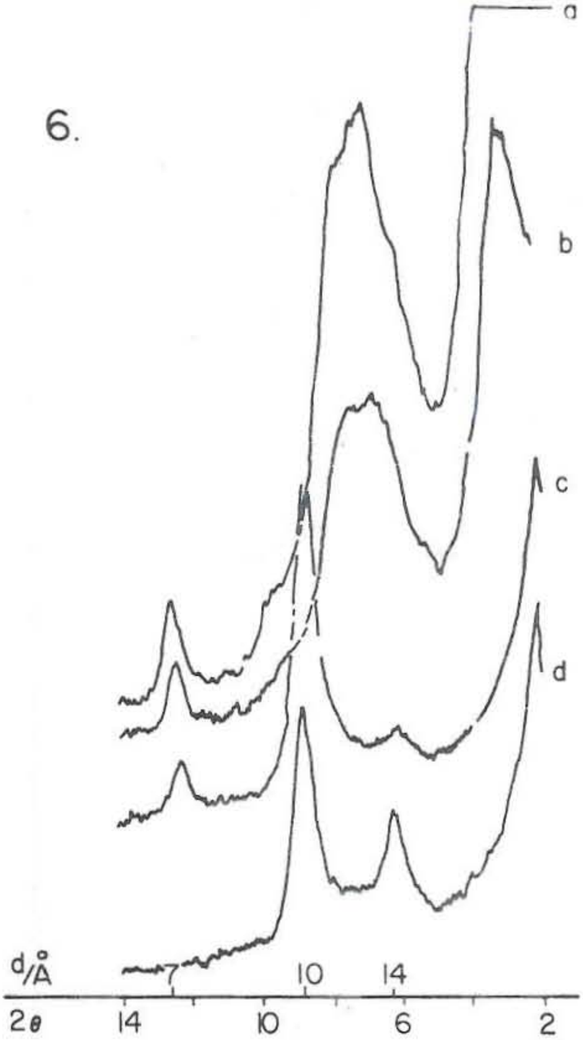


Fig.9 XRD patterns of 21 analyzed clay samples. Explanation:
a Untreated, b Glycolated, c Heated to 550°C for 2 hours,
d Heated to 700°C for 2 hours, e Heated between 550°C-700°C.
Further explanations in the text and in Appendix II.

5.


a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2

6.


a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2

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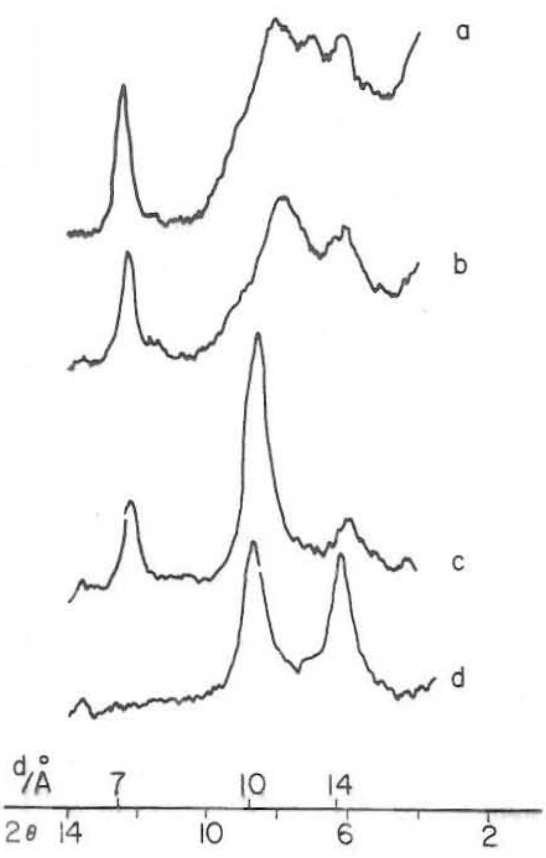
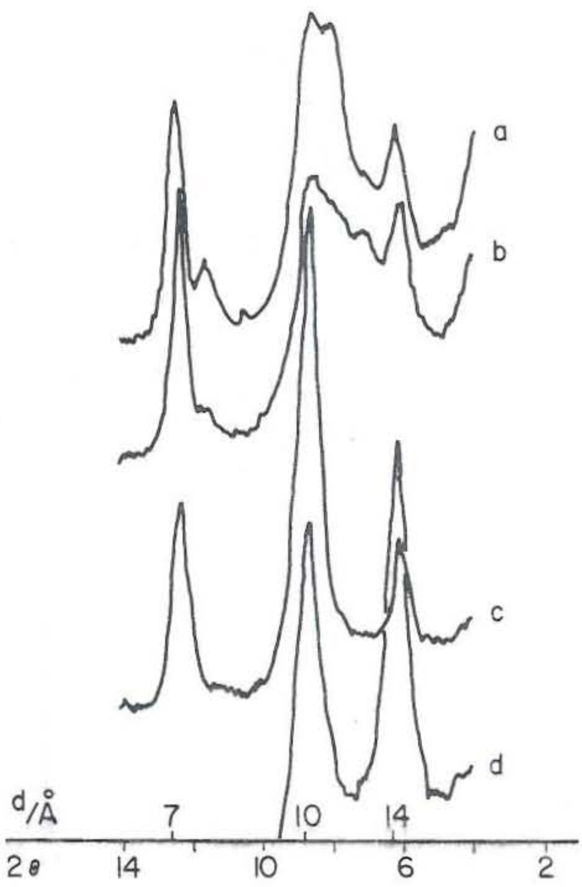
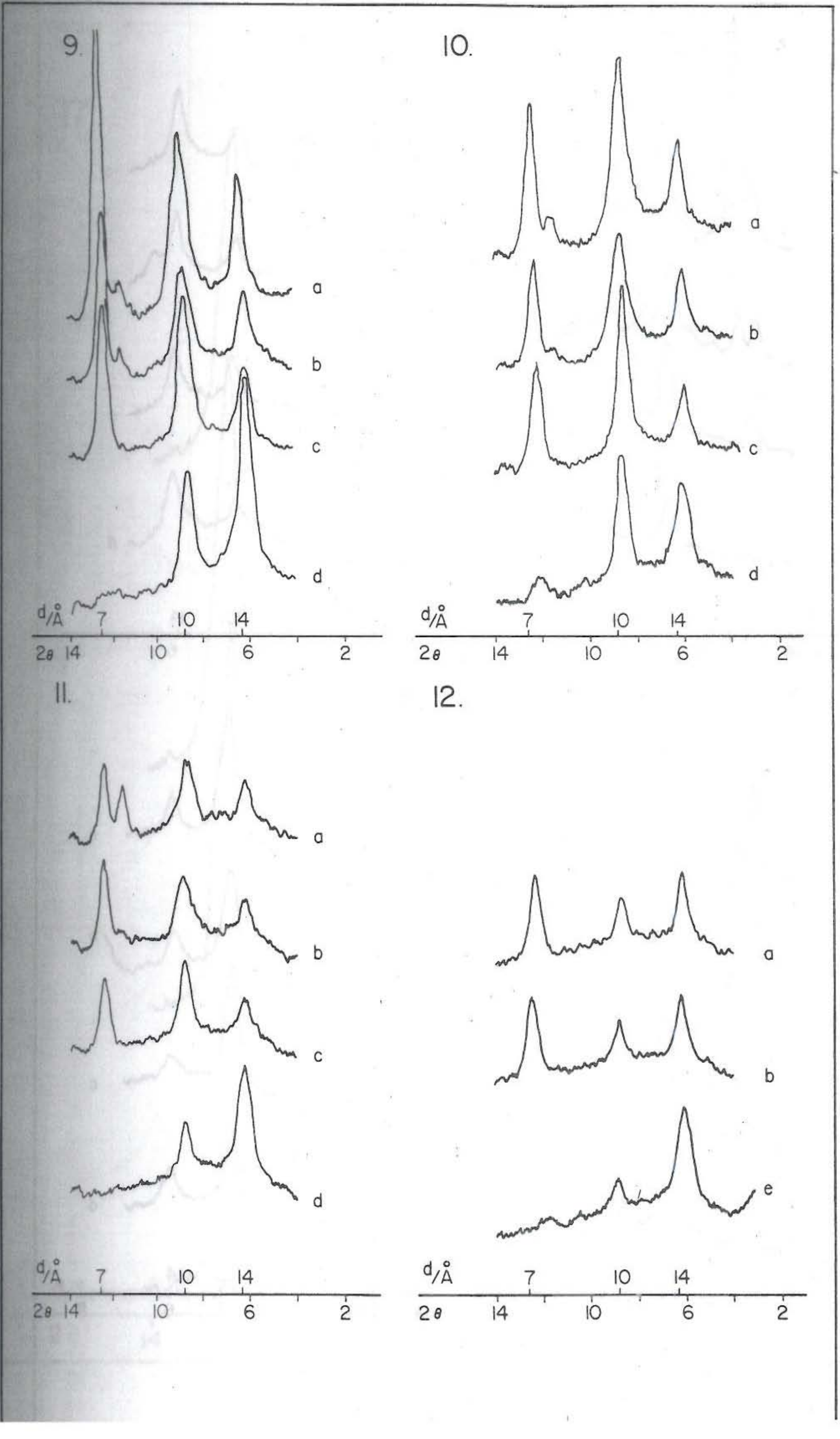
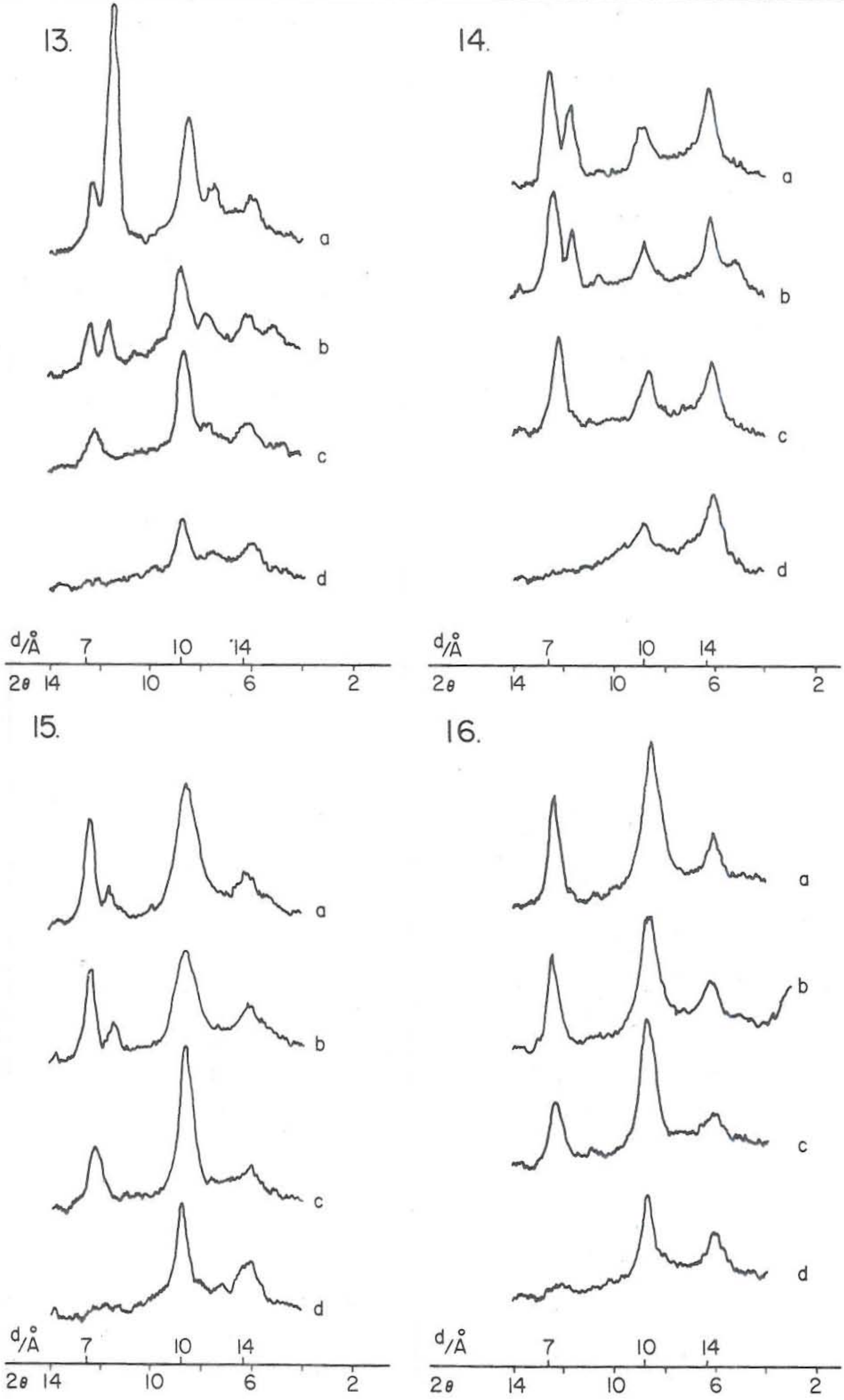
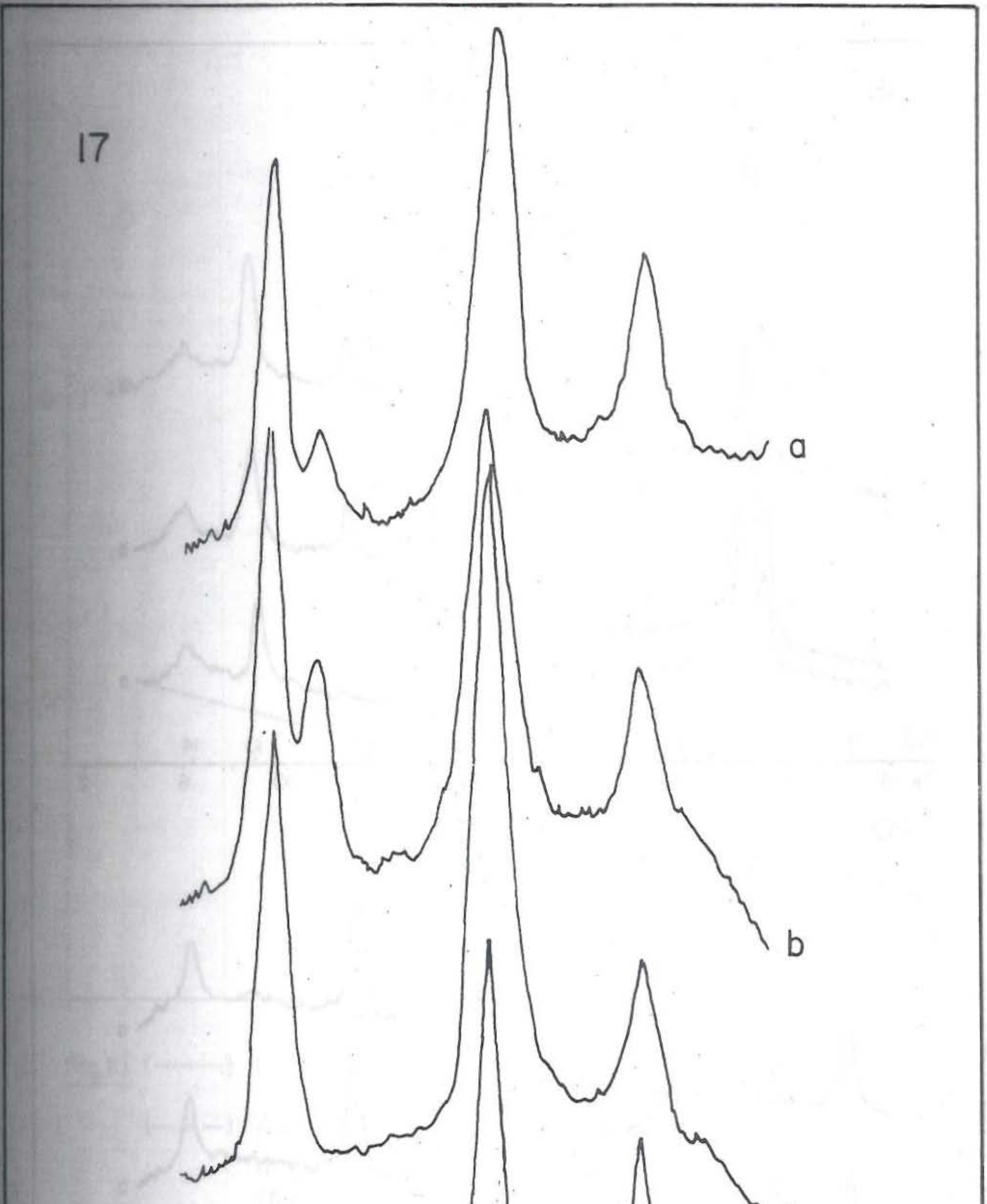

a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2

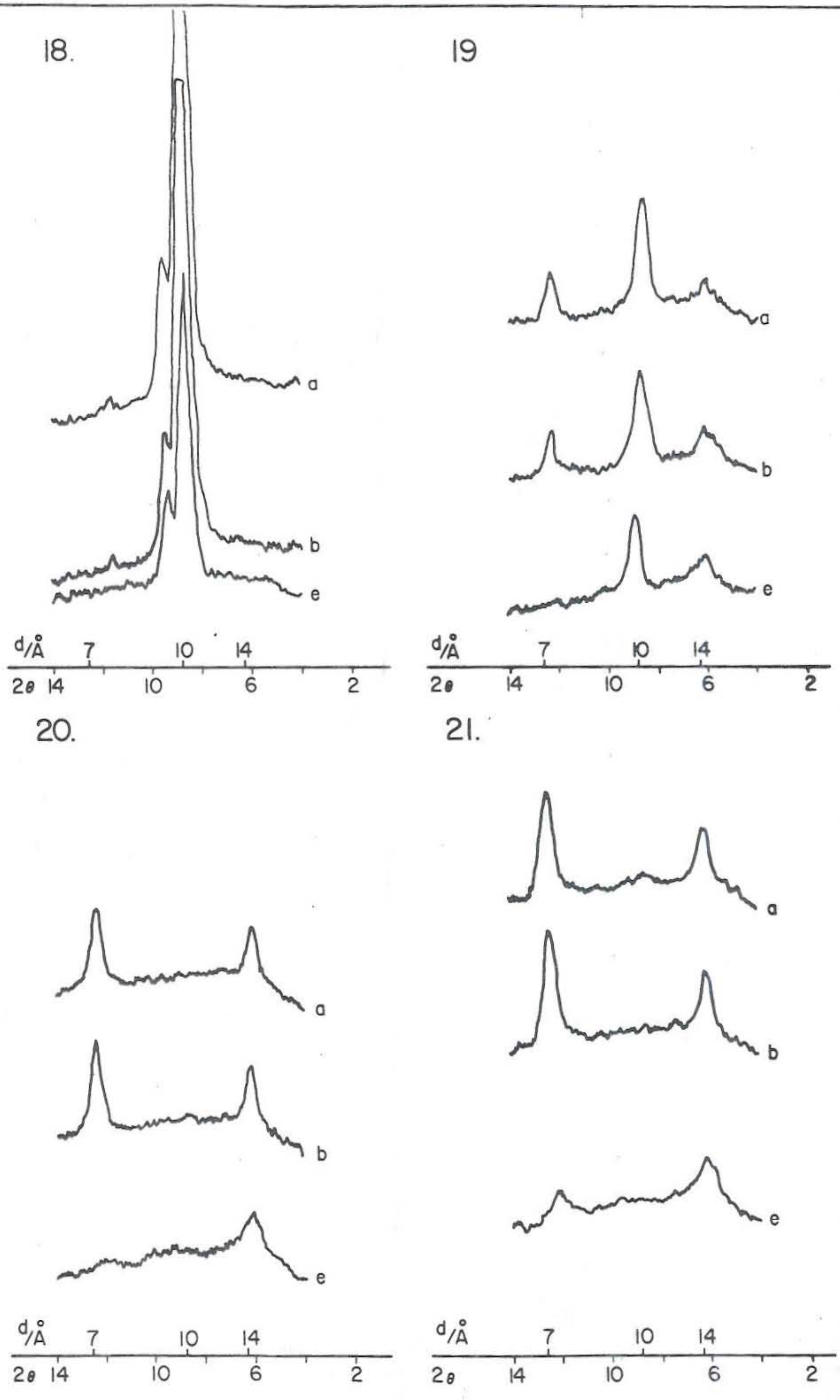
8.


a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2


9.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2
10.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2
11.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2
12.
a
b
e
d/Å 7 10 14
2θ 14 10 6 2


13.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2
14.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2
15.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2
16.
a
b
c
d
d/Å 7 10 14
2θ 14 10 6 2


17
a
b
c
d
d/Å
7
10
14
2θ
14
12
10
8
6
4
2


18.
19
20.
21.
a
b
e
d/Å 7 10 14
2θ 14 10 6 2

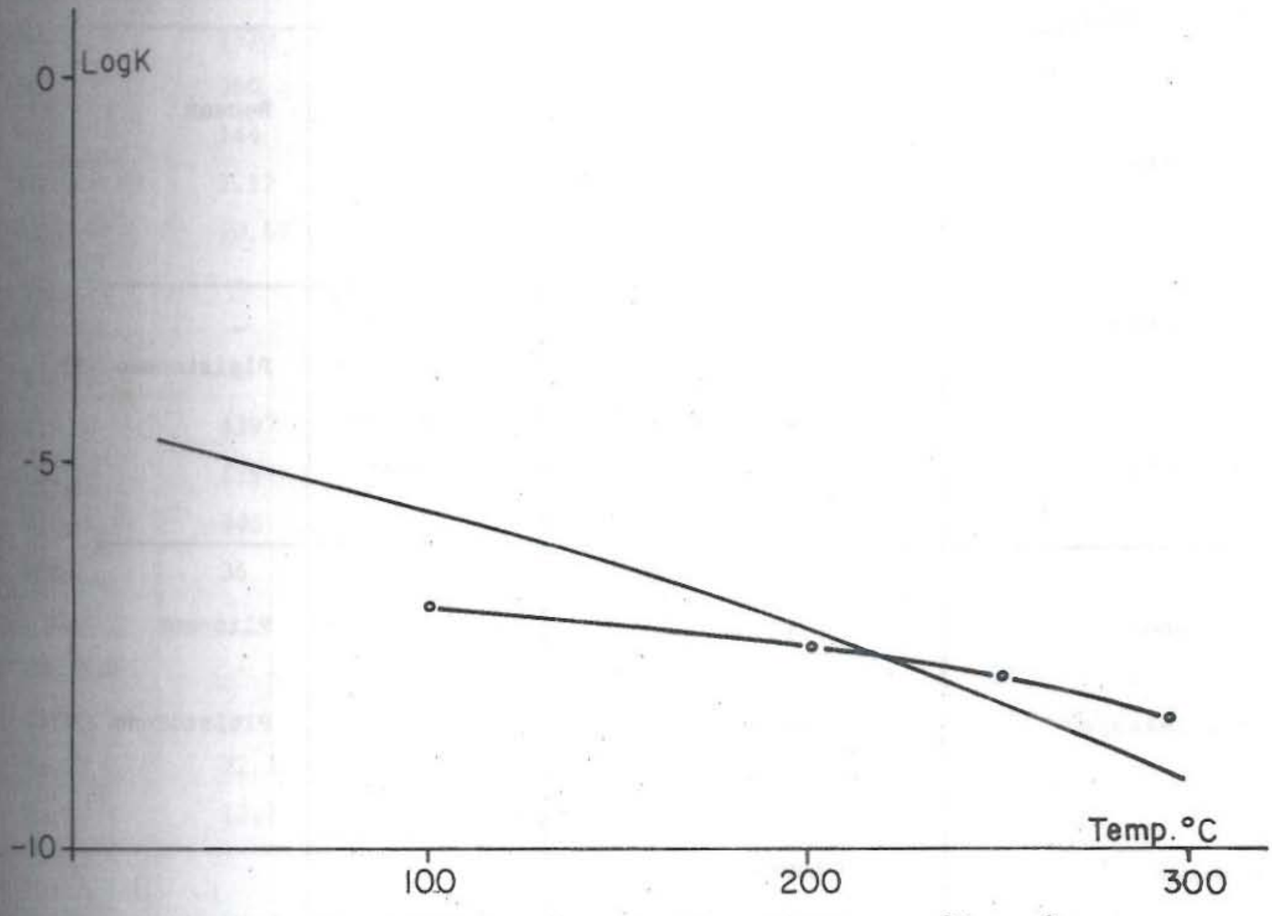


Fig. 10. (———) LogK/°C for the reaction $CaSO_4 \rightleftharpoons Ca^{2+} + SO_4^{2-}$

(—∘—) Plot of the $[Ca^{2+}][SO_4^{2-}]$ for the deep water in OKOY-5 by step-boiling of the fluid from the silica temperature

Table I

A SIMPLIFIED STRATIGRAPHIC SECTION OF THE SOUTHERN NEGROS AREA
(modified after Tolentino and Loo (1972); KRTA (1979)

Stratigraphic Nomenclature	Lithological Description	Probable Age
Quaternary Sedimentary Deposits	Unconsolidated gravel piedmont and talus deposits, beach gravel and thermal deposits	Recent
	Reef limestone with well preserved bryozoans, NE of Balinsasayao; recrystallized at Palimpinon	Pleistocene (?)
Gintabon Balinsasayao and Cuernos de Negros Volcanics	Hb - rich dacites and pyroclastics Ring plain deposits of Hb-dacitic lahars or Leucocratic andesites Palimpinon breccia Andesite lava sequence Pyroxene andesite, hb-andesite, porphyritic pyroxene, andesite	Pliocene Pleistocene (?)
	UNCONFORMITY	
Southern Negros Formation (SNF)	PALEOSOL Hydrothermally altered conglomerates with some interbedded sandstone+ calcareous siltstone	Upper Miocene Pliocene (?)
Calcareous Siltstone	Impervious, grey-black calcareous siltstone at times fossilerous and pyritic	Upper Miocene

Table 2

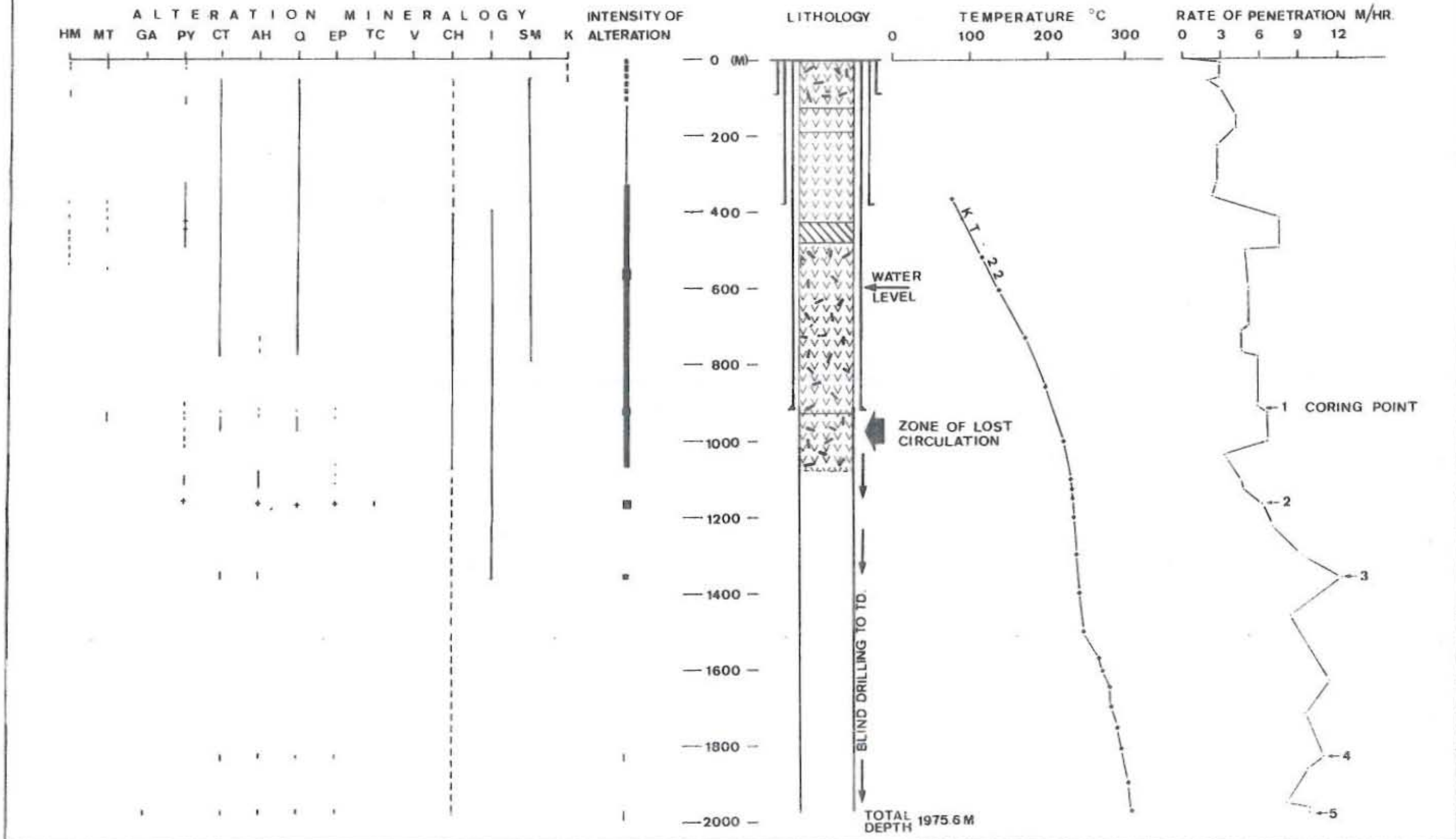
DISCHARGE CHEMISTRY OF WELLS IN S. NEGROS Concentrations in ppm.

Well no.	N - 1	N - 2	N - 3	Okoy-2	Okoy-5
pH	8.23	8.12	8.09	7.28	7.57
Na	2529	2612	3027	2308	2743
K	350	193	772	446	576
Ca	144	708	95.8	28.1	62
Mg	2.17	7.55	-	1.42	0.25
Li	10.57	9.86	15	11.15	13.57
Rb	-	-	3.6	3.15	4.06
Cs	-	-	-	1.99	2.27
B	-	-	664	49.6	54.5
Cl	4397	4407	5744	4392	4716
SO_4	135	88	46.2	215	95.4
SiO_2	345	155	787	760	897
HCO_3	36	92	93.3	87.7	88.4
CO_2/H_2S	-	-	16.84	25.7	21.9
Cl/B	-	-	27	27	26.4
Na/Li	72.1	70.56	60.96	62.4	60.99
Na/K	12.2	23.02	6.67	8.80	8.11

Source: Internal reports of PNOC-EDC (Camales and Galia) and DSIR (Glover).

TABLE 3

WELL OKOY–5, S–NEGROS



WELL DATA:

LOCATION:	518,050E – 1027,300N
CELLAR ELEVATION:	939.5 M
DATE SPUDDED:	OCT. 20,1978
DATE COMPLETED:	DEC. 3,1978
TOTAL DEPTH:	1975.6 M CHF

LEGEND:

HM - HEMATITE	AH - ANHYDRITE	CH - CHLORITE
MT - MAGNETITE	Q - QUARTZ	I - ILLITE
GA - GARNET	EP - EPIDOTE	SM - SMECTITE
PY - PYRITE	TC - TALC	K - KAOLINITE
CT - CALCITE	V - VERMICULITE	

WEAK-MODERATE
MODERATE
MODERATE-HIGH
HIGH
+ ABUNDANCE OF MINERAL

HB – ANDESITE
ANDESITE
ZONE OF PYRITIZATION

Table 4 DESCRIPTION OF ROCK TYPES IN WELL OKOY-5

Hb-Andesite, which is the most common rock type in the well, is generally porphyritic and variably altered. The hornblende phenocrysts, although seen fresh in cuttings from the upper 100 m, are generally pseudomorphous with depth and are replaced by magnetite, hematite, and chlorite minerals. This occasionally creates a chaotic appearance in the rock fabric. Vein mineralization is common in the form of calcite, quartz and anhydrite. Pyrite disseminations are common.

Andesite is variably altered, light to dark green with plagioclases that are often altered to clays, calcite and quartz. The groundmass is usually composed of finely granular mosaic of quartz and feldspars with common crosscuttings of calcite. Other alteration minerals include magnetite, hematite and pyrite. This rock type ranges from about 200 to 425 m.

Volcanic Breccia is highly altered, light grey with a matrix composed of fine to coarse mosaic of quartz and albite. It includes fragments of the same composition as the matrix. Epidote and quartz are seen altering plagioclases along veins and interstices. Common vein mineralogy includes quartz, anhydrite, albite, epidote and pyrite. Pyrite also appears as abundant in disseminations. This rock type is only noted in core 2 (1161 m).

Porphyritic Pyroxene Andesite is moderately altered to a dark green colour with a matrix now composed of chlorite, quartz, anhydrite and clay. Plagioclases and pyroxenes are both altered to calcite, chlorite, pyrite and illite. Other minerals include albite, magnetite and leucoxene. This rock type is only noted in core 3 (1352 m).

Volcaniclastics are those rock types mainly composed of angular andesitic fragments set in a calcareous siltstone matrix. They are generally weak to moderately altered with commonly zoned plagioclases that are either partly altered to quartz or calcite. Vein mineralogy includes gypsum, epidote, chlorite and sparse andradite garnets. This rock type has been identified in cores 4 and 5 (1822 and 1971 m).

Note: see also petrological analysis of cores and cuttings in Appendix I.

LOCATION: 518,050E - 1027,300N
CELLAR ELEVATION: 939.5 M
DATE SPUDDED: OCT.20.1978
DATE COMPLETED: DEC. 3.1978
TOTAL DEPTH: 1975.6 M CHF
HM - HEMATITE
MT - MAGNETITE
GA - GARNET
PY - PYRITE
CT - CALCITE
AH - ANHYDRITE
Q - QUARTZ
EP - EPIDOTE
TC - TALC
V - VERMICULITE
CH - CHLORITE
I - ILLITE
SM - SMECTITE
K - KAOLINITE
WEAK - MODERATE
MODERATE
MODERATE - HIGH
HIGH
+ ABUNDANCE OF MINERAL
ANDESITE
ZONE OF PYRITIZATION

TABLE 5

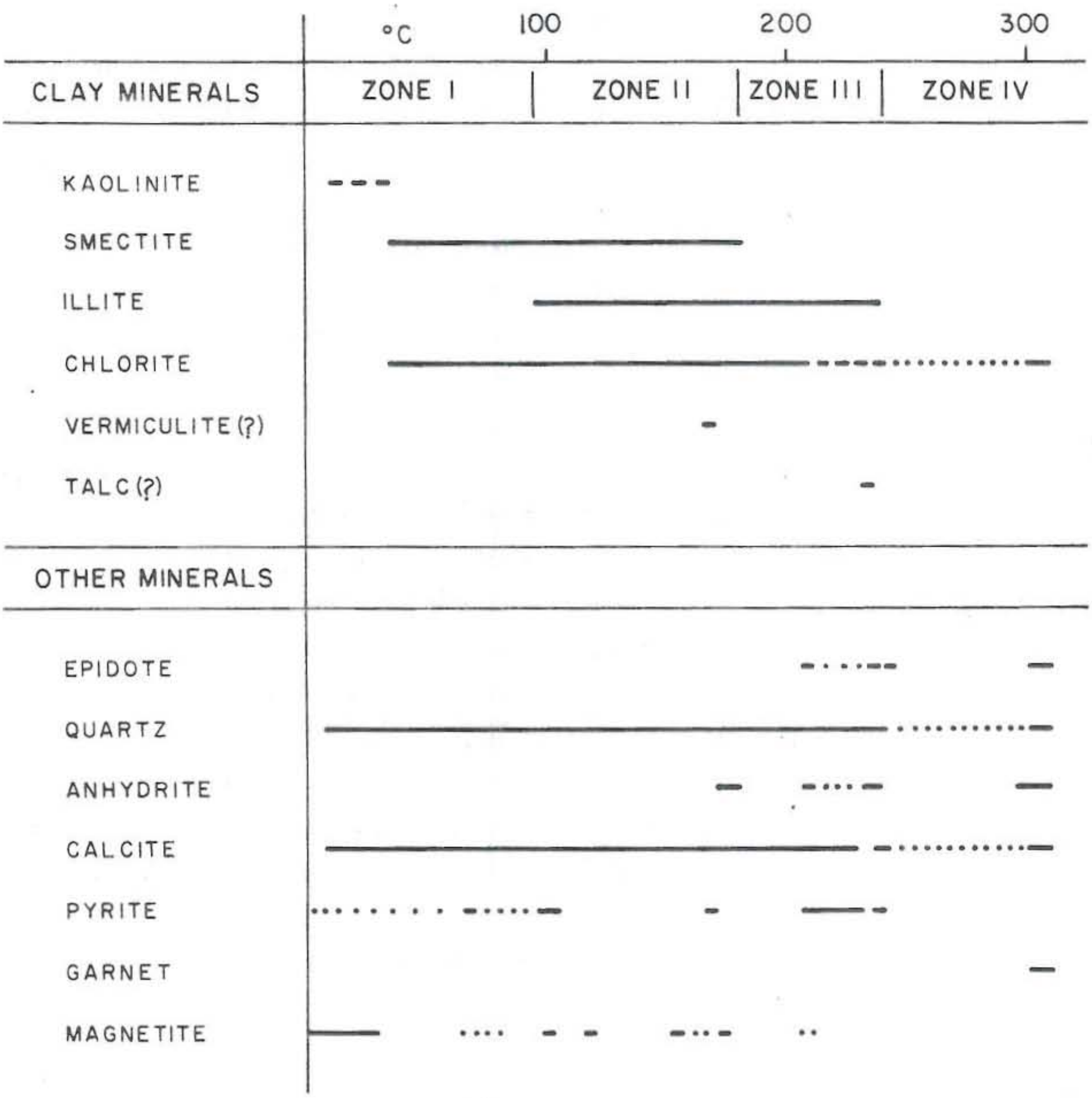

°C
100
200
300
CLAY MINERALS
ZONE I
ZONE II
ZONE III
ZONE IV
KAOLINITE
SMECTITE
ILLITE
CHLORITE
VERMICULITE (?)
TALC (?)
OTHER MINERALS
EPIDOTE
QUARTZ
ANHYDRITE
CALCITE
PYRITE
GARNET
MAGNETITE

Table 6

SUMMARY OF THE METHODS APPLIED IN THE IDENTIFICATION OF ALTERATION MINERALS

ALTERATION MINERALS	MEGASCOPIC	PETROGRAPHIC	X-RAY DIFFRACTION	MICROPROBE	INFRARED
KAOLINITE			X		X
MONTMORILLONITE			X		
ILLITE		X	X		
CHLORITE	X	X	X	X	X
VERMICULITE					X
TALC			X		X
EPIDOTE	X	X		X	
QUARTZ	X	X	X		
ANHYDRITE	X	X	X		
CALCITE	X	X	X	X	
PYRITE	X	X	X		
GARNET		X		X	
MAGNETITE	X	X			
HEMATITE	X	X			
ALBITE		X		X	

Table 7

MICROPROBE ANALYSES OF SOME ALTERATION MINERALS IN CORE 4 (1822 m) OF WELL OKOY-

Wt %	Calcite	Epidote	Garnet	Chlorite
SiO_2	0.13	38.57	36.05	27.41
TiO_2	-	0.10	-	-
Al_2O_3	1.67	26.36	0.22	20.28
FeO (total)	1.25	11.61	30.89	20.99
MnO	0.27	0.25	0.34	0.47
MgO	0.05	-	0.29	20.29
CaO	52.36	23.76	33.05	-
K_2O	0.03	-	-	-
P_2O_5	0.09	-	0.09	-
TOTAL %	55.85	100.66	100.93	89.43
No. of Cations	1{0}	12{0}, OH	24{0}	20{0}16{OH}
Si	.002	3.15	6.42	5.5
Al	.016	2.53	1.042	4.8
Fe	.017	0.79	4.596	3.5
Mn	.004	0.02	0.052	0.1
Mg	.001	-	0.076	6.1
Ca	0.92	2.08	6.312	-
K				

Calculated as Fe^{2+}

LL OKOY-5

Table 8

X-RAY DIFFRACTION DATA OF PYRITE IN CORE 2 (1161 m)

d (Å)	I/I.
3.13	19
2.71	100
2.42	35
2.20	50
1.91	38
1.63	38

Table 9

Compositional variation from rim to center in two garnet crystals from core 4 (1822 m) in well Okoy-5. In the center of grain 2 epidote has replaced the garnet.

	(1)		(2)	
Weight %	Rim	Center	Rim	Center
FeO	29.82	30.89	31.39	11.94
MnO	0.25	0.34	0.44	0.15
MgO	0.26	0.29	0.15	0.01
Al_2O_3	-	0.22	0.01	26.21

Table 10

Range and average spacing of 001 reflections (in Å) with their average intensities (samples 4, 6, and 7 in Appendix II). Mg rich variety of chlorite.

d(001) spacing in Å	Range	Average	I/I.
001	14.02 - 14.24	14.13	100
002	7.07	7.07	40
003	4.7o - 4.72	4,71	31
004	3.53 - 3.56	3.56	29
005	2.70 - 2.76	2.75	12

Table 11

Range and average spacing of 001 reflections (in Å) with their average intensities from 10 samples of Fe-rich variety of chlorite.

d(001) spacing in Å	Range	Average	I/I_o
001	14.0 - 14.7	14.35	84
002	7.0 - 7.13	7.06	100
003	4.61 - 4.76	4.73	42
004	3.51 - 3.55	3.53	52
005	2.8 - 2.84	2.82	38

Appendix I

PETROLOGICAL ANALYSES OF CORES AND CUTTINGS, OKOY-5

Depth

120 m Moderately-highly altered andesite with the matrix largely composed of finely granular mosaic of quartz. Fragments of zoned feldspars are partially to completely altered to clay and quartz. Some plagioclases are unaltered but the majority is obliterated by clays. Secondary mineralogy includes quartz + calcite + magnetite.

140 m Weakly altered andesite with matrix composed of quartz + plagioclase + calcite. Common zoning in feldspars. Plagioclases altered to calcite + quartz. Other minerals include magnetite + clay + minor chlorite.

190 m Weakly altered volcanics with much clay in a quartzofeldspathic groundmass. Plagioclase is altered to clay + calcite ,ferromagnesians are altered to calcite+minor magnetite. XRD showed some smectite, swelling chlorite, plagioclase, calcite, quartz and hornblende.

195 m Weakly-moderately altered andesite with plagioclase altering to calcite, occasionally to chlorite. Microveinlets filled with calcite often cut across plagioclases. Other minerals include hematite + magnetite.

200 m Weakly-moderately altered andesite with the matrix composed of fine grained plagioclases + a notable amount of quartz. Plagioclase is altered to calcite. Veinlets of calcite are also seen crosscutting plagioclases. Minor magnetite.

460 m Moderately altered volcanics with abundant quartz + calcite fragments. Plagioclase is altered to calcite in fractures. Sequence of alteration: plagioclase is altered to quartz which in turn is altered to calcite. Other minerals include magnetite + pyrite + hornblende.

720 m Moderately altered andesite volcanics with a quartzofeldspathic groundmass. Other minerals include anhydrite + quartz + pyrite + magnetite (marginally oxidized into hematite). Boxwork structures of hematite. XRD showed irregularly mixed illite - smectite + chlorite.

900 m Highly altered andesite volcanics with quartz + anhydrite + calcite (minor). Ferromagnesians are altered to pyrite/magnetite. XRD showed interlayered illite - chlorite. Common associations; (pyrite + magnetite + hematite), (calcite + chlorite + quartz), (chlorite + incipient epidote and pyrite).

930 m Highly altered andesite with the matrix dominantly composed of very fine mosaic of quartz + calcite + anhydrite. Plagioclase alters to calcite along microfractures. XRD showed that it is illite rich + chlorite.

1100 m Weakly-moderately altered andesite in quartzofeldspathic medium-fine grained groundmass with much (euhedral-clustered)pyrite. Ferromagnesians (hornblende) are altered to pyrite. Veinlets of anhydrite are deposited after quartz.

555 m Highly altered volcanics composed largely of microgranular quartz + anhydrite Plagioclase is altered to clay. Other minerals include pyrite (rare) + insignificant amount of chlorite. XRD showed that the clays are all irregularly mixed illite, smectite and chlorite. A fragment examined appeared "ignimbritic" with distinct layerings.

913-916 m (core nr. 1) Moderately-highly altered light grey porphyritic andesite with the matrix composed of quartz + clay + albite (common) + chlorite. Plagioclase is altered to calcite + quartz + illite. Microveinlets are often filled by chlorite including microgranular quartz. Epidote (incipient to well crystallized) occurs along with calcite + gypsum + anhydrite + chlorite. Leucoxene is incipiently crystallized to patches of coarse - medium-grained mosaic quartz. Other minerals include magnetite + hematite. XRD showed it to contain interlayered illite and chlorite.

1161-1164 m (core nr. 2) Highly altered light grey volcanic breccia. Matrix is composed of fine to coarse mosaic of quartz + albite with included fragments of same composition. Distinct veinlets and cavities often filled with quartz + anhydrite + albite. Epidote + quartz, altering plagioclases along veins, interstices and microfractures that cut across it. Abundant pyrite disseminations. Common vein mineral associations: quartz + anhydrite, quartz + albite, epidote + quartz + pyrite, quartz + pyrite + epidote + anhydrite. XRD showed it to contain abundant illite + talc (?). No chlorite detected.

1352-1354 m (core nr. 3) Moderately altered dark green porphyritic pyroxene andesite. The matrix is composed of chlorite + calcite + quartz + anhydrite + clay. Plagioclase is altered to calcite, chlorite, pyrite, illite while pyroxene is altered to chlorite, calcite,pyrite, illite. Pyrite is also found filling up veinlets and fractures. Other minerals include albite, magnetite, leucoxene (?). XRD detected the presence of interlayered illite - chlorite (chlorite is poorly crystalline).

1822-1825 m (core nr. 4) Weakly-moderately altered volcaniclastics, composed largely of lithic angular fragments of andesite in a calcareous siltstone matrix. Primary feldspars (in andesite) are weakly altered to almost a fresh set on a pilotaxitic groundmass. Zoning is common. Occasional calcite veins with gypsum + epidote + chlorite + garnet. Garnet is altered to finely crystalline epidote. Occasional amphibole + pyroxene. XRD detected only chlorite.

1971-1974 m (core nr. 5) Weakly-moderately altered volcaniclastics (similar to core 4) with fragments of plagioclase, quartz and calcite. Some plagioclases are either altered by quartz or calcite. Microveinlets were likewise observed being filled up by calcite in association with gypsum, epidote and scattered pyrite. Albite is also seen replacing primary feldspars. Sparse andradite garnet crystals were also identified. XRD detected only chlorite.

Appendix II

XRD ANALYSES OF 21 SAMPLES FROM OKOY-5

Sample	Depth	Analysis
	Zone I	
1	55-60	Poorly defined 14Å and mixedlayered minerals + Ch + K
2	170-175	Sm + thermally unstable, swelling 14Å minerals
	Zone II	
3	415-420	Irregularly mixed I-M + thermally unstable mixed-layer minerals
4	495-500	I-M + Ch + slightly swelling Ch.
5	570-575	I + Ch + probably irregularly mixed-layer I/Ch/Sm
6	640-645	Irregularly mixed I-M+Ch
7	715-720	" " I-M+Ch
8	785-790	" " I-M+Ch+slightly swelling Ch
	Zone III	
9	840-845	I + Ch
10	855-860	I + Ch
11	885-890	I + Ch, probably I/Ch, mixed-layer in small amount
12	913-916[1]	I + Ch
13	930-935	I + Ch + mixed-layer I/Ch
14	980-985	I + Ch (probably some swelling chlorite)
15	1040-1045	I + Ch (Ch - imperfectly crystalline)
16	1055-1060	I + Ch
17	1070 - 1075	I + Ch
18	1161-1164[2]	I + talc "no Ch"
19	1352-1354[3]	I - Ch poorly defined
	Zone IV	
20	1822-1825[4]	Ch
21.	1971-1974[5]	Ch

[1] Number of core

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