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OVERPRINTING EVENTS FROM CROSSCUTTING VEINS AND MINERAL ASSEMBLAGES IN ULUBELU GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

The distribution of hydrothermal minerals associated with the Ulubelu geothermal system of Indonesia records several episodes of hydrothermal alteration during the history of the system. X-ray diffraction and petrographic analyses identify six alteration zones composed of characteristic secondary mineral assemblages: smectite; smectite with kaolin; illite/smectite with epidote; epidote with adularia; and chlorite/smectite with epidote and adularia. Four episodes of overprinting are recorded by fluid-inclusion data and crosscutting relationships observed between the various alteration minerals. The first stage is represented by early quartz-bearing veins at depths between 514 and 1195 m with fluid-inclusion homogenisation temperatures of 210° to 230° C. The second stage is characterised by two episodes of prehnite-quartz vein formation with homogenisation temperatures of 240° to 260°C. A third stage is recognized as an argillic-phyllic overprinting between the depths of 600 and 1052 m that may be due to the descent of acidic steam condensate along major faults. The last stage of alteration is dominated by the deposition of young calcite-quartz veins at 893m and 1100m with fluid-inclusion homogenisation temperatures ranging from 200° to 230°C. These relationships record the thermal and chemical evolution of the geothermal system from initial heating to temperatures of 260°C, the formation of clay minerals from acidic fluids, and cooling to present reservoir temperatures (230°C).

1. INTRODUCTION

The Ulubelu geothermal field is located near the southern tip of the island of Sumatra, approximately 100 km northwest of Tanjung Karang, the capital city of the Lampung Province (Fig. 1).

Recent geological investigations in the area include geological (M. Masdjuk, 1991), geochemical (R. Pujianto, 1991) and geophysical surveys (A. Rachman, 1991), and lineament analysis from landsat images (1994). Surficial alteration mapping and descriptions of hydrothermal brecciation in the Ulubelu field have also been conducted (Siahaan, 1997; 1998).

To date three exploration wells have been drilled. All three wells are completed within a high-temperature geothermal reservoir that is capable of commerical production. This paper reviews the alteration mineralogy of rock samples (core and cuttings) retrieved during drilling. The objective has been to determine the physical and chemical conditions responsible for the formation of the alteration minerals. Changes in these conditions through time are used to evaluate the evolution of the geothermal system.

About 60 core samples from the wells were examined petrographically and analyzed by X-ray diffraction (bulk XRD and clay fraction). Fluid-inclusion homogenisation and ice-melting temperatures were also measured on selected vein samples.

2. GEOLOGIC SETTING OF ULUBELU FIELD

The Ulubelu field lies in the Bukit Barisan mountain range at the southeastern tip of Sumatra. The field is located within a volcanic depression that is surrounded by the Tertiary volcanoes of Gunung Sula (1440 masl) to the east, Gunung Rendingan (1770 masl) to the north, and Gunung Tanggamus (2104 masl) to the south (Fig. 1).

The lithology in the bottom part of the wells consists of andesitic lava of Gulan Kukusan and Gulan Sula, and dacite of Gulan Duduk. In the upper part of the wells, the rocks are composed of tuff and andesitic lava of Gulan Rindingan and pyroclastic deposits from Gulan Kabawok.

Surficial thermal manifestations are indicated by the presence of fumaroles, mud pools, and steam-heated water which are controlled by a NW-SE graben inside the semi-circular depression (Fig. 1).

The island of Sumatra was formed by the subduction and collision between the Indo-Australian and Eurasian plates during the Plio-Pleistocene. The oblique convergence of these plates formed the Sumatra fault system with dextral strike-slip displacement, which extends for 1600 km along the volcanic chain of western Sumatra. The presence of the volcanoes, as well as the thermal manifestations, are associated with the Semangko transform segment along the volcanic arc. The southern end of Sumatra is crossed by the Semangko fault where it changes from a right-lateral strike-slip fault to a normal fault with downthrow into the Semangko Bay.

3. HYDROTHERMAL ALTERATION

3.1 Distribution and Zonation of Hydrothermal Minerals

The secondary minerals found in the Ulubelu geothermal system are typical of alteration minerals found in high-temperature, neutral-pH geothermal systems. Whereas the clay minerals, smectite and kaolin, are dominant at the top of reservoir, silicate minerals such as quartz, adularia, epidote, prehnite, laumontite, albite, and cristobalite, as well as pyrite and titanite are common deeper within the reservoir (Fig. 2). Hematite and halloysite are present along the surface and at shallow depths within the wells.

Secondary quartz occurs at all depths but is most abundant deeper in the geothermal reservoir. Quartz veins are present between the depths of 514m and 1195m in well UBL-1. The abundance of quartz veins increases with increasing depth to about 1095m, where 2 mm long, euhedral crystals are present. Epidote first occurs as a replacement of plagioclase and pyroxene at 529m, and is deposited in veins at 571 to 1177m depths. In the veins, epidote occurs with laumontite at 571m, with wairakite and adularia at 618m, and with prehnite at 1097m depth. Adularia at 618m appears to be partially sericitized and replaced by illite. Illite is present from 618m to 1195m. At 813m depth, adularia occurs both as a replacement of plagioclase and as a vein mineral. Prehnite is present in veins from 850m to 1195m (total depth of well UBL-1). Albite replacement of plagioclase (andesine) is common at all depths. Laumontite is first found at 650m and reoccurs at 1097m, where it is associated with prehnite and quartz. Chlorite occurs from 45m to the total depth as a replacement of plagioclase, pyroxene, volcanic glass and tuffaceous material. Titanite occurs from 400m to 800m as disseminated, anhedral crystals, sometimes together with pyrite.

XRD analyses of clay samples from well UBL-1 indicate that there is not a systematic decrease in the amount of smectite in the mixed-layer clays with increasing depth and/or temperature in the well. Mixed-layer illite-smectite (I/S) contains between 5 and 35% smectite interlayers at depths between 450m and the total depth of 1195m. Mixed-layer chlorite-smectite is also present.

The distribution and association of hydrothermal minerals in the well UBL-1 can be divided into six zones (Figs. 2 and 3):

The smectite zone is present in the shallowest part of the well, from the surface to 108 m, and from 417 m to 487 m depths. Other minerals that are present in this zone include chlorite, quartz, pyrite and hematite. Halloysite and cristobalite are present to about 100m. Measured temperatures in this zone are between 30° and 200°C, and are generally in agreement with the stability temperatures of smectite and cristobalite (<180°C; Browne, 1997).

The smectite-kaolin zone is encountered from 159 m to 360 m. Minor amounts of kaolin are also found at 650m, 750m and 1052 m depths. Measured temperatures in the shallow kaolinitic zone are between 75° and 200°C.

The illite/smectite-epidote zone is situated from 450m to 618 m, and between the depths of 650m and 780m. Some minerals associated within this zone are chlorite, albite, calcite, quartz, laumontite, and wairakite. The clay minerals consist of mixed layer illite-smectite with an illite content between 70 and 95% (001 at 9.48 – 9.97Å). These illite-smectite clays likely formed at temperatures between 200 and 220°C (Browne, 1997). Measured temperatures in this zone are between 190°C to 210°C, consistent with the formation of the I/S clays but slightly lower than temperatures that would be expected from epidote-wairakite mineral assemblages (generally above about 240°C; Bird et al., 1984; Browne, 1997).

The epidote-adularia zone is distinguished by the absence of illite and occurs in two intervals, between 618 and 650m and between 780 and 870m. Associated minerals include chlorite, quartz, albite, laumontite and prehnite. Measured temperatures in this zone are lower than the formation temperature of epidote, but are consistent with the formation temperature of laumontite (below 210°C; Browne, 1997).

The chlorite/smectite-epidote-adularia zone extends from 893 m to 1177 m where the measured temperatures are about 210°C to 230°C. No illite is present in this zone. The portion of interlayered chlorite in mixed-layer chlorite-smectite is about 90%. Associated minerals include quartz, calcite, prehnite, kaolin, and anhydrite.

The illite/smectite-adularia zone occurs at the bottom of the well at 1195m depth. From the XRD analyses, the mixed-layer illite-smectite contains about 65% illite interlayers (with a basal reflection at 9.28Å). Prehnite, calcite and quartz are also present. The measured temperature in this zone is approximately 230°C.

4. FLUID INCLUSION GEOTHERMOMETRY

4.1 Data and Interpretation of Homogenisation Temperatures

Fluid inclusions are samples of fluids (liquid and/or vapor) trapped in minerals during or following formation of the mineral (Roedder, 1984). Analysis of fluid inclusions provides useful information about the temperature and chemical composition of fluids in geothermal environments.

At Ulubelu, four vein samples from well UBL-1 were studied using fluid-inclusion geothermometry. The samples represent a variety of crosscutting vein assemblages and are dominated by quartz and calcite.

The vein samples include (Figs. 3 and 4):

- a quartz vein cut by calcite-quartz at 893m;
- a prehnite-quartz vein cut by another prehnite-quartz vein at 1052m;
- a quartz-prehnite vein cut by calcite-quartz at 1097m;
- and euhedral crystals of quartz from a quartz vein at 1096 m.

In general, the width of the veins increases with increasing depth in the drillhole; e.g. at depths from 531 m to 950 m, the size is from 1 mm to 3 mm wide, and from 950 m to 1195 m depth the size varies from 2 mm to 7 mm wide.

All the fluid inclusions analysed were two-phase, liquid-rich inclusions with variable vapor contents (30 to 70%). Most of the fluid inclusions appear to have been primary (that formed during initial crystal growth). These inclusions are between 4 and 15 µm long and 2 to 6 µm wide.

<u>Veins from 893 m</u>
Veins of early quartz are cut by younger calcite-quartz veins at 893 m. The homogenisation temperatures of the early quartz and the later calcite-quartz are between 210°C to 220°C, and 220°C to 230°C, respectively. The average temperature of homogenisation (Th) of fluid inclusions from the late calcite-quartz vein are about the same as the present measured temperature at this depth in the well. The Ths show that fluid temperatures may have increased by about 10°C between the deposition of the early quartz veins and present-day conditions.

<u>Veins from 1052 m</u>
Veins of earlier prehnite-quartz are cut by later prehnite-quartz veins at 1052m depth. The fluid-inclusion homogenisation temperatures for these veins are between

240°C to 250°C, and 250°C to 260°C, respectively. The Ths for all these prehnite-quartz veins are much higher than the present-day measured temperature of 230°C. Hence, the prehnite-quartz veins may have formed during an earlier and hotter period in the history of the geothermal system.

Veins from 1097 m

Veins of prehnite-quartz are cut by later calcite-quartz veins at 1097 m depth. The homogenisation temperatures of these vein assemblages vary between 240°C to 250°C, and 200°C to 210°C, respectively. The differences in the homogenisation temperatures indicate that there has been a cooling of the geothermal system. Average Ths for the late calcite-quartz veins are about the same as the present measured temperature. This implies that the fluid inclusions in the calcite veins may represent modern geochemical conditions in the Ulubelu geothermal system.

Homogenisation temperatures from a euhedral quartz crystal at 1096m also range from 200° to 210°C. This quartz vein could also have formed under the present conditions.

Ice-melting temperatures of fluid inclusions in the calcite vein from 1097m vary from -0.7° to 1.5°C, with the majority melting between –1° and –0.5°C. Apparent salinities of the fluids trapped in these inclusions range from 0.9 to 1.8 weight % NaCl equivalent. These low salinity values are typical of geothermal fluids with a meteoric origin.

5. DISCUSSION

5.1 Overprinting Alteration Assemblages

Textural and chemical characteristics of the vein and alteration assemblages are used to determine the thermal and geochemical evolution of the Ulubelu hydrothermal system. Changes in the thermal regime and/or in fluid compositions during different alteration episodes resulted in the overprinting of younger assemblages upon older assemblages. Distinct alteration episodes can be recognized using the following methods (Browne, 1997):

- clay mineralogy- older systems produce coarser clay minerals than the present geothermal system;
- petrography- young veins crosscut older veins and older veins are commonly more crystalline; and
- fluid inclusion geothermometry- systematic changes both laterally and with depth, and in comparison to present measured temperatures.

The distribution of the clay and alteration minerals, and analysis of mineral geothermometers also provides information about the history of alteration. Aspects of the vein mineralization that are especially important include the:

- position of the vein relative to other veins;
- dip of the vein- horizontal or vertical orientation;
- size of the vein;
- distribution of the vein minerals with depth; and,
- the paragenetic sequence of minerals in the veins.

5.2 Stages of Alteration Activity

At least four stages of overprinting are recorded in cores from the Ulubelu wells (Figures 2, 3 and 4):

Stage-1: Early Quartz Veins

Quartz veins are present from 514 to 1195 m. Between 514 and 601 m, strong quartz veining occurs in the illite/smectite-epidote zone. The quartz veins commonly have dips ranging from 45° to 90° and widths of about 1 mm to 2.5 mm. At 514 m, two quartz veins occur perpendicular to each other.

The first occurrence of epidote corresponds with the mixed-layer illite-smectite zone, where the amount of interlayered illite (70 to 90%) suggests formation at temperatures between 200° and 220°C. At these depths, epidote appears to have formed as incipient epidote, at the low end of its thermal stability field.

Early quartz and epidote also occur between the depths of 700 and 1195 m. In this depth interval, homogenisation temperatures of fluid inclusions in quartz range from 210° to 230°C. To summarize, the illite-smectite clay alteration, quartz veining, and weak epidote wallrock alteration all appear to have formed early in the history of the geothermal system at fluid temperatures between 210° and 230°C.

Stage-2: Prehnite-Quartz Veins

Prehnite-quartz veins occur in intensively fractured rock between the depths of 850 and 1195 m. The veins increase in size from 2-3 mm at 850 m, to 2-7 mm at 1149m depth. The dips of the fractures range from 45° to 90° and many of these fractures are partially open.

At 1052 m, prehnite-quartz vein-B cuts the prehnite-quartz vein-A at right angles. The homogenisation temperatures of fluid inclusions in quartz from vein-A are 250° to 260°C, and in vein-B, 240° to 250°C, suggesting a slight temperature decrease between the formation of these two veins.

The prehnite-quartz veins occur in the epidote-adularia and chlorite/smectite-epidote-adularia zones. Fracturing and veining is most intense at the contacts with relatively fresh andesite dikes at 950 m and 1149 to 1166 m. These dikes and sills are interpreted as intrusions associated with Gulan Kukusan that has been dated at 3.95 mya.

Stage-3: Argillic Overprint

Argillic overprinting is recorded at 650, 750 and 1052m depths by the presence of kaolin, quartz, calcite, anhydrite, interlayered illite-smectite and chlorite. The argillic overprint formed after the prehnite-quartz veining and is interpreted to be due to the descent of acidic steam condensate from shallow levels (i.e., the smectite-kaolin zone) along open fractures and major faults into deeper portions of the reservoir.

Stage-4: Calcite-Quartz Veins

Young calcite veins occur at 650, 706, 893, and 1097m depths. The widths of the calcite veins vary from 1 to 2 mm and the veins dip about 60 to 70°.

Calcite-quartz veins clearly cut prehnite-quartz veins at the depth of 893m. Fluid-inclusion homogenisation temperatures in the vein calcite are in the 220° to 230°C range, whereas the quartz in the prehnite veins have warmer Ths of 240° to 250°C. This calcite overprinting of prehnite veins is recognized in the depth interval from 600 to 1097m.

At 1097m, fluids trapped in young calcite veins have apparent salinities of 0.9 to 1.8 weight % NaCl equivalent and homogenisation temperatures from 200° to 230°C. Because present measured temperatures (Kuster data, Figs. 4 and 5) are also in this range, the deposition of these Stage 4 calcite-quartz veins is interpreted to represent modern reservoir conditions. The low salinities suggest that the geothermal fluids consist of heated meteoric water. The mineralogy of the intergrown calcite-quartz veins reflects boiling in the geothermal reservoir and the release of CO_2 gas.

CONCLUSIONS

The location of the Ulubelu geothermal field is structurally controlled at the intersection of a volcano-tectonic depression with two major NW-SE and NNE-SSW lineaments that are associated with the Semangko fault system.

Four stages of hydrothermal alteration can recognized based on crosscutting mineral relationships, clay zoning, and fluid-inclusion analyses: early quartz veining (stage 1), prehnite-quartz veining (stage 2), argillic overprinting (stage 3), and young calcite-quartz veining (stage 4).

Fluid-inclusion homogenisation temperatures of crosscutting veins indicate the thermal evolution of the Ulubelu geothermal system, starting with the initial heating of the system (stage-1 to stage-2 alteration), followed by cooling (from stage-2 to stage-4) to present reservoir conditions (Figs. 4 and 5). The cooling trend from stage-2 (temperatures up to 260°C) to stage-4 (temperatures about 230°C) may have been of a long duration, possibly from 3.95 mya to the present day (Fig. 5).

Despite the episodic nature of the alteration, most of the secondary minerals were deposited in a relatively narrow temperature range (200° to 260°C). Most of the overprinting mineralization also occurred under neutral pH fluid conditions, except for during the argillic stage when slightly acidic fluids must have been present.

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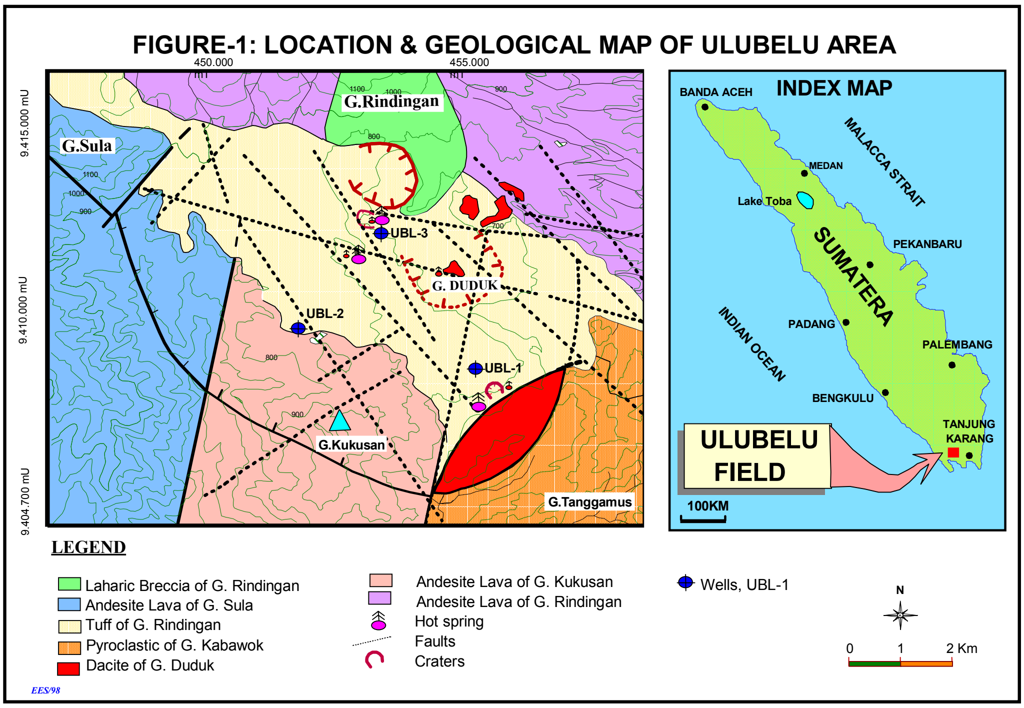
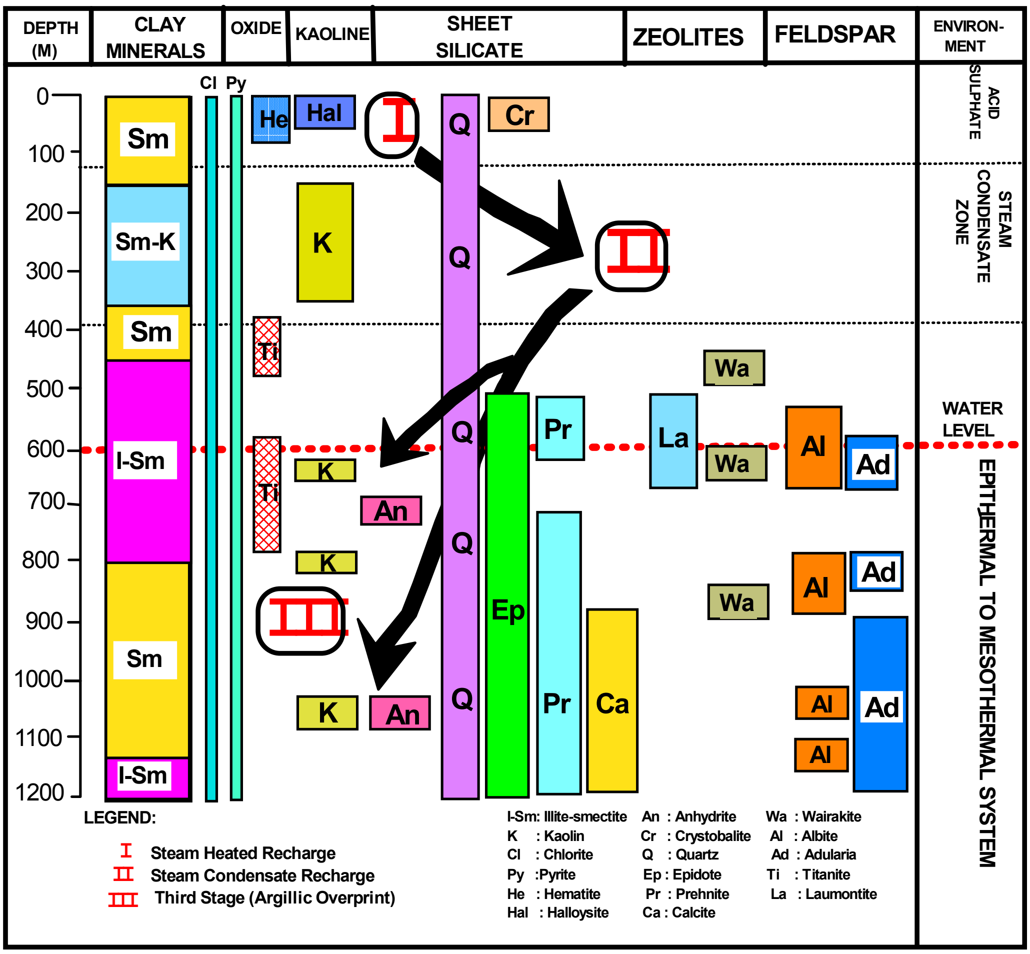


FIGURE-1: LOCATION & GEOLOGICAL MAP OF ULUBELU AREA

FIGURE-2: ALTERATION MINERALOGY AND OVERPRINTING STAGES IN ULUBELU FIELD



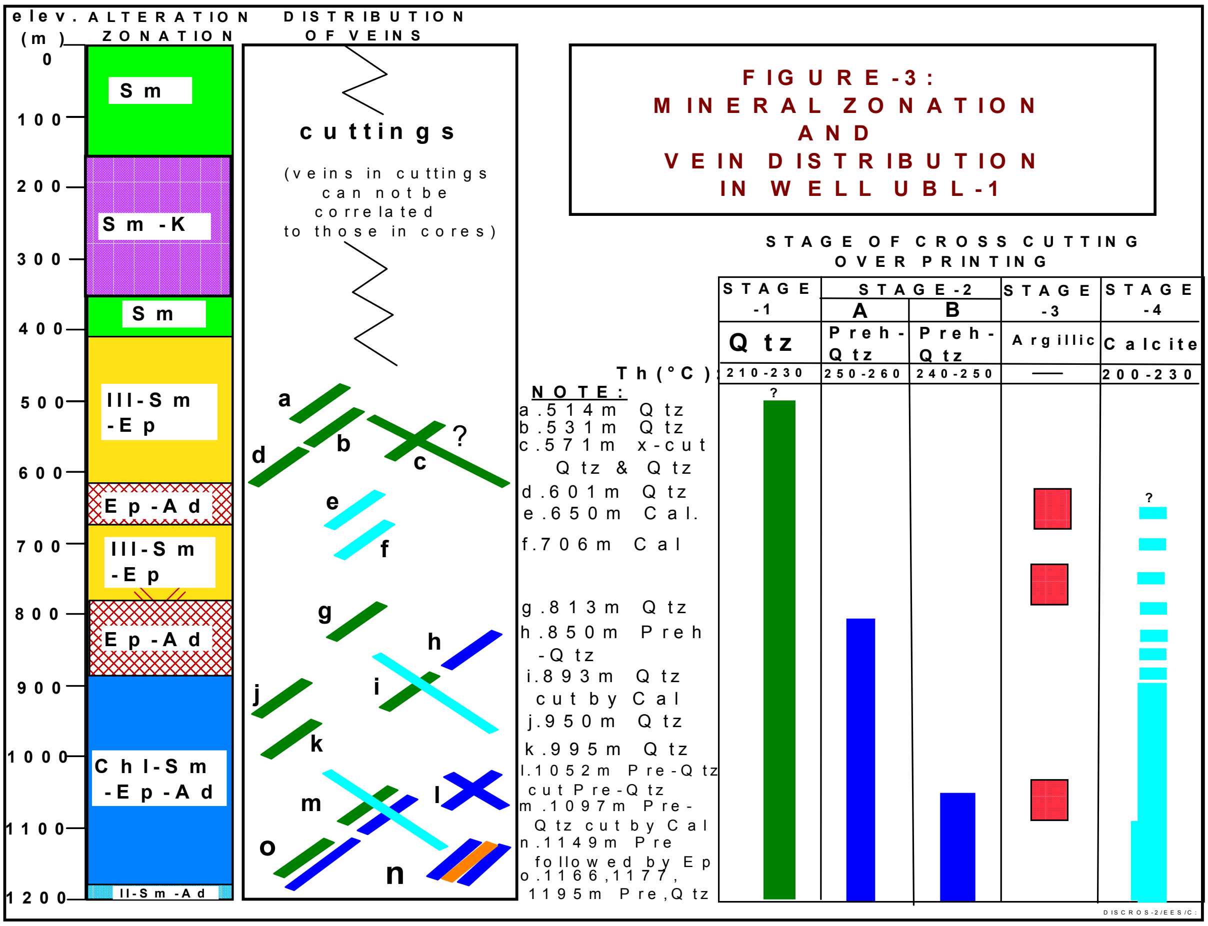


FIGURE-3:
MINERAL ZONATION
AND
VEIN DISTRIBUTION
IN WELL UBL-1
elev. (m)
ALTERATION ZONATION
DISTRIBUTION OF VEINS
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Sm
Sm-K
Sm
III-Sm -Ep
Ep-Ad
III-Sm -Ep
Ep-Ad
Chl-Sm -Ep-Ad
II-Sm-Ad
cuttings
(veins in cuttings can not be correlated to those in cores)
a
b
c
d
?
e
f
g
h
i
j
k
l
m
n
o
Th(°C)
NOTE:
a.514m Qtz
b.531m Qtz
c.571m x-cut Qtz & Qtz
d.601m Qtz
e.650m Cal.
f.706m Cal
g.813m Qtz
h.850m Preh -Qtz
i.893m Qtz cut by Cal
j.950m Qtz
k.995m Qtz
l.1052m Pre-Qtz cut Pre-Qtz
m.1097m Pre-Qtz cut by Cal
n.1149m Pre followed by Ep
o.1166,1177, 1195m Pre,Qtz
STAGE OF CROSS CUTTING OVER PRINTING
STAGE -1
STAGE-2
STAGE -3
STAGE -4
A
B
Qtz
Preh-Qtz
Preh-Qtz
Argillic
Calcite
210-230
250-260
240-250
—
200-230
?
?
DISCROS-2/EES/C

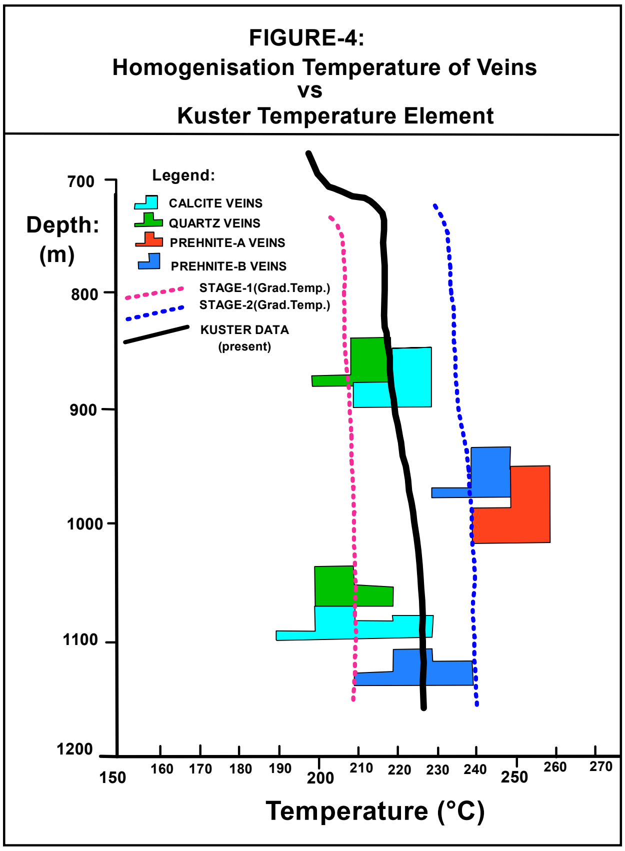


FIGURE-4:
Homogenisation Temperature of Veins
vs
Kuster Temperature Element
Depth: (m)
700
800
900
1000
1100
1200
Legend:
CALCITE VEINS
QUARTZ VEINS
PREHNITE-A VEINS
PREHNITE-B VEINS
STAGE-1(Grad.Temp.)
STAGE-2(Grad.Temp.)
KUSTER DATA (present)
150
160
170
180
190
200
210
220
230
240
250
260
270
Temperature (°C)

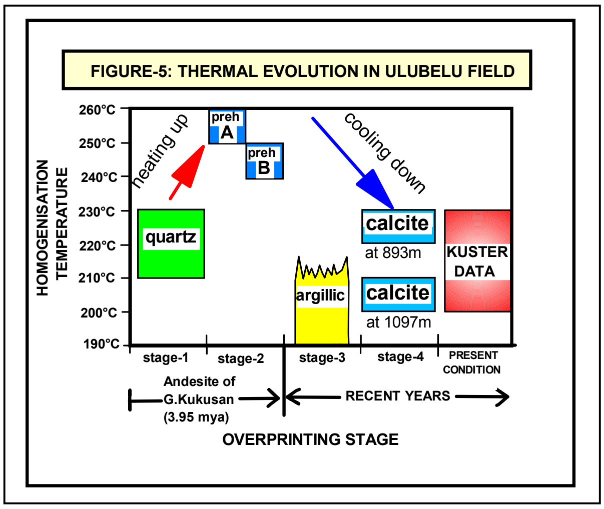


FIGURE-5: THERMAL EVOLUTION IN ULUBELU FIELD
HOMOGENISATION TEMPERATURE
260°C
250°C
240°C
230°C
220°C
210°C
200°C
190°C
heating up
cooling down
preh A
preh B
quartz
argillic
calcite
at 893m
calcite
at 1097m
KUSTER DATA
stage-1
stage-2
stage-3
stage-4
PRESENT CONDITION
Andesite of G.Kukusan (3.95 mya)
RECENT YEARS
OVERPRINTING STAGE