BOREHOLE GEOLOGY AND ALTERATION
MINERALOGY OF WELL PGM-5
MIRAVALLES, GUANACASTE, COSTA RICA

Oscar More Protti

BOREHOLE GEOLOGY AND ALTERATION MINERALOGY OF WELL PGM-5

MIRAVALLES, GUANACASTE, COSTA RICA

Oscar Mora Protti*,
UNU Geothermal Training Programme,
National Energy Authority (NEA),
Grensasvegur 9, 108 Reykjavík,
ICELAND.

*Permanent address:
Instituto Costarricense de Electricidad,
Proyecto Geotérmico Miravalles,
P. O. Box 10 032-1000,
San José,
COSTA RICA

ABSTRACT

A description is given of the borehole geology and alteration
mineralogy of well PGM-5 in the Miravalles Geothermal Field
(Costa Rica). The drillhole intersected six stratigraphic units
consisting of lahars, andesitic lava flows, pyroclastic rocks,
acid-andesite, ignimbrite and volcano-sedimentary units. The
lithology of PGM-5 differs somewhat from other deep wells in
the area, in the presence of an acid-andesite and/or ignimbrite
units and a question is raised on the total subsidence of the
caldera floor, which may be about 1 km less than the 1.4 km
assumed by the presently accepted model. Further comparison
is recommended.

By combining measured circulation losses and a sequence of
temperature profiles from the well, the position of 9 aquifers
was determined.

On basis of the clay minerals, three alteration zones were
distinguished: 1) Smectite zone, 2) Mixed-layer clay mineral
zone and 3) Chlorite-illite-epidote zone, believed to be formed
at temperatures up to 200° C, 200-240° C, and from 240-300° C
respectively. The maximum reservoir temperature measured is 238°
C. Comparison of the two, the mineral temperatures and the
measured, indicates that some cooling of the reservoir has taken
place in geological time. Further study and comparison with the
other wells is recommended.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 Introduction and scope of work

The importance of cores and cuttings as instruments in the study
of geothermal systems, have been known for few decades. They
have been used in attemps to sort out or interpretate the
hydrothermal evolution of any system, based on the mode and
occurrences of the alteration minerals.

The first studies in geothermal development in Costa Rica, took
place in 1963 when, upon a request of the Instituto Costarricense
de Electricidad (ICE), a mission of experts from the United
Nations, recommended a detailed study in the areas of Miravalles
and Rincón de la Vieja volcanoes. The oil crisis on the world
in 1973-74 rebounded strongly in Costa Rica, where oil was
used to produce electricity during the summer season. For
this reason in 1975-76, started the study to determine the
possibility to develop the natural resources to substitute the
conventional electric power plants. From this technical
prefeasibility study an area was determined with geothermal
potential inside the "Caldera de Guayabo" (Guayabo's caldera),
in the southwest slope of the Miravalles volcano. Thus, ICE
decided to send some people to other countries with vast
experience in utilization of geothermal fields, to take
training in different disciplines.

Presently in the Miravalles Geothermal Field, eight usable deep
wells have already been drilled (from 1300 to 2267 m depth),
providing about 40 MWe of the 110 MWe planned for.

The author was awarded a United Nations University Fellowship
to attend the 1989 UNU Geothermal Training Programme at the
National Energy Authority (NEA or Orkustofnun) in Iceland.

The author's specialized training in borehole geology and
alteration mineralogy, included a practical training in cutting

1

analysis in mapping hydrothermal evolution from cuttings and in the field, interpretation of cuttings analysis to other types of well data, excursion to various types of geothermal fields (active and extinct); theoretical and practical analysis of x-ray diffraction (XRD) and finally an introductionary training in the study of fluid inclusions for geothermometry.

This report is the result of about 10 weeks research on the borehole geology and alteration mineralogy of well PGM-5.

1.2 General geology and tectonic setting of Costa Rica

Costa Rica (50900 km^2) the southernmost country of Central America, is crossed by a chain of high mountains, from close to the Nicaraguan border (in the northwest) in a SE-direction along the country and the western part of Panama. These mountains from NW to SE are (fig. 1):

    Guanacaste Volcanic Mountains,
    Central Volcanic Mountains and
    Talamanca Mountains.

Three different orogenic phases gave rise to the formation of these mountain ranges. The first one probably occurred during Late Mesozoic. The second one started in the Oligocene and reached the maximum activity during Miocene. These were followed by the third orogenic phase, during Late Miocene and Pliocene (ICE, 1976a).

In a cross section across the Guanacaste Mountain Range, the country can be divided into three sectors of different age: the External Arc on the Pacific side, the Intraoceanic Magmatic Arc (represented by the mountain ranges) in the central part and the Trans Arc Basin in the Caribbean side (fig. 1).

The origin of the arc is related to the subduction of the Cocos Plate underneath the Caribbean Plate. The plate boundary on the surface is along the Middle-American Trench, along the Central America Pacific coast between Mexico and Costa Rica.

In Costa Rica, the External Arc is formed by peridotites and the Nicoya Complex (Upper Cretaceous) and is covered by Upper Cretaceous-Miocene marine series which is aproximately 5 000 m thick. This marine series is constitued by shales and sandstones, alternated with several thin fossiliferous limestone and calcarenite layers.

The Magmatic Arc in Guanacaste, the northwestern part of the country, is constitued by Tertiary and Quaternary volcanic rocks. The Tertiary rocks form an andesitic volcanic plateau with abundant pyroclastites and ignimbrites alternating with detrital sediments. The Quaternary rocks are mainly lavas related to the strato-volcanoes, which line up in a NW-SE direction. These are Orosí, Rincón de la Vieja, Miravalles and Tenorio volcanoes. The composition of the lavas is basaltic andesite, rhyodacite, and rhyolite. Further to the south is the Arenal Volcano, some 42 km away from the Guanacaste Mountain Range.

The Trans Arc Basin is composed of Quaternary aluvial deposits and lahars, eroded from the mountain range, and some Tertiary volcanics (ICE, 1976a).

2 THE MIRAVALLES GEOTHERMAL FIELD

2.1 LOCATION

The Miravalles Geothermal Area is located in the Guanacaste Volcanic Mountain Range, which is the most important feature in the northwestern part of Costa Rica (fig. 2).

The geothermal field is situated in the Bagaces Canton, Guanacaste Province, on the southwestern slope of the Miravalles Volcano, some 250 km from San Jose City. The field is located within a caldera which forms a collapse structure 13 km in diameter, named "Caldera de Guayabo". This field is quite famous due to the presence of several fumaroles, solfataras and warm and hot springs.

Presently an effort is being made to exploit the geothermal field for two 55 MWe units. Eight deep exploratory wells will be used for the first 55 MWe unit, providing about 40 MWe.

2.2 GEOLOGY

The studies made by the Instituto Costarricense de Electricidad (ICE) (ICE, 1976a), Electroconsult (ELC, 1983, 1984a, 1984b) and others (Mora, 1988), provide the following information on the geology from both the inside and the outside the studied area (fig. 3):

Pre-caldera lavas. Probably Late Pliocene age, are exposed in the north, west and southwestern part of the caldera and in the inner walls of the caldera rim. These are pyroxene andesitic lavas which differentiate from alumina-rich basalts to andesites. In other parts, this unit is not exposed.

Pyroclastic flows. These cover the pre-caldera lavas and is probably related to the Guayabo Caldera formation. This unit

4

is composed of several pyroclastic flows (tuffs) with different characters; the main constituents are pumice and lava clasts in an ash matrix and pyroclastic "surge" deposits close the bottom. The average thickness of the pyroclastic flows is near 30 m (Mora, 1988).

Cabro Muco-La Giganta volcanic complex. It is located at the southeastern part of the caldera rim, appearing like an isolated unit underlying the Miravalles volcanic products. The rocks are andesites and pyroxene basaltic-andesite lavas.

Cerro Los Caballos eruptive center. This eruptive center forms an ellipsoidal dome possibly time-related to the Cabro Muco-La Giganta activity and it is composed of porphyritic andesitic lavas.

Lahars. The lahar deposits cover almost all the caldera floor in the west and southern part. They are composed by different types of lava blocks, in a sand and/or gravel matrices. These lahars are probably derived from an explosive collapse of a part of the Paleomiravalles volcano, before the actual Miravalles volcano became active.

Paleo-Miravalles volcano. The products of this volcano have a petrographic composition similar to Cabro Muco-La Giganta products, covering the northeastern part, along the eruptive centers lined up SW-NE.

Miravalles volcano. All the Miravalles lavas are pyroxene andesites younger than 50 000 years old. The lava flows flowed to the west and south part of the caldera.

Post-Miravalles lava flows. In the southern part of the Miravalles volcano four recent lava flows are recognized, lined up along a N-S fault. The oldest one is by far the biggest and separates into two flows to join again at lower altitude levels.

La Fortuna lacustrine and alluvial sediments. These are sandy and silty sediments approximately 10 m thick, finely stratified and covering the lahar deposits in the La Fortuna area.

2.3 GEOCHEMISTRY

During 1975 and 1976 ICE made a regional chemical study on Guanacaste Province, including the southern areas of Rincón de la Vieja and Miravalles volcanoes. Waters and gas from hot springs and fumaroles, were sampled and analyzed to determine the water types and their chemical composition. From this study it was concluded that the area showed the characteristics of a water dominated geothermal system, with a total dissolved solids from 8000 to 15000 ppm. The use of geothermometers suggested temperatures between 200 and 240° C (ICE, 1976b).

The first drilling started in 1979 with three deep wells, showing a water dominated reservoir close to 240° C, the water extracted was neutral to slighty alkaline, with 7000 to 7500 ppm of total dissolved solids.

From 1984 to 1986, six additional deep wells were drilled and PGM-2 was redrilled from 1300 to 2000 m depth. Additional studies were made on the geochemistry of samples from the new wells.

The average chemical composition of the reservoir fluids in PGM-5 is:

pH	=	5.2	Na^+	=	1600 ppm
K^+	=	185 ppm	Ca^{2+}	=	47 ppm
Mg^{2+}	=	0.06 ppm	Fe^+	=	0.24 ppm
Li^+	=	5.2 ppm	Cl^-	=	2700 ppm
SO_4^{2-}	=	30 ppm	HCO_3^-	=	15 ppm
B^+	=	40 ppm	CO_2	=	1480 ppm

SiO_2 = 486 ppm $\qquad\qquad$ H_2S = 20 ppm

TDS = 5128 ppm.

The chemical composition of gas in PGM-5 is:

CO_2 = 97.25 % $\qquad\qquad$ H_2S = 1.48 %

CH_4 = 0.07 % $\qquad\qquad$ H_2 = 1.20 %

Remarks: The % of volume exclude the contamination of air. The % of weight of gas at 8 bar separation pressure is around 0.65 %.

All the deep wells drilled (except PGM-2) showed similar chemical composition and total dissolved solids between 4500 and 8500 ppm.

The PGM-5 is located along an E-W belt, defined by an extensive hydrothermal manifestations (like fumaroles, warm springs and surface alteration). This belt is probably controlled by an E-W fault system and its possible intersection with a NW-SE fault system (fig. 4). The PGM-5 is located 100 m south of an active fumarolic zone and 1.5 km west of the most active fumarole (Las Hornillas).

2.4 GEOPHYSICS

Geophysical studies on Guanacaste Province, and specially on the Miravalles and Rincón de la Vieja areas, have been made almost continuously since 1975. Different methods have been used, like electrical resistivity, gravimetry and magnetometry (ICE, 1976c; ICE, 1981).

At present the most used technique is electrical resistivity with vertical electric sounding (Schlumberger type), the electrode spacing is AB/2 = 4000 m maximum and with maximum penetration of 1500 m depth. These studies revealed a resistivity anomaly, some of wich can be related to surface thermal

manifestations. The circular electrical sounding made in PGM-5 area, revealed the presence of one extremely low resistivity layer (1 Ohmm), between 40 and 280 m depth. Below this layer and the maximum sounding penetration (1500 m) values of 20 Ohmm were found (ELC, 1984a).

3 BOREHOLE GEOLOGY AND ALTERATION MINERALOGY

3.1 INTRODUCTION

The PGM-5 deep well (Lambert coordinates 299 513 N - 405 521 W, at 585 m.a.s.l., fig. 4), was drilled as a part of a feasibility program to the first geothermoelectric 55 MWe unit. The purpose of this well was to investigate the north-eastern part of the geothermal area and to evaluate the possibility of finding fluids with thermodynamic conditions able to produce dry steam (ELC, 1984a).

During drilling continuous logging of cuttings and cores were carried out, and the chemical composition and the outlet mud temperature recorded, as well as the circulation losses. In addition few down hole temperature measurements were made during drilling.

Samples of cuttings were obtained at 3 m intervals and three cores were taken, at 606, 1490 and 1846 m depth. The hole was drilled with mud except during "blind" drilling, when water was used (1717 to 1846 m).

After the drilling was finished, several tests were made: showing the higest temperature of 238° C, transmisivity around 5 millidarcy/cubic pound and a power potential of 5.6 MWe (ELC, 1984a).

3.2 DRILLING HISTORY

PGM-5 was the fourth geothermal hole drilled (PGM-4 has not been drilled) in the Miravalles Geothermal Field. It is situated close to a geothermal alteration area (Las Hornillas Fault) and close to an important resistivity low (La Unión), due to the inter-section of three important faults (fig. 4).

The well was drilled between February 20th and May 19th, 1984. The drilling started with a 26" bit rotary drilling (fig. 5) down to 98 m and cementing of a 20" surface casing. The drilling continued with a 17 1/2" bit down to 603 m depth, a cementing of a 13 3/8" production casing, the float shoe was placed at 553 m. In this interval two total circulation losses at 222 and 602 m were met. 9 5/8" liner was placed in a 12 1/4" hole down to 1846 m (slotted below 1513 m to the bottom) (ELC, 1984a).

The cutting recovery was about 90%. Below 1717 m depth a total lack of cuttings is due to a total circulation loss down to the bottom. Three cores were taken at 606, 1490 and 1856 m respectively.

3.3 AQUIFERS

Circulation losses were measured at the following depths (fig. 6a):

Total loss (more than 15 l/s) at 222 m, 441 m, 602 m, 1505 m, 1621-22 m, 1642-45 m, 1669-70 m and from 1717 to 1846 m depth.

Intermediate loss (5-15 l/s) at 1430 m, 1570 m, 1579 m, 1582 m, 1595 m, 1605 m and 1626 m depth.

Small loss (<5 l/s) at 314 m, 564 m, 617 m, 625 m, 665 m, 676 m, 681m, 705 m, 790 m, 815 m, 915 m, 932 m, 937 m, 943 m, 960 m, 1000 m, 1120 m, 1260 m, 1350 m, 1456 m, 1466 m, 1497 m and 1503 m depth.

According with these circulation losses, aquifers are located at the following depths:

222 m	total loss	cemented
314 m	small loss	" "
441 m	total loss	" "

```
       602 m    total loss
       676 m    small
       943 m    small
      1430 m    intermediate
      1505 m    total
      1579 m    intermediate
   1621-22 m    total
   1642-45 m    total
   1669-70 m    total
 1717-1846 m    total.
```

According to seven temperature measurements, aquifers below
production casing are at the following depths:

```
   1700-1846 m    main aquifer,
  ~1350-1400 m    the second largest,
  ~1500-1600 m    the third best,
   1000-1100 m    small aquifer and
         650 m    small aquifer.
```

In summary, by combining the data from the measured circulation
loss and the temperature measurements, the aquifers of the well
are marked at the following depths (figs. 6a and 6b):

```
   222 m    large          lithological boundary
   314 m    small          flows contact or fault/fracture
   441 m    large           "  "       "  "    "    "  "     "  "
   620 m    small           "  "       "  "    "    "  "     "  "
   943 m    small          lithological boundary
  1100 m    small              "   "         "   "
  1505 m    intermediate   flows contact or fault/fracture
  1620 m    intermediate   lithological boundary
 >1710 m    large              "   "         "   "
```

The first one (at 222 m depth) was plugged by sealing material
and subsequently cemented. Before cementing, a temperature logg
was made and the rock temperature estimated 225° C (by using
the Horner method; ELC, 1984a). This aquifer may be fed from

11

the deeper part through the Las Hornillas or another fault
system. The aquifer at 441 m was cemented but according to
the rock temperature evaluation contains fluid close to 185°
C and at 600 m the rock temperature is about 225° C.

The interval between 900 and 1120 m depth, is the main producer
zone in other wells, but in PGM-5 it is less permeable than in
other wells.

The deepest aquifer zone (1717 to 1854 m) is harnessed for steam
production. The highest temperature minerals found in this
interval are epidote, chlorite, illite, quartz, albite, adularia
and sphene.

3.4 ROCK TEMPERATURE

Figure 6b shows 7 temperature measurements of PGM-5 measured
in the following dates:

(1)   24 hours after well completion, 84-05-04,
(2)   after 11 days heating, 84-05-29,
(3)   after blow test, 84-06-07,
(4)   measured 88-02-05,
(5)   measured 88-05-05,
(6)   measured 88-07-13,
(7)   measured 88-10-05 and
(8)   the approximate rock temperature.

The rock temperature at 100 m depth lies between 120-140° C
(fig. 6b), the rock temperature increase from 100 to 300 m to
about 170° C. According to the series of measurement from 1988
(number 4, 5, 6 and 7), a systematic cooling is seen suggesting
the rock temperature from 0-400 m lies somewhere between the
temperature measurements number 2 and number 7, suggesting the
aquifer at 222 m is only about 140° C hot.
The temperature measurements made during 1988, show the
reservoir temperature from 600 m to the bottom, between
230-240° C

3.5 STRATIGRAPHY

Cutting samples were collected at 3 m interval (0 to 1717 m depth). They were studied under a stereocospic microscope; thin sections were made at 20 m interval (or 5 to 10 m in interesting zones) and analyzed under polarizing microscope.
Six stratigraphic unit were distinguished based on lithological and petrological criteria. These units are described below, firstly like a unit and followed by the description of the different layers found in these units. The units are from top to the bottom (ELC, 1984a; 1986) (fig. 5):

Post-Cabro Muco Volcanic Unit. 0 - 244 m depth, consist of recent products of andesitic lava flows, pyroclastic rocks and lahars.

0 - 23 m: Lahar, formed by altered lava blocks with different textures in a finer grained sandy-silty rock matrix.

23 - 37 m: Porphyritic andesite lava flow, partially altered and very dark due to high magnetite content.

37 - 97 m: Reworked tuffs of different colours, composed of blackish-grey porphyritic andesite and finer-grained tuff.

97 - 116 m: Partially altered greyish-green lava flow of banded porphyritic andesite.

116 - 244 m: Highly altered tuffs and lahars.

Cabro Muco Andesitic Unit. 244 - 520 m depth, formed by series of andesitic lava flows related to the Cabro Muco-La Giganta volcanic complex.

244 - 520 m: Andesite lava flows composed of andesine, clino-pyroxene and rare amphibole phenocryts in a microcrystalline matrix composed of plagioclase, quartz, K-feldspars and ferromagnesian minerals, moderately altered.

13

Acid-andesite Unit. 520 - 865 m depth, these acid-andesitic lava flows are characterized by relatively high silica content, and are rich in K-feldspar in the matrices.

520 - 865 m: Acid-andesite lava flows composed of plagioclase, clinopyroxene, magnetite phenocrysts and rare hornblende in a microcrystalline matrix formed by plagioclases, quartz, K-feldspars and ferromagnesian minerals.

Volcano-sedimentary Unit. 865 - 930 m depth, consists of tuff with phenocrysts of plagioclase and andesitic lava fragments. Includes lacustrine sandstone and shale intercalations.

865 - 930 m: Volcanogenic sandstone and shale, intercalated in a tuff layer. The sedimentary character is seen from rounded clasts and grain sorting.

Lava-tuff Unit. 930 - 1380 m depth, formed by the alternations of andesite lava flows and intercalations of tuffs. The tuff contain some plagioclase phenocrysts and andesitic lava fragments in a glassy matrix.

930 - 1120 m: Tuff with with plagioclase and rare hornblende phenocrysts and andesitic lava fragments.

1120 - 1220 m: Porphyritic acidic-andesite lava flows with oligoclase and ferromagnesians phenocrysts in a matrix formed by plagioclase, quartz, K-feldspar and ferromagnesian minerals.

1220 - 1260 m: Tuffs formed of plagioclase phenocrysts in a glassy matrix, including some basaltic fragments with olivine pseudomorphs.

1260 - 1310 m: Porphyritic andesite lava flows with pilotaxitic-fluidal texture, andesine plagioclase, clinopyroxene phenocrysts and magnetite.

1310 - 1350 m: Tuff with plagioclase phenocrysts and traces of
primary hornblende in a glassy matrix.

1350 - 1380 m: Porphyritic andesite lava flow with pilotaxitic
fluidal texture, similar to above.

Ignimbrite Unit. 1380 and 1854 m depth. Consists of a welded
tuff with lithic fragments in vitric matrix. It shows character-
istic texture of consolidated nature resulting from high
temperatures, like flow banded fluidal texture and lineations
of colapsed glass. A basaltic-andesite is interbedded between
1620 and 1680 m depth. At present, it has not been possible to
corelated this unit with any of the pyroclastic units outcroping
outside the Guayabo caldera. However, the presently accepted
model of the caldera subsidence assumes a correlation between
the ignimbrite formation and the pyroclastic flows on the
surface. In other words, it assumes a caldera subsidence of
approximately 1.5 km, which is questioned by the present
author, but requires further study.

1380 - 1620 m: Dense welded tuff formed by different types of
lava clasts altered and flattened or banded glass.

1620 - 1680 m: Dark-porphyritic basaltic-andesite lava flows
with plagioclase, ferromagnesians and traces of olivine
phenocrysts.

1680 - 1717 m: Welded tuff similar to above, formed by flattened
glass, lava and crystal fragments.

1717 - 1846 m: No cuttings due to total circulation loss.

1846 - 1854 m: Core of welded tuff similar to above. This core
showed a greyish-green welded tuff with slightly streakened
glass, lava and crystals fragments, opened and filled subvertical
fractures filled with quartz, adularia and some calcite.

3.6 HYDROTHERMAL ALTERATION

3.6.1 Analytical methods

During the author's training the existing knowledge of the secondary mineral distribution in PGM-5, was confirmed as well as improved by several means. This involved the application of the x-ray diffractometry (XRD) for mineral analysis, not the least for clay minerals, selective collection of drill cuttings of minerals veins and amygdales for time relation studies, and a systematic recording of mineralization for subsequent comparison with the aquifer location. An unsuccessful attempt was made also to measure fluid inclusion homogenization temperature in quartz and calcite.

In PGM-5 different alteration grades were encountered, associated to different depths, rock compositions (acid or basic), rock permeabilities, temperatures and the chemistry of circulating fluids.

The author's training involved sample preparation (Hardardóttir, 1984) and interpretation of the XRD-data, mainly to determine the clay minerals but also other alteration minerals. For clay minerals the scanning speed varied from ½ to 1° per minute and for the bulk power analysis 2° per minute. The X-rays diffractometer used is a Phillips PW 1050/25 wide range goniometer connected to a PW 1130/00 x-ray generator. A Cu-radiation lamp was used in all the analysis. The diffractograms were interpreted using the ASTM Search Manual, Brindley & Brown (1980) and other diffraction data references like standard diagrams at Orkustofnun.

Figure 5 shows the mineralogical distribution of PGM-5 and the individual minerals are discussed below.

3.6.2 Mineral Distribution

Calcite. Calcite is widespread in all the hydrothermal fields

16

in the world, replacing primary minerals and as precipitates in open space mineralization. It forms over a wide temperature range up to 300° C (Fridleifsson G. ó., pers. comm.), for which reason in PGM-5, it can not be used as a temperature indicator.

However, calcite may form in great quantities in open space mineralization, and can therefore be useful in locating cap rock zones (if such exist), in estimating primary porosity and in locating faults or fracture zones in the well. The same is true for other common mineral deposits like silica minerals (opal, chalcedony and quartz), sulphides (pyrite, phyrrotite, chalco-pyrite), zeolites and clay minerals.

In PGM-5 calcite occurs throughout the well and a clear relationship seems to exist between large quantity of calcite several meters above two circulation losses at 222 m, and 1380 m depth respectively, and at some lithological boundaries, as at 930 m depth.

The time-relation studies show that calcite is generally younger than the other minerals and that may be time related with quartz and clay minerals.

Silica minerals. These are opaline silica (amorphous), chalcedony (amorphous to microcrystaline) and quartz. The formation of these minerals is both time and temperature depended in geothermal systems; opaline silica forms at the lowest tempera-tures up to several tens of degree centigrades, chalcedony from there to less than 200° C and quartz from approximately 100° C upwards throughout the temperature range of geothermal systems. In Icelandic high temperature systems (like at Nesjavellir), the first appearance of quartz (and wairakite) is found at approximately 200° C, a fact which has been used for determining the final length of production casings (Fridleifsson, G. ó., pers. comm.).

In PGM-5 chalcedony occurs sporadically at different depths down the well (fig. 5) and was observed by the stereoscopic microscope as a milky white to light blue amorphous deposits. The first appearance is at 64 m depth (filling a vesicle) and the last at 1645 m depth. Opaline silica was found close to the surface of the well. However, it also showed up by the XRD method, where the diffractograms show an oval shaped curve along $2\tilde{o}$ values from 17-35° (at depths 7 m, 61 m, 100 m, 222 m, 240 m and 380 m) (see fig. 8).

Like calcite, quartz is a common alteration mineral. It is easily identified by the stereoscopic microscope, in thin sections and by the XRD method.

The vertical distribution of quartz, presents peaks at the same depth as calcite, clearly associated also with total or partial circulation losses (222, 930, 1260 and 1380 m depth). The first appearance of quartz was at 61 m depth, determined in thin section from the lahar and may be of detrial origin.

As the silica solubility decreases with the temperature, the quartz occurrence in the upper part (180-240 m depth), may be associated with the cooling and supersaturation of hot fluid from the reservoir, flowing upwards via fractures or faults.

From 900 m depth to the bottom, the occurrence of quartz is continuous within the chlorite-illite-epidote zone. Quartz occurs as pure hydrothermal crystals in amygdales and veins as well as coarse or fine grained mosaic, replacing glass or feldspar.

Zeolites. Zeolites are common hydrothermal alteration minerals in many geothermal systems and have been used extensively as temperature indicators (e.g. Kristmannsdóttir, 1978; Kristmannsdóttir and Tomasson, 1978). Only two types of zeolites were found in PGM-5, laumontite and wairakite.

Laumontite. In cuttings it is present as fibrous colourless to milky white crystals, prismatic shape, strong cleavage and low hardness. It is present at two depth intervals, at 231-244 m depth, at lithological boundaries, and from 990 to 1174 m depth within an originally porous tuff unit.

In thin sections, laumontite is colorless, has low relief, low birefringence, fibrous to elongated crystals with low extinction angle and -ve sign.

By XRD method, the diffractograms present a big peak at $d/Å$ = 9.45-9.5 Å in samples treated with $CaCl_2$, which expands to 9.6 upon glycosaturation and shrinks down to 8.66-8.84 Å upon heating to 550-600° C (fig. 7), an interpretation aided by icelandic test-data on pure laumontite (Fridleifsson, G. Ó., pers. comm.).

Laumontite is believed to be formed at a temperature range of 120-180° C (Kristmannsdóttir, 1978). In PGM-5 the temperature between the first and the last occurrence varies from 153 to 233° C which may indicate heating of the well at lower levels. This fact is supported by rather turbid appearance of laumontite in thin sections, as well as partial replacement by quartz and clay minerals.

Wairakite. Is a high-temperature Ca-Al-zeolite and was observed with the stereoscopic microscope at 1240 and 1260 m depth, where it occurs as a cubic milky white crystal. In thin sections it was observed in the interval between 1100 and 1260 m depth, identified by its octahedral shape, low birefringence, low relief (almost isotropic) and its neat polysynthetic twinning which distinguishes it from the isotropic analcime.

Using the XRD method in the analysis of the bulk powder sample, wairakite was determined from its big peak at $d/Å$ = 3.39-3.41 Å (fig. 7).

It is observed at about 200 to 250° C in Wairakei (New Zeland; Steiner, 1977), and above 200° C in several geothermal fields in Iceland (Kristmannsdóttir, 1978). Wairakite and prehnite are favoured in active Icelandic geothermal fields at temperatures between 200-300° C (Fridleifsson, G. Ó., pers. coom.).

In PGM-5 wairakite is found below the laumontite occurrences (>1200 m depth), indicating a temperature increase assuming contemporaneous formation once upon the time. Wairakite appears associated to the chlorite-illite-epidote zone (fig.5).

Prehnite. It is a common hydrothermal alteration mineral. Its formation temperature is not well known, but seems to be favoured at 200-300° C (Friðleifsson, pers. comm.). In PGM-5 it was indentified with the stereoscopic microscope, in thin sections and by XRD method.

In cuttings it is present as translucent milky white crystals with semi-spherical shape, due to the radial growth of prehnite. In thin sections, it is recognized by sheaf like (bow-tie) structure, high birefringence, good cleavage in one direction, parallel extinction and +ve sign. In XRD it shows a big peak at d/Å = 3.08 Å (figs. 7).

It was first observed at 560 m depth (in thin sections). Is particulary common between 560 and 660 m depth, but continues intermitently in small amount down to 1424 m depth.

It is present as indidual cutting grains, replacing feldspars and pyroxenes and filling voids and veins. In PGM-5, prehnite is found in both the mixed-layer clay and the chlorite-illite-epidote zones.

Epidote. Epidote is extremely common alteration mineral in high temperature geothermal systems world wide. Therefore it is frequently used as a prefix for index mineral zones (see later).

The result of early studies of the first occurrence of epidote compared with measured temperatures (e.g. Kristmannsdóttir, 1978) suggested the minimum temperature for epidote formation is close to 230-240° C, epidote becoming increasingly more abundant with increasing temperature.

In PGM-5 epidote occurs spodically at 560, 650 and 710 m depth, where the measured temperature is close to 230° C, but becomes common below 900 m depth where it is used with chlorite and illite to mark an alteration zone.

Epidote was recognised in the stereoscopic microscope from its yelow colour and prismatic crystals. In thin sections, by its yellow colour, high refractive index and its high birefringence.

Epidote is found almost everywhere with in the chlorite-illite-epidote zone, both as rock replacement mineral and in amygdales and veins.

Secondary felspars. These are albite and adularia. They are extremely common replacement minerals of primary felspars and glass, and ubiquitous part of the chlorite-illite-epidote zone. The increase of these minerals, and in particular adularia, have been correlated with increasing permeability (e.g. Browne, 1970, 1977). Evidently, this relationship can not been used too rigourously, however, as the overall result of mineral precipitation within the rocks is to reduce primary permeability. Therefore, it would depend on other parameters, like original porosity, rock composition and time, whether this relationship holds or not (Fridleifsson, G. Ó., pers. comm.)

In PGM-5 the distribution of albite is not shown because of difficulties of distinguishing it from primary andesine on basis of extinction of albite twinning in the matrix feldspar in the intermediate to acid rocks. Matrix feldspars with low-extinction angle, however, are present in all thin section from the chlorite-illite-epidote zone.

The presence of adularia was studied by the staining method
(Broch, 1961) showing secondary K-feldspar in increasing amount
from 1400 m depth downwards (ELC, 1984 a).

The occurrence of adularia could be taken as indicative of both
high temperature and good permeability, coinciding with the
producer aquifer below 1500 m. The increasing occurrence of
adularia in the ignimbrite unit, however, can just as well be
related to the high potassium content of the host rock.

Anhydrite. Is the only sulphate found in the well, being rare
and occurring in small crystals.

It was determined firstly in thin sections by its moderate
relief, strong birefringence in clusters of anhedral to
subeuhedral colorless crystals, rectangular cleavage and
parallel extinction.

By XRD it was inferred presenting a big peak at d = 3.49 Å, in
the interval from 1000 to 1350 m depth (fig. 7).

Sphene. Is a secondary mineral identified in thin sections by
its extremaly high relief, dull brown color in natural light
incomplete extinction under crossed nicols due to strong
dispersion.

Sphene occurs first at 991 m depth (thin sections), and is a
ubiquitous mineral of the chlorite-illite-epidote zone.

Iron oxides. Hematite seems to be the only type of iron oxide
in PGM-5. It is a secondary mineral, resulting from oxidation
of the primary iron ore and the ferromagnesian minerals.

The vertical distribution of the iron oxide is shown in
figure 5. From the top to 40 m depth and 1200-1300 m depth it
is particulary abundant.

Sulphides. Two types of sulphides were identified in PGM-5, pyrite and chalcopyrite. Pyrite seems to be more abundant. Both types of sulphides are commonly oxidized and their small grain size hampers detailed identification. A detailed identification of the sulphides requires a study in polished thin sections, which was not undertaken.

Small sulphides grains are found disseminated down the well, and they were never found in large quantities which is often the case in other high temperature geothermal system.

Biotite. Was detected in a single mineral at 1500 m depth in the ignimbrite unit. Its hydrothermal origin is questionable, but it has been found in other wells as an accessory mineral, as well as apatite, occassionally seen in thin sections in PGM-5.

Clay minerals:

The clay minerals were studied in thin sections along with other minerals, but due to the small grain size, it is usually impossible to distinguish between the clay types accurately except by using the x-ray diffractometry method.

The clay minerals are described below in order of appearance and increasing formation temperature.

Representative XRD patterns of 24 samples analysed are shown in the figures 8 to 10. The result of the XRD analysis is compiled in the appendix.

Smectite. Is a common name for low-temperature clay minerals like montmorillonite, saponite, beidellite, nontronite and hectorite. In well PGM-5 pure smectite is found by XRD from the surface to 380 m depth. Below 400 m depth, mixed layered clays with illites and/or chlorites are found down to 1424 m depth. In stereoscopic microscope, the smectite shows green or brown colours.

23

It is belived that most of the low temperature clay minerals
in PGM-5 are montmorillonites, while representative bulk of
chemical analysis are needed to confirm this believe. Therefore,
the smectite group name is used in the following discussion.

In thin sections, smectite shows green to brown colours changing
to yellowish-green to green in polarized light. It replaces the
glass in the rock matrices, and some primary minerals (feldspars
and/or ferromagnesians) and fills voids and fractures.

Several samples were runned in XRD and the diffractograms of
samples treated with $CaCl_2$ shows a 12-17 Å peaks, which expands
to 16.8-17 Å upon glycolsaturation and disappears or shrinks
down to 9-12 Å upon heating to 550° C (fig. 8 and 9).
The occurence of smectite is independent of rock type, and it
is found in altered rocks from the surface to 380 m depth.
Below 200 m smectite becomes intermixed with illite and/or
chlorites.

Mixed layered clays. The mixed layer clays were observed in
cuttings and thin sections, but identified by XRD method, as
interstratified smectite-illite, smectite-chlorites and
smectite-illite-chlorite.

Mixed layer smectite-illite (rich in stratified smectite) shows
peaks from 10.4 to 12.25 Å while the mixed layer illite-
smectite, deficient in stratified smectite, shows peaks at
10.16-10.28 Å (Steiner, 1977). In PGM-5, the mixed layer clays
occurs from 222 m depth to the bottom (figs. 8 to 10), and is
present in almost all the rock types in this well, the tempera-
ture in this interval varies from 154 to 236° C.

Mixed layers smectite-chlorite occurs discontinuously below
881 m depth and smectite-illite-chlorite was determined at
579, 759 and 1229 m depth (figs. 9 and 10).

Swelling chlorite. Is determined by the XRD method (fig. 10),
where the diffractogram show peaks at 14.5-15 Å and 29.4-30 Å

in samples treated with $CaCl_2$, swelling to 31.5 Å upon glycolsaturation and shrinking to 13.5-14 Å upon heating to 550-600°C. It was identified in traces in the samples at 222 m depth and clearly from 240 to 881 m depth. The measured temperature in this interval increase from 153 to 230° C.

The first occurrence is at the same depth as the first aquifer (222 m depth).

Chlorite. Chlorite is formed at the expense of the primary ferromagnesian minerals or glass or deposits in vesicles and veins from Fe-Mg-rich fluids.

In general, the chloritic minerals can be observed in thin sections as minute radiating aggregates but need to be distinguish by XRD method from the mixed-layer clay minerals.

In thin sections they present weak to moderate pleochroism from yellow, brownish-green, and dark or olive-green colours, low birefringence and near parallel extinction. In thin sections it appeared that chlorite was present from 290 m depth down to the bottom. However, the XRD analysis showed mixed layer clays between 290 and 950 m depth.

According to the Fe-Mg content, the birefringence colour is supposed to change. Penninite for instance, is thought to be present from anomalous dark blue birefringence colours, while this needs to be confirmed by chemical analysis.

The clorite presence was confirmed in detail by the XRD method, from 680 m depth to the bottom. The diffractograms show 7-7.6 Å and 14-14.5 Å peaks in samples treated with $CaCl_2$, unchangeable upon glycolsaturation or heating to 550-600° C (fig. 9 and 10).

Chlorite is associated with other clay minerals forming mixed-layers with smectites and illites. Illites and chlorites are the most common clay minerals below 950 m depth, while the

latter is more abundant below 1619 m depth in acid rocks. The
first occurrence of chlorite along with illite and epidote,
mark a high temperature mineral zone.

Illite. Illite is along with the chlorite, the most common clay
minerals in PGM-5. It was recognized by the characteristic 10
Å (9.93-10.04 Å) peak in the XRD analysis, not changing upon
glycolsaturation or heating to 550-600° C (fig. 8 to 10).

The first occurrence of pure illite is at 951 m depth, con-
tinuous to the bottom. It is found interstratified with smectite
and chlorite below 380 m depth in the mixed-layer zone.
Illite is the dominant clay minerals between 1424 and 1619 m
depth, clearly related to the rock composition (appearing in
potassium-rich tuffaceous rocks) while chlorite is the most
abundant clay minerals above and below this depth interval in
more basic rock types (andesites).

Sericite is a poorly defined name often given to any colourless
clayish like aggregate of layer-lattice minerals possibly
intermediate betwe micas and clay minerals (Whitten & Brooks,
1972).

In PGM-5 the term sericite was at first used for a clay-like
colourless substance of low relief and high birefringence. Its
distribution, however, coincided with that of the XRD-analized
illite. According to Kerr (1959) a minutely crystalline variety
of muscovite is called sericite which further is very similar
to hydromuscovite which is also called hydromica and illite
(Kerr, 1959, p 385-388, 413). According to the Encyclopedia of
Mineralogy (edited by Keith Frye, 1981) sericite is a "fine-
grained" mica group mineral, commonly muscovite but also
paragonite or illite" (p. 712). From this discussion it is
evident that sericite is indistinguishable from illite in well
PGM-5, and it is recommended that the usage of the sericite term
is abandoned in future discussion of the Miravalles Geothermal
Field. The term illite should be used instead, due to its
inevitable importance in delineating the zonal distribution (see

chapter 3.6).

Kaolinite. Kaolinite is a clay mineral formed mainly at the expense feldspars, and is common wheathering product of rocks and thereby formed at low temperatures.

It was identified only by XRD method in samples from 222, 240 and 380 m depth, presenting a basal reflection at d = 7.19 Å in samples treated with $CaCl_2$, two basal reflections at 7.19 Å and 3.57 Å upon glycolsaturation, these peaks disappearing upon heating to 550-600° C as expected for kaolinite (Brindley & Brown, 1980).

Kaolinite is a hydrated alumina silicate while illite is a hydrated potassium-alumina silicate.

3.7 ALTERATION ZONES

Alteration mineralogy is important to determine the hydrothermal conditions (in the past and present) at all depth levels.

The factors which affect the formation of hydrothermal minerals are temperature, pressure, type of host rock, reservoir permeabilities, fluid composition and duration of activity (e.g. Browne, 1984). Deduction of temperature and permeability of a system, can consequently be deduced from the alteration mineralogy. Pressure has been found to have only a minor effect on the formation and/or deposition of hydrothermal alteration minerals except by governing the maximum fluid temperatures in the open geothermal systems, and thereby the onset of boiling which can have drastic effect on mineral deposition within the rock formations.

An empirical relationship has been found to exist between rock temperature and the types of secondary minerals in active geothermal systems. Accordingly it has be made possible to

27

connect the occurrence of a given mineral to a range in
formation temperature. Without much further discussion it is
of fundamental importance to know whether a mineral or mineral
assemblage is being formed under the present-day measured
temperature conditions when such correlations are made in active
systems, a fact which has often been bypassed in the litterature
leading to contradicting formation temperature of minerals
(Fridleifsson, G. Ó., pers. comm.). Evidently any mineral is
formed in a given P-T-compositional field, while only some of
them are temperature sensitive. Amongst T-sensitive minerals
are the zeolites and clay minerals. Other minerals have a
wide range of formation temperatures, their precipitation
more dependent on the gas content of the fluids or boiling,
while they are useless as temperature indicators.

Well established clay mineral zones are known from Iceland
concerning the transition of smectite (Sm) to mixed-layer clays
of smectite/chlorite (MLC) to chlorite (Chl) at temperatures
from 0-200° C, 200-240° C and >240° C respectively (e.g.
Palmason et al., 1979)., and from New Zeland concerning
montmorillonite (Sm) to MLC of smectite/illite to illite at
temperatures from 0-140° C, 140-220° C and >220° C respectively
(e.g. Browne, 1984). These changes have been used to map clay
mineral zones with given temperature limits. Many other
minerals have been found to be formed only within the temperature
limits defined by these zones, e. g. laumontite (120-180° C)
with in the upper temperature limits of the smectite zone and
epidote (>230° C) within the chlorite-illite-epidote zone.

From the clay mineral distribution in well PGM-5 it is possible
to define temperature dependent mineral zones in the well
indexed by the clay minerals. These are as follows:

Smectite zone. From surface to 380 m depth (fig. 5) where the
smectite (probably montmorillonite) is the most abundant clay
mineral. The presently estimated rock temperature from the
measured temperature is up to 190° C (see fig. 6b).
Other alteration minerals in this mineral zone are calcite,

quartz, hematite, pyrite, (interstratified illite- smectite), swelling chlorite and minor occurences of other minerals like kaolinite and laumontite. This zone is located in lahar, andesite and tuffaceous rocks.

Mixed-layer clays zone (or transitional zone). This transitional zone is characterized by mixed-layer clays (smectite-chlorite and minor occurrences of smectite-illite) and swelling chlorite. Pure illite is not present. Other alteration minerals are calcite, quartz, prehnite, laumontite, hematite, minor epidote and occasional sphene.

The present day rock-temperature varies from 190 to 230° C, more or less within the temperature limits of the mixed-layer clay zones discussed above.
The abundance of MLC of smectite-chlorite over smectite-illite may related to the rock composition in the zone which is located in andesite, acidic-andesite, tuff and shale and sandstone rocks.

Chlorite-illite-epidote zone. This extends from 951 to the bottom, and is characterized by the high content of chlorite, the first occurrence of pure illite, as well as continuous occurrence of epidote increasing in abundance downwards. The host rock are tuff, ignimbrite, andesite and acid-andesite lava flows.

In the upper part of the welded tuff (ignimbrite), from 1424 to 1619 m depth (e.g. 1451 m depth, fig. 10), illite is more abundant than the chlorites, due to the high potassium content the rock. However, chlorite is more abundant below 1619 m depth, undouptly due to the rock composition (basaltic-andesite).

Other alteration minerals occurring in this zone are calcite, quartz, prehnite, laumontite, epidote, albite, adularia, hematite wairakite, anhydrite and biotite.

The present day rock temperature in PGM-5, estimated from the measured temperature, are just below 240° C (230-238° C), while

the higher temperature chlorite-illite-epidote zone (ch-il-ep zone), can only mean that temperatures within the reservoir have be somewhat higher in the past than they are today.

Interesting also is the fact that the mixed-layer clay minerals are present everywhere in the ch-il-ep zone, much in accordance with the present-day reservoir temperature.

From the lack of hydrothermal minerals formed above 300° C (like actinolite or garnet) it can be postulated that the temperature within the reservoir in PGM-5 has not risen above 300° C. By similar arguments the presence of epidote in the MLC-zone may imply a slightly higher fluid temperatures in the past than at present.

On figure 6b the mineral temperatures are shown stippled. The direction of changes with respect to heating or cooling, however, requires a knowledge of the mineral evolution (time relation) which is discussed shortly below.

3.8 MINERAL EVOLUTION AND DISCUSSION

The first attempts of the present author to map the hydro-thermal evolution in an area, was made in the fossil alteration zones of the extinct Geitafell Central Volcano (Fridleifsson, 1983 a,b), with the guidance of Dr. Guðmundur Ó. Fridleifsson. Subsequently, this practical training was applied in the study and interpretation of hydrothermal evolution of well PGM-5.

Some examples of time relationship studies in PGM-5, indicate that sphene is (possibly) the oldest phase, from the transition zone to the bottom, while its appeareance in dull clayish vesicle rims is more suggestive of reaction between earlier clay and fluids to produce sphene.

Clay minerals occur in two generations, before and after quartz, this relationship was found in the chlorite-illite-epidote zone.

In the same cutting, in the MLC-zone at 850 m depth, prehnite and quartz occur after one of the clay minerals generation, in which case prehnite and the quartz are contemporaneous. In another example, prehnite occurs before quartz in the ch-il-ep zone at 1150 m depth.

Epidote is deposited after an early clay mineral generation at 1000 m depth and probably before the second quartz episode in the MLC-zone at 900 m depth (possibly implying cooling). Calcite is possibly of two generations, in one case calcite is found deposited after the second clay mineral phase at 1100 m depth; in another case, it is possibly the last alteration mineral deposited in this hydrothermal system, altering clay minerals and deposited above the quartz at 1100-1150 m depth.

While the present study on time relations shows incomplete result, similar studies may be tried on future wells. One method applied in this study was to collect cuttings of veins and amygdales over 50-100 m intervals in order to sort out the time relationship. Part of such mineral collection was powdered for XRD-studies by mistake instead of thin section preparation. The remaining material of such collections in PGM-5 enlargened the field of occurrence for some minerals, like laumontite, while evidences looked for of cross cuttings veins and amygdales infilling sequences were limited.

As a concluding remark the most common alteration minerals filling veins and voids are quartz and calcite (occurring as pure filling mineral or together), with or without other alteration minerals.

4 SUMMARY AND CONCLUSIONS

PGM-5 was drilled as an exploration well to determine the western extension of the geothermal resources of Miravalles Geothermal Field.

PGM-5 is located in a different structural block than the others drillholes in the area. This well is confined by some of the principal N-S and E-W fault systems.

The lithology of PGM-5, is similar to other deep wells drilled previously. It consist of six stratigraphic units i.e. Post-Cabro Muco unit (lahar, andesitic lava and pyroclastic rocks) from the surface to 244 m depth; Cabro Muco andesitic unit (porphyritic andesitic lava flows) untill 520 m depth; Acidic-andesite unit (andesitic lava flows with high silica content) up to 865 m depth; Volcano-sedimentary unit (sandstone and shales interbedded with reworked tuff flows) till 930 m depth; Lava-tuff unit (andesite lava flows alternating with tuffs) untill 1380 m depth and Ignimbrite unit (welded tuff with interbedded basaltic-andesite lava, 50 m thick) to the bottom. Generally accepted model of the caldera subsidence of 1.5 km is questioned in this report, but requires further study.

On basis of temperature measurements and total/partial circula-tion losses, aquifers were determined at the following depths: at 1710-1846 m the main producer aquifer; at 222 m and 444 m as large aquifers; at 1505 and 1620 m as intermediate aquifers and finally at 314 m, 620 m, 943 m and 1400 m as small aquifers. These aquifers are associated to lithological boundaries, to the contact between two flows of the same unit or related with fractures and/or faults.

The temperatures measured in the well, correspond fairly well with the temperatures indicated by the alteration mineralogy. Still it is apparent from the mineralogy that the reservoir has been few tens of °C hotter in the past than today.

Three chief clay mineral zones were distinguished in the well:

1) A smectite zone, characterized by the occurrence of pure smectite (montmorillonite type) from the top to 380 m depth, formed at temperatures below 200° C.

2) A mixed-layer clay zone, characterized by interlayered (mixed) smectite-illite and smectite-chlorite, from 380 to 951 m depth and swelling chlorite. This zone is transitional between 1) and 3) and is believed to indicate a temperature range between 200-240° C. The present-day rock temperature is about 230°C.

3) A chlorite-illite-epidote zone, below 950 m to the bottom of the well, characterized by the index minerals and albite, adularia, sphene and some prehnite and wairakite. In the interval from 1424 m to 1619 m depth, illite becomes more abundant than chlorite due to the rock composition in this interval (welded tuff, potassium-rich). The same relationship holds for adularia over albite. The highest temperature measured in this interval is 238° C. The mineral zone, however, is believed to be formed at temperatures above 240° C up to ca. 300° C, implying the reservoir has been hotter in the past. From the presence of mixed-layer clay minerals, it is possible this cooling has taken place long time ago. While time relation studies would throw some light on the direction of temperature changes in the system, a comparison with other wells within the Miravalles Field would be quite interesting in order to map the possible boundaries of the hydrothermal plume.

ACKNOWLEDGEMENTS

REFERENCES

Brindley, G. W. & Brown, G., 1980. Crystal atructures of clay minerals and their R-Ray identification. London. pp. 495.

Broch, O. A., 1961. Quick Identification of Potash Feldspar, Plagioclase and Quartz for Quantitative Thin Sections Analysis. American Mineralogist, 45, p. 1020-1025.

Browne, P. R. L., 1970. Hydrothermal Alteration as an Aid in Investigating Geothermal Fields. Geothermics, Special issue 2, 564-570 p.

Browne, P. R. L., 1977. Hydrothermal Alteration in Active Geothermal Fields. Annual Reviews of Earth and Planetary Science 6, 229-250 p.

Browne, P. R. L., 1984. Lectures on geothermal energy and petrology. UNU Geothermal Training Programme, Report no. 1984-2, Iceland. 92 p.

ELC, 1983. Proyecto Geotérmico Miravalles. Informe Geológico y vulcanológico; Milan, Italia; GMV-D-5828.

ELC, 1984a. Proyecto Geotérmico Miravalles. Pozo PGM-5 - Informe de Perforación y Control Geológico; Milano, Italia; GMV-D-5056.

ELC, 1984b. Proyecto Geotérmico Miravalles. Estudio Geológico y Estructural de detalle; Milano, Italia; GMV-D-6077.

ELC, 1986. Proyecto Geotérmico Miravalles. Informe Geológico Final; Milano, Italia; GMV-D-6436.

Fridleifsson, G. Ó., 1983a. The Geology and Alteration Alteration History of the Geitafell Central Volcano, Southeast Iceland. Ph. D. Thesis, Grant Institute of Geology, University of Edinburgh, 371 p.

Fridleifsson, G. Ó., 1983b. Mineralogical evolution of a Hydrothermal system. GRC. Trans. Vol. 7. P. 147-152.

Frye, K., 1981. The Encyclopedia of Mineralogy. Pennsylvania, Hutchinson Ross Publishing Company, 794 p.

Hardardóttir, V., 1984. Manual on X-Ray Diffraction and operational techniques for Philips Diffractometer (PW 1130). OS-84098/ JHD - 45B, 19 p.

ICE, 1976a. Proyecto Geotérmico de Guanacaste, Informe de Previabilidad Técnica. Anexo A-Geología, San José, Costa Rica.

ICE, 1976b. Proyecto Geotérmico de Guanacaste, Informe de Previabilidad Técnica. Anexo B-Geoquímica, San José, Costa Rica.

ICE, 1976c. Proyecto Geotérmico de Guanacaste, Informe de Previabilidad Técnica. Anexo C-Geofísica (Resistividad Eléctrica), San José, Costa Rica.

ICE, 1981. Informe Parcial del Proyecto Geotérmico Mediante Resistividad Eléctrica, San José, Costa Rica.

Kerr, P., 1959. Optical Mineralogy. Mc Graw-Hill, New York, 442 p.

Kristmannsdóottir, H. and Tomasson, J., 1978. Zeolites Zones in Geothermal Areas in Iceland, in: Natural Zeolites Occurrence, Properties, Use. Ed. Sandand Mumpton, Pergamon, pp. 277-284.

Kristmannsdóttir, H., 1978. Alteration of Basaltic Rocks by Hydrothermal Activity at 100-300° C. International Clay Conference, Elservier Scientific Publishing Comp., Amsterdam, pp. 359-367.

Mora, O., 1988. Geología de las Piroclastitas en los Alrededores de Bagaces, Provincia de Guanacaste, Costa Rica. Tesis de Licenciatura, Escuela Centroamericana de Geología, Universidad de Costa Rica, San José, Costa Rica.

Palmasson, G., Arnorsson,S., Fridleifsson,I.B., Kristmanns-dottir,H., Saemundsson,K., Stefansson,V., Steingrimsson,B., Tomasson,J. and Kristjansson,L ; 1979. The Icelandic Crust: Evidence from Drillhole Data on Structure and Processes in Deep Drilling Results in the Atlantic Ocean: Ocean Crust (eds. M. Talwani et al., 1979; American Geophysical Union, Washington, Geodynamics project: Scientific report no. 48, p. 43-65.

Selected Powder Diffraction Data for Minerals, 1974. Ed. Berry, L. G. Published by the Joint Committee on Powder Diffraction Standars. Philadelphia, Pa. 833 p.

Steiner, A., 1977. The Wairakei Geothermal Area North Island, New Zeland: Its Surface Geology and Hydrothermal Rock Alteration. New Zeland Geol. Survey, Bull. 90. pp. 42-104.

Whitten, D.G. & Brooks, J. R., 1972. A Dictionary of Geology. Penguin Books Ltd. England. 513 p.
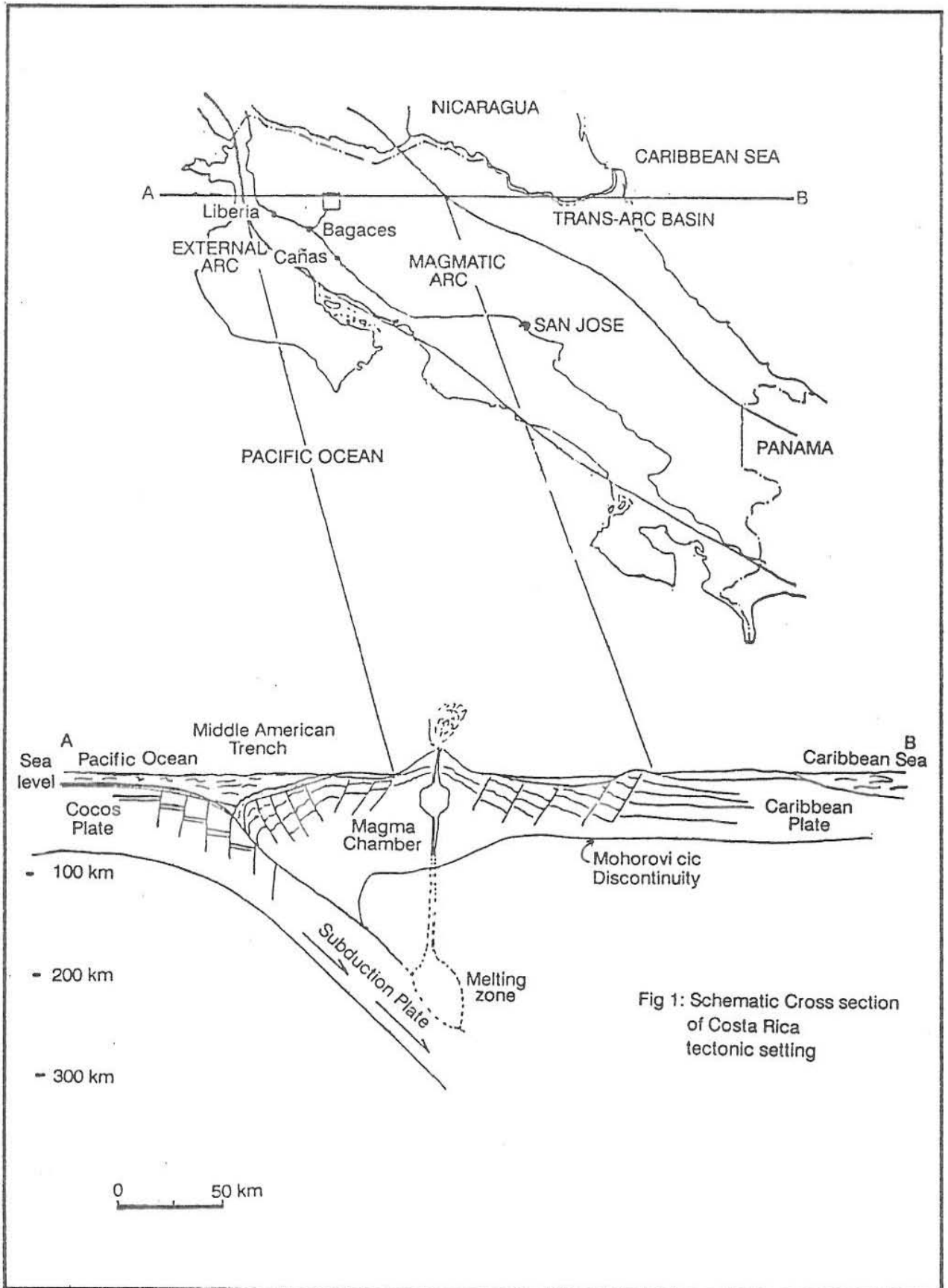
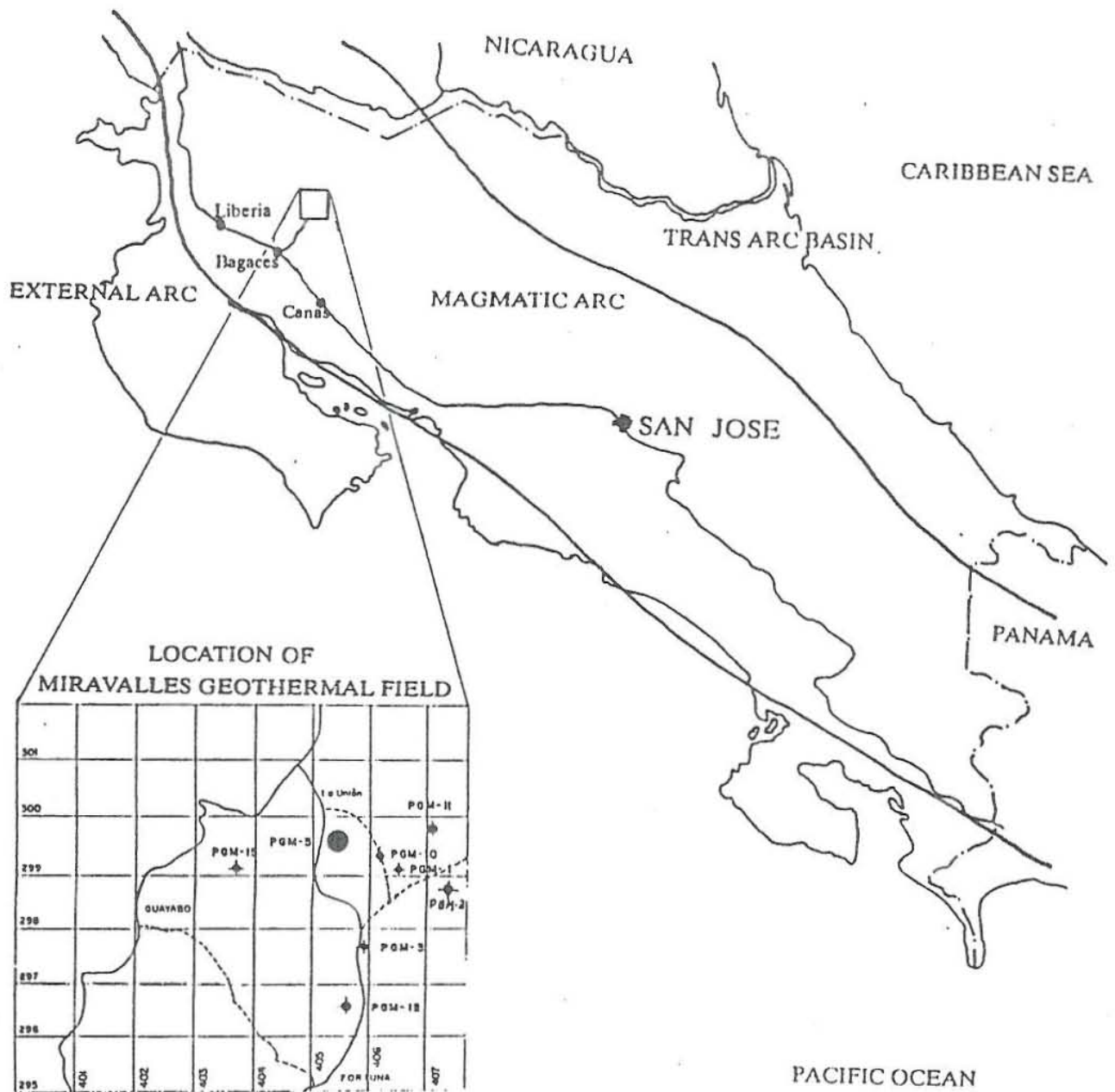Fig 1: Schematic Cross section of Costa Rica tectonic setting

Figure 2: The Miravalles Geothermal Field.
Map location.

FIGURE 3 : SIMPLIFIED GEOLOGICAL MAP OF MIRAVALLES
GEOTHERMAL FIELD AND SURROUNDINGS

LEGEND

- ◆ DEEP WELL DRILLED
- ◇ DEEP WELL PROPOSED
- PRINCIPAL FAULTS
- CALDERA RIM
- CRATER
- PIEDMONT DETRITICAL DEPOSITS
- INTRACALDERA LACUSTRINE SEDIMENTS
- POST-MIRAVALLES LAVA FLOWS
- MIRAVALLES VOLCANO
- LAHARS
- PALEO-MIRAVALLES VOLCANO
- LOS CABALLOS ERUPTIVE CENTER
- CABRO MUCO-LA GIGANTA VOLCANIC COMPLEX
- PYROCLASTIC FLOWS
- PRECALDERA LAVA FLOWS

JHD HSÞ 9000 OMP
89.10.0533 Gyða

41

Fig 4 SURFACE GEOLOGY AND LOCATION OF WELL PGM-5
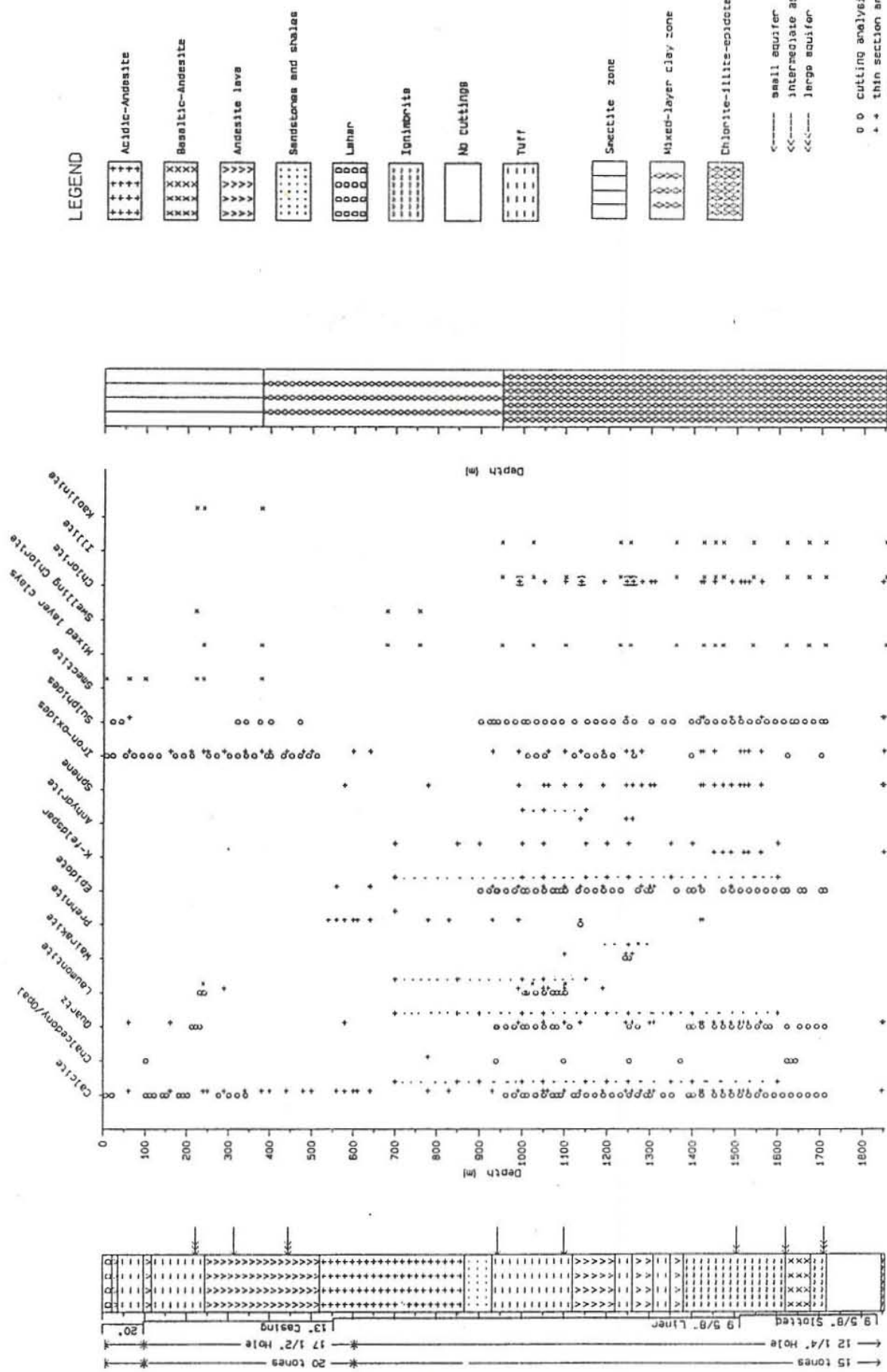
Figure 5: Simplified lithological section of PGM-5 and secondary
mineral distribution
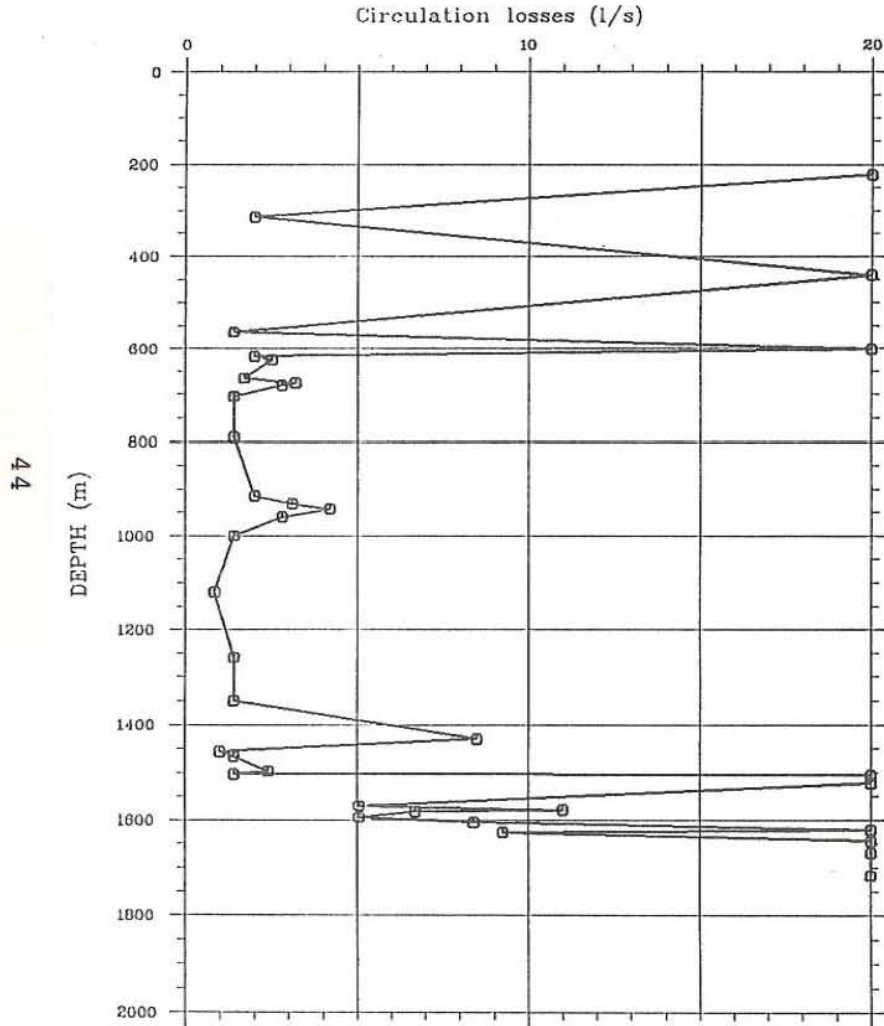
MIRAVALLES GEOTHERMAL PROJECT
WELL PGM – 5

Circulation losses (l/s)

Figure 6a: Circulation losses of PGM-5.

MIRAVALLES GEOTHERMAL PROJECT
WELL PGM – 5

Temperature (°C)

Maximum temperature from mineralogy

Minimum temperature from mineralogy

1 —※— 24 hrs after well completion (84-05-14)

2 —▲— 11 days heating (84-05-20)

3 —⊟— After Blow-test (84-06-07)

4 —▲— Measured 88-02-05

5 —┼— Measured 88-05-05

6 —○— Measured 88-07-13

7 —✳— Measured 88-10-05

8 —⊟— Approximate rock temperaure
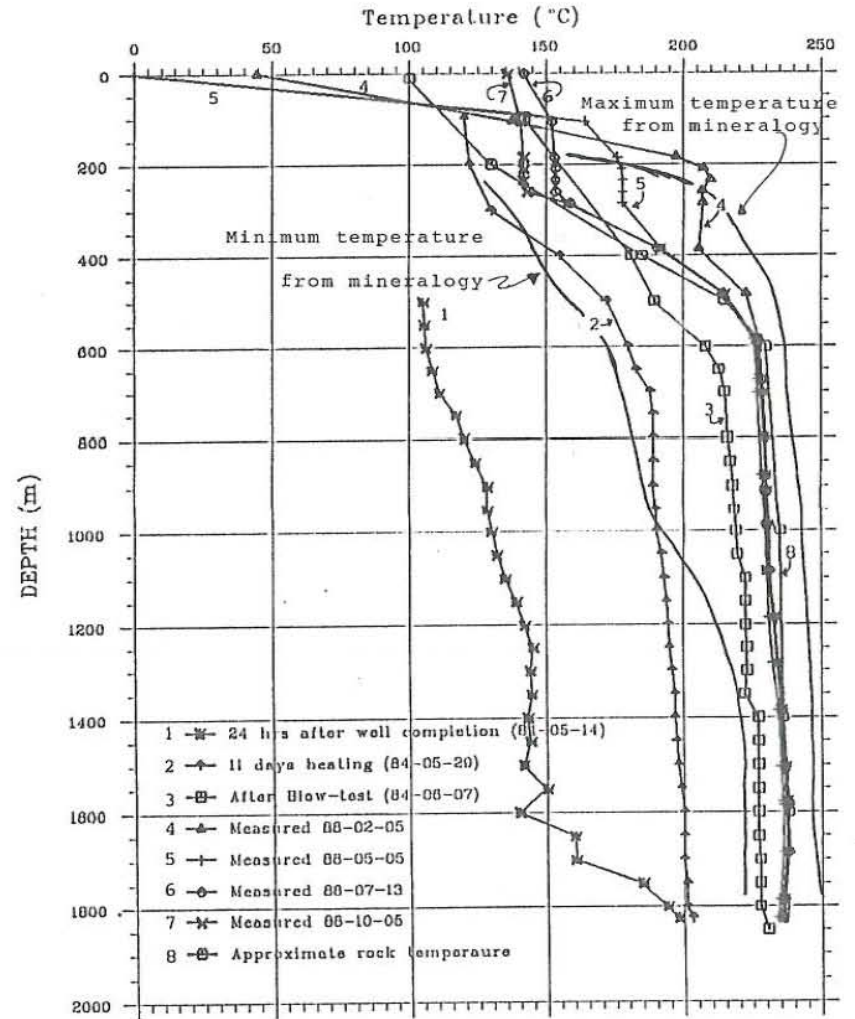
Figure 6b: Temperature profiles of PGM-5 (an estimated rock
temperature is shown in profile no. 8)
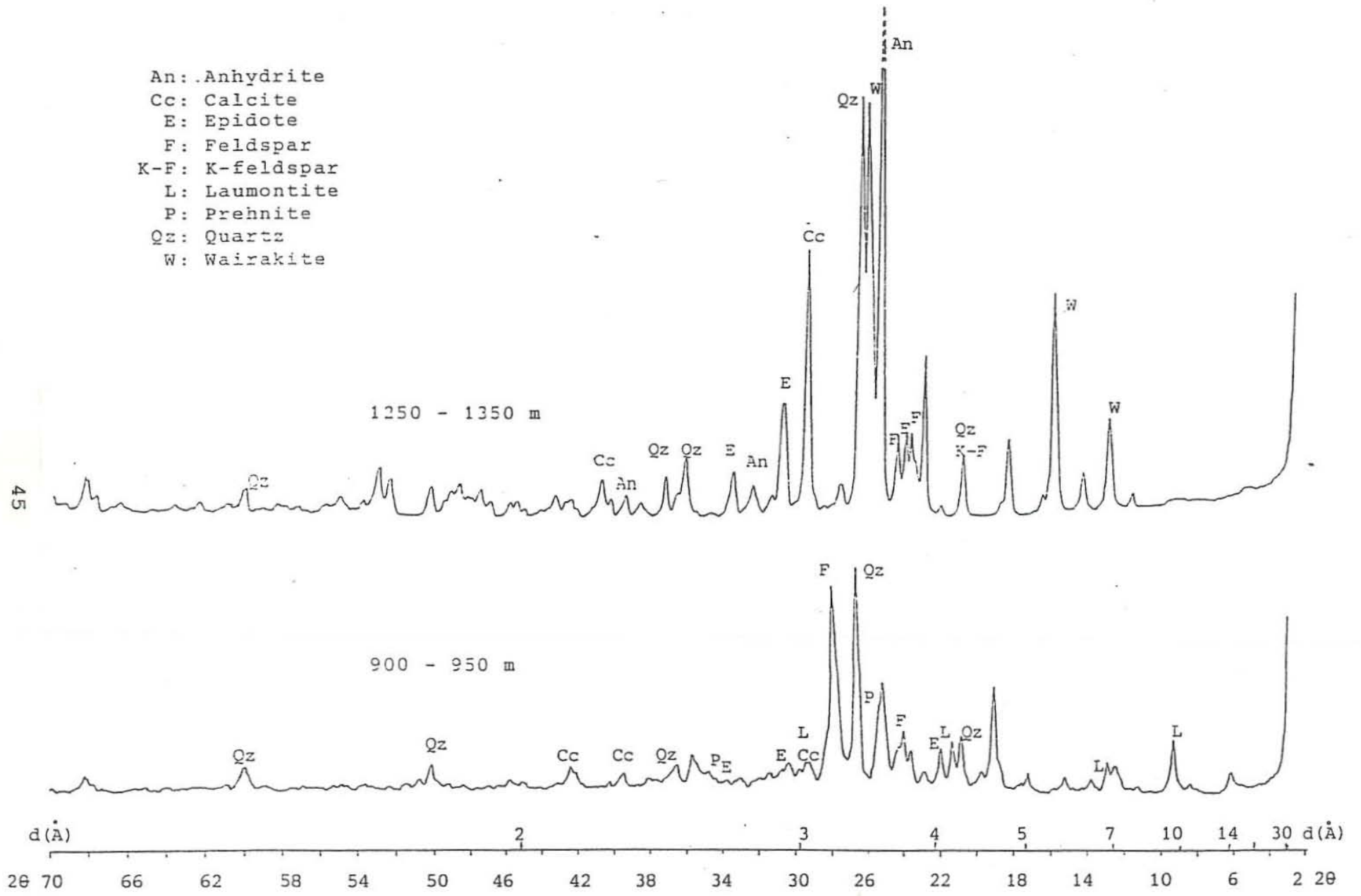
Figure 7: X-ray diffractogram pattern of some minerals.

Sm: Smectite

Il: Illite

a: treated with $CaCl_2$
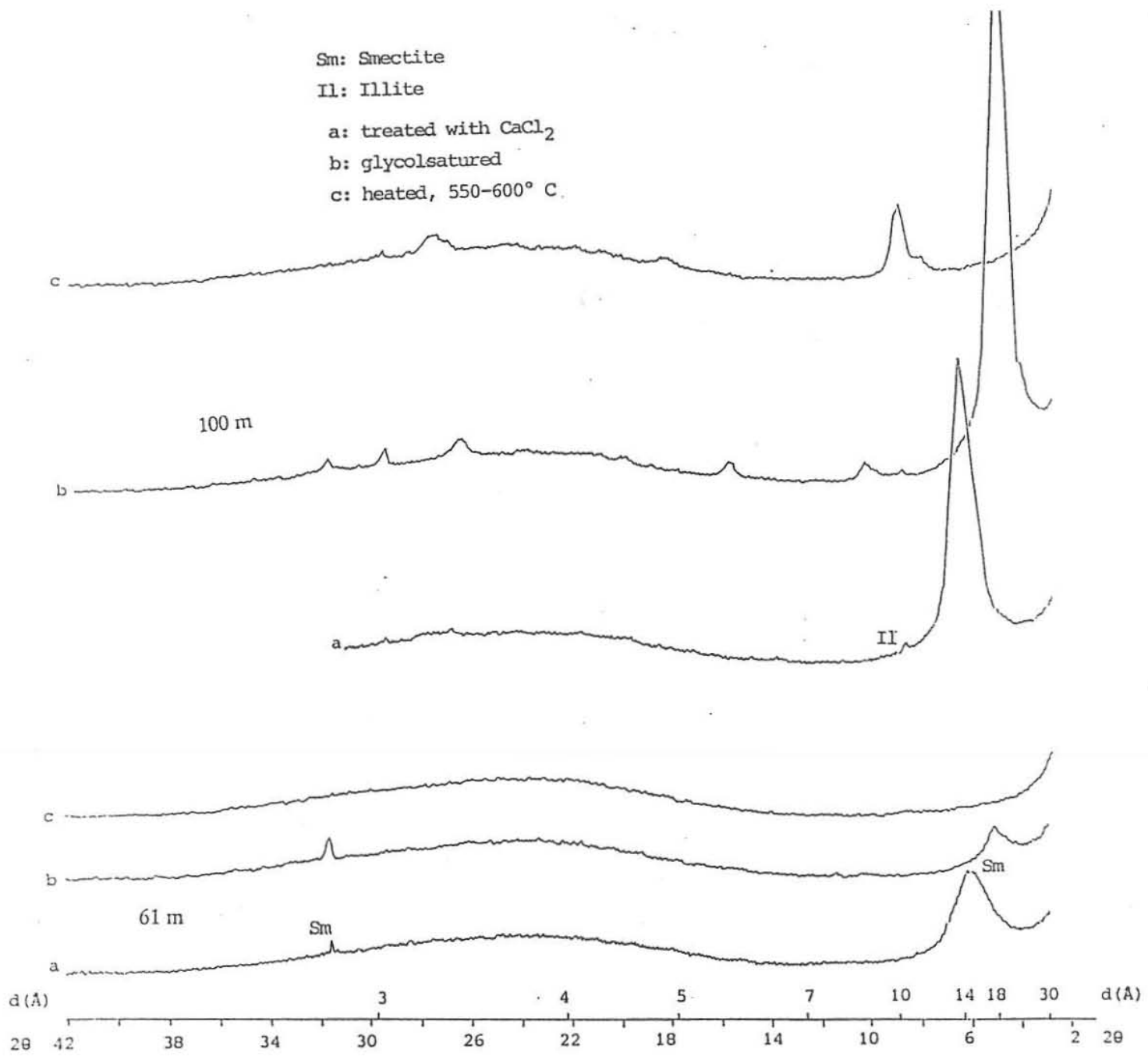
b: glycolsatured

c: heated, 550-600° C

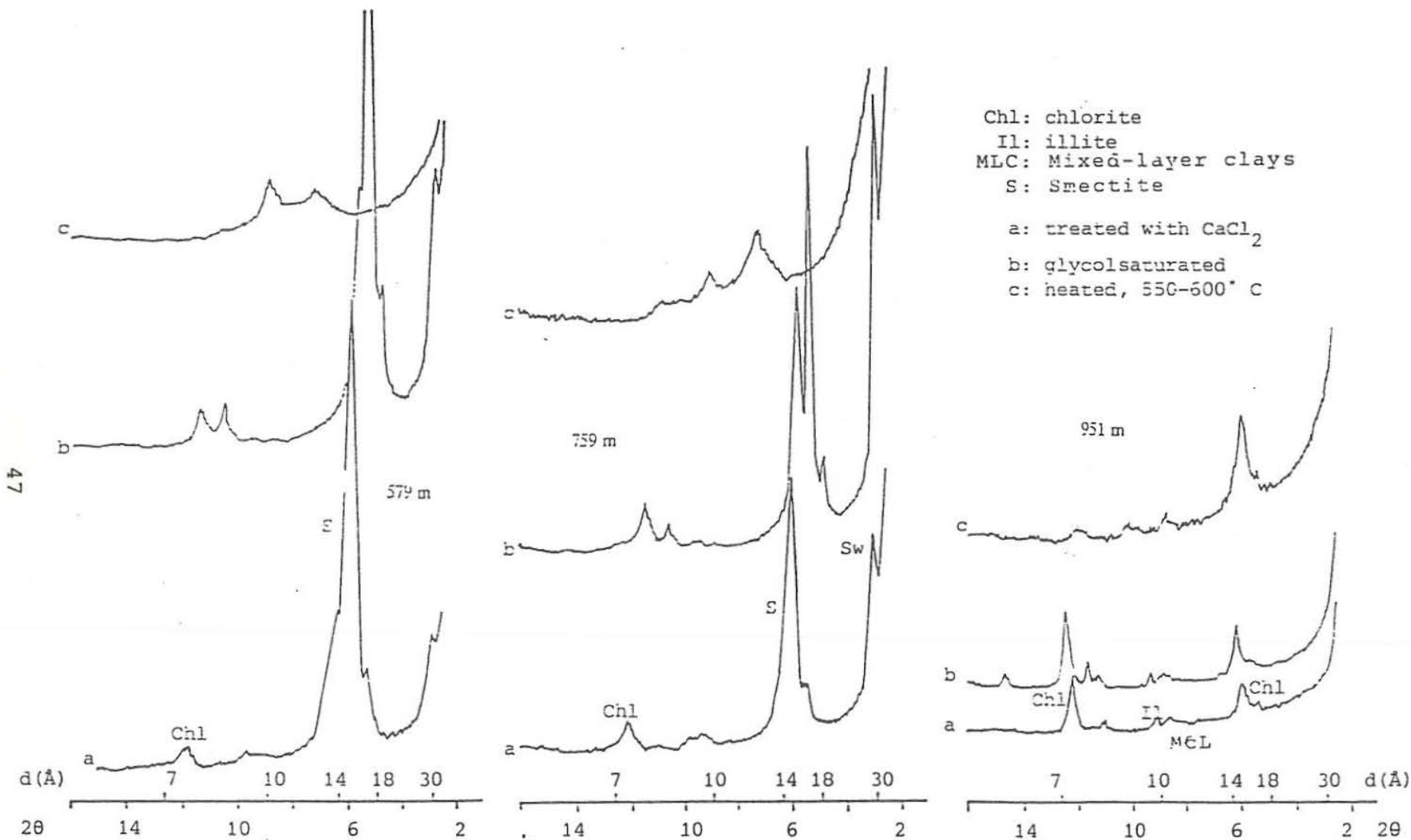Figure 8: X-ray diffractogram pattern of smectite and illite

Figure 9 : X-ray diffractogram pattern of smectite, illite, mixed-layer clays and chlorite.
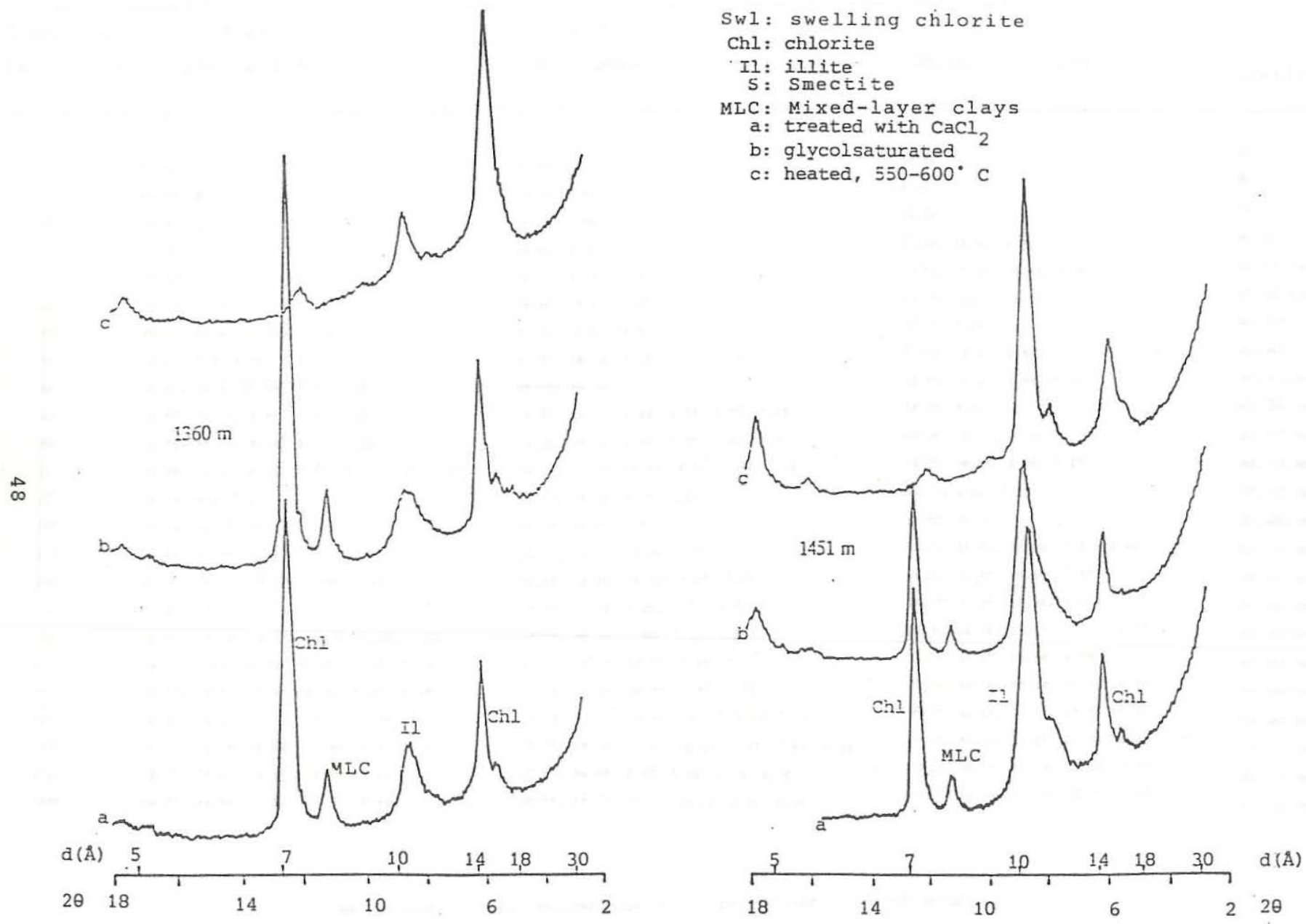
Figure 10: X-ray diffractogran pattern of illite, chlorite and mixed-layer clays.