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Epithermal Mineral Zonation in An Active Island Arc: The Bacon-Manito Geothermal Systems, Philippines.

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ABSTRACT

The Bacon-Manito geothermal field exhibits chemical zonation of thermal features that is typical of island arc andesite hydrothermal systems. Zonation of hydrothermal minerals in the vadose zone in the production wells reflects this chemical distribution of surface fluids. The interface between the vadose zone and the chloride reservoir fluids is marked by distinct changes in hydrothermal minerals: the influx of anhydrite and calcite, and the transition of kaolinite to chlorite and cristobalite to quartz. The hydrothermal mineralogy and fluid inclusion data indicates that the epithermal region of the eastern sector of Bac-Maw approximated "boiling point with depth" conditions in the past. Cooling of the system and downward percolation of cool acid sulphate and neutral sulphate-bicarbonate fluids from the vadose zone into the hot chloride reservoir has caused precipitation of quartz, anhydrite and calcite in fractures, and produced a 800m sealed cap on a neutral chloride reservoir, locally trapping two phase, gas rich pockets.

INTRODUCTION

The Bacon-Manito (Bac-Man) geothermal field is situated along the active Bicol Island arc volcanic chain in the southern portion of the island of Luzon (Fig. 1). This line of recent and active composite andesite eruptive centers is postulated , (Ancharya and Aggarwal 1980), to be a product of the westward subduction of the Philippine Sea Plate along the Philippine Trench. The Bac-Man Project lies between the two active volcanoes Mt. Bulusan 30 km. to the south-east and the majestic Mt. Mayon 30 km. to the north-west.

The Bac-Man project covers an area of almost 300 km.^{2} over which 23 exploration, delineation, production and reinjection wells have been drilled in the highland region, and three in the northern Manito lowlands (Fig. 2). The project area is rugged, the older western sector being highly eroded and the younger eastern sector capped by recent basic andesite cones and collapse features (Lawless et al. 1983). The most prominent of these features are the basaltic andesite cones of Mt. Pangas (1076m elevation) and Mt. Pulog. The current geothermal systems is probably heated by the intrusive equivalents of these basic to intermediate volcanics.

Bac-Man is currently under exploitation by the Philippine National Oil Company (PNOC) for a first stage 110MWe electricity generation development. Eleven production wells (Pal-2D to-4D, and-6D to-13D) have been completed to vertical depths of 1.5-3.0 km., horizontal throws of up to 1.5km. and 75-80MWe output. Four reinjection wells (Pal-XRD to-4RD) have been completed to depths of 1.5-2.0 km. and throws of 1.0km. These wells have penetrated predominantly intercalated andesite to basaltic lavas and pyroclastics with minor volcaniclastic and calcareous sediments and intermediate to basic intrusives.

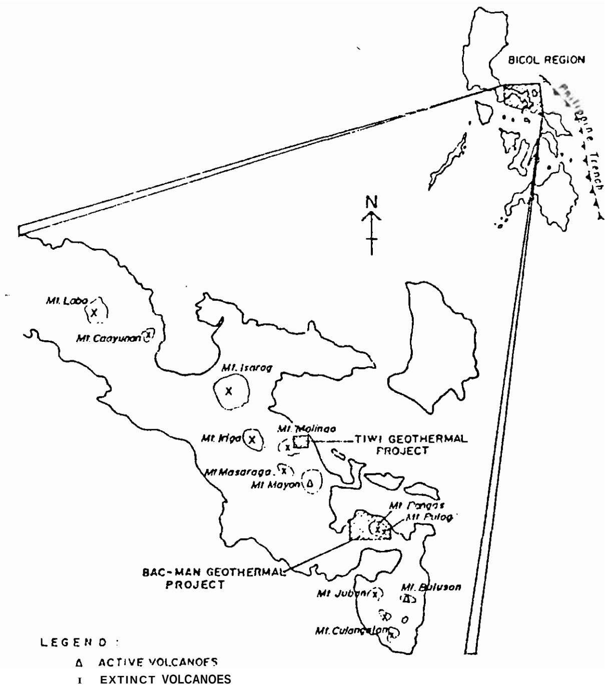


Fig. 1 LOCATION OF THE BAC-MAN GEOTHERMAL **FIELD** WITHIN THE BICOL VOLCANIC **CHAIN.**

0 10 20 30 40 50 Km.
GRAPHIC SCALE

Over the past few years drill cuttings from both production and reinjection wells have been petrographically analysed every 5-10 meters. Since many wells have been drilled with water below about 1000m rsl (relative to sea level), this detailed analysis has been restricted to the epithermal (0-1.5km., ambient-250°C) environment of this geothermal system. This paper outlines the zonation of alteration mineralogy observed at shallow levels in Bac-Man, which reflects the epithermal hydrology in an island arc geothermal setting.

Distribution of Thermal Features

In the steep undulating terrain of an island arc geothermal system the chloride reservoir water level is usually deep (Henley and Ellis 1983) resulting in an extensive vadose zone. Within this vadose zone at Bac-Man there is a zonation of thermal features at various elevations above the outflow of reservoir chloride fluids (Fig. 2 and Fig. 3) typical of an andesite island arc volcano (Barnett et al. 1984) and which may be summarized as follows:

(i) Solfatara-Mt. Pangas (900-1000m rsl)

(ii) Acid SO_4^2 springs-Cawayan, Puting Bato, Damoy and Inang Maharang (300-700m rsl)

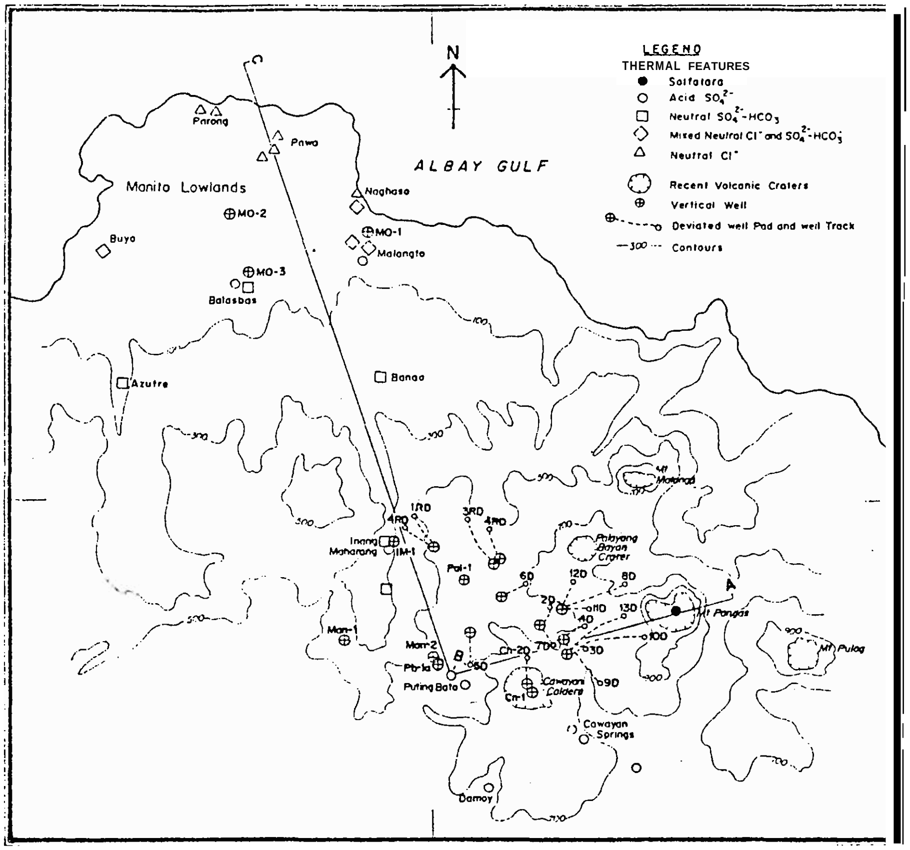


Fig. 2 LOCATION OF THERMAL FEATURES & WELL TRACKS
BACON-MANITO GEOTHERMAL PROJECT

1 .5 0 1 2 3KM
GRAPHIC SCALE

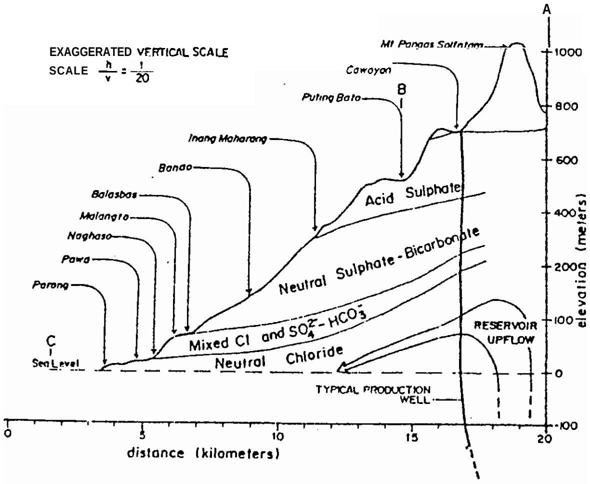


Fig. 3 CROSS SECTION A-B-C ILLUSTRATING VERTICAL DISTRIBUTION OF THERMAL FEATURES.

(iii) Neutral SO_4^{2} - HCO_3- Bicarbonate springs- Inang Maharang, Banao, Azufre Balasbas and Malangto (70-300m rsl)

(iv) Mixed SO_4^{2}- HCO_3^- and Cl^- - springs-Buyo, Malangto and Naghaso (20-70m rsl)

(v) Neutral Reservoir Chloride springs-Parong, Pawa and Naghaso (sub-tidal to 20m rsl)

The acid sulphate springs at Balasbas and Malangto are anomalous in this zonation.

Hydrothermal Mineralogy

The distribution and relative abundances of some significant hydrothermal minerals down to -1000m rsl in Pal 13D, a "typical" Bac-Man production well is illustrated in Fig. 4. There are minor inconsistencies in this distribution within these wells and significant variations in wells outside the area penetrated by these wells.

(i) Mineralogy - Surface to 200m rsl

The changes in alteration mineralogy with depth closely reflect the zonation observed in the chemistry of the surface thermal features:

(a) Surface to 600m rsl is a zone of fresh to very weakly altered pyroclastics and lavas. The alteration minerals are predominantly smectite and hematite which are probably weathering products.

(b) 400 to 700m rsl defines the elevation range within which acid alteration assemblages of Alunite (Al) + Kaolinite (K) + Cristobalite (Cr) ± Tridymite (Tr) ± Opal(O) ± Smectite (Sm) ± Quartz (Q) is encountered (400-500 m rsl in the "typical" well). This corresponds to the elevation range of acid sulphate springs at 300-600m rsl (Fig. 3) These high level acidic zones do not have extensive horizontal distribution and are therefore interpreted to be restricted to fracture zones. Similar alunite + kaolinite bearing fracture zones are observed at the surface at 700m rsl in the Cawayan area.

This acidic mineralogy is interpreted to have been produced from rock leaching by sulphuric acid formed by oxidation of H_2S which has risen up fracture zones from the deep reservoir fluid. Oxidation would be limited to elevations in which free oxygen occurs.

(c) At approximately 200–400m rsl the alteration mineralogy Sm + Cr ± K ± Gypsum (Gy) ± Calcite (Ct, or in some cases Dolomite, Ankerite and Siderite) is encountered. This zone, characterized by the appearance of the sulphate gypsum and the carbonate minerals is the product of rock reaction with the neutral sulphate-bicarbonate fluids that outflow at the surface at. 70–300m rsl. The sulphate-bicarbonate fluid has formed by the condensation of C02 emanating from the deep chloride reservoir and mixing with the overlying acid-sulphate fluids. Locally there is an influx of gypsum at the upper portions of this zone which marks the depth of initial mixing.

(d) A zone with mineralogy reflecting both the chloride reservoir fluids (Chlorite, Ch, + Anhydrite, Ah,+ Q) and the sulphate-bicarbonate zone (K + Gy + Cr) is observed at around 200m rsl with a thickness of up to 50-100m. This corresponds to the mixed chloride sulphate-bicarbonate thermal springs observed in the Manito lowlands at 20-70m rsl.

The above mineralogy is consistent with formation in a vadose zone.

(ii) Mineralogy 250 to 150m rsl

This depth interval is marked by the following distinct changes in alteration mineralogy:

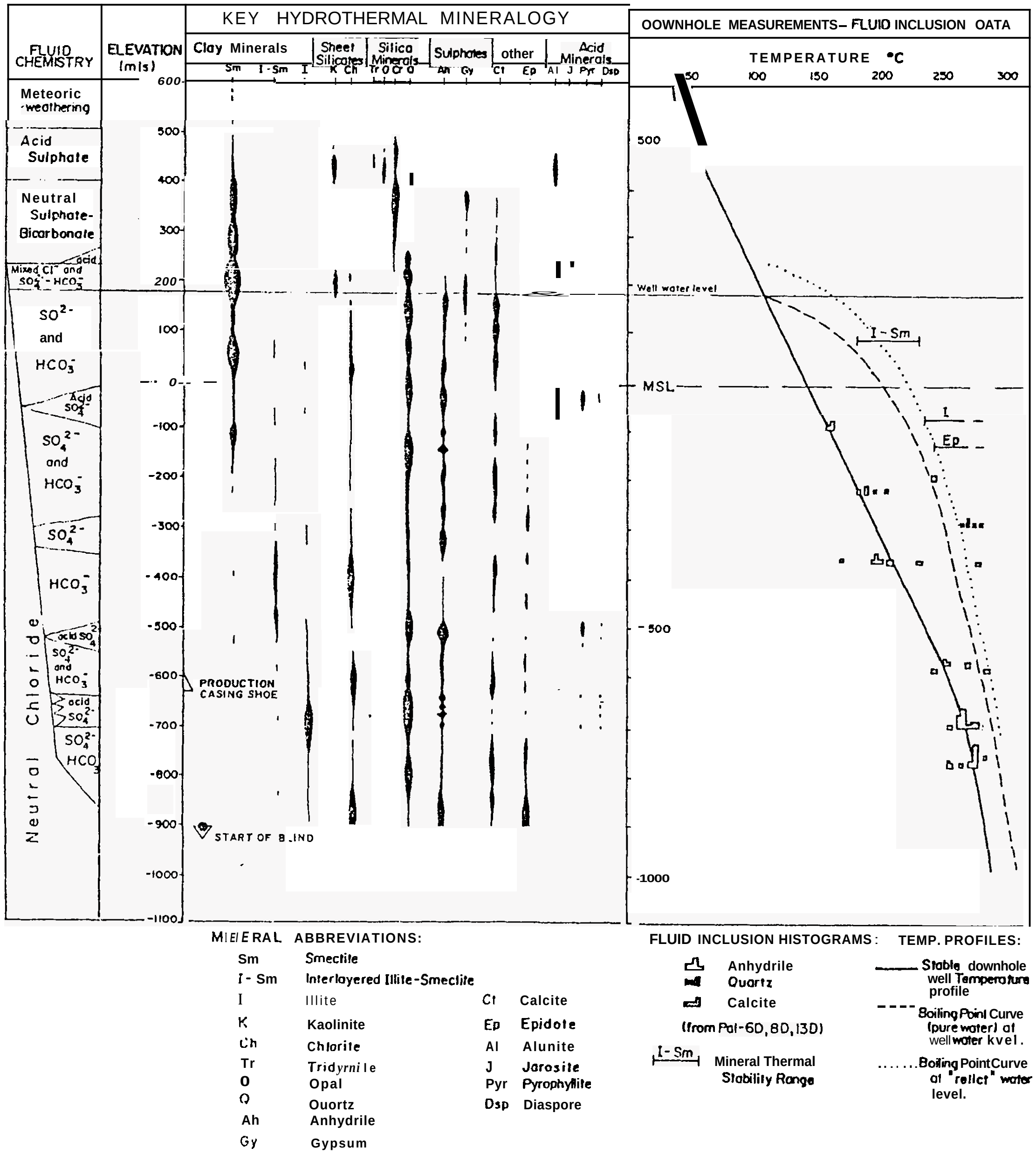
(a) Transition from Kaolinite to Chlorite

Kaolinite is stable in the vadose zone where the fluid pH is sufficiently low (through gas oxidation and condensation) to favour its formation. Chlorite on the other hand is Stable at the neutral pH and elevated temperatures of the chloride reservoir..

(b) Influx of Anhydrite

Anhydrite is precipitated by sulphate rich fluids from the vadose zone mixing with the high temperature-high calcium rich chloride reservoir

Fig. 4 THE DISTRIBUTION OF SOME SIGNIFICANT HYDROTHERMAL MINERALOGY COMPARED TO THE DISTRIBUTION OF FLUID CHEMISTRY, DOWNHOLE INCLUSION TEMPERATURES IN A "TYPICAL" BAC-MAN PRODUCTION WELL.



fluid. There is a sharp influx of anhydrite at 180m rsl. This coincides with the piezometric surface of the reservoir. Anhydrite also occurs 50-100m above this level in very minor amounts where it is locally altered to gypsum. Anhydrite in this interval may indicate a relict higher water level or simply a mixing zone.

The hydrated calcium sulphate, gypsum, continues to be encountered below the chloride reservoir level. Its disappearance with depth is thought to be temperature dependent (empirical maximum thermal stability of approximately 150-175°C).

(c) Influx of Calcite

As for anhydrite, the inverse solubility of calcite and tht mixing of bicarbonate rich and calcium rich fluids causes the precipitation of calcite as the cool bicarbonate fluids from the vadose zone mix with the hot chloride reservoir fluid.

(d) Transition of Cristobalite to Quartz

Cristobalite is the predominant silica phase within the vadose zone, whereas quartz is the major silica species within the chloride reservoir. Empirically, silica phase geothermometry indicates that the deep chloride reservoir is in equilibrium with quartz, whereas near surface fluids are in equilibrium with cristobalite or amorphous silica.

Although cristobalite is not encountered below the interpreted chloride reservoir level, quartz is locally encountered above it at two elevations:

1) Quartz may extend up to 150m above the interpreted reservoir water level. This is only observed in the eastern production wells and may indicate a relict high water level in the area of fluid upflow. This hypothesis is supported by fluid inclusion, downhole measurements and mineral distribution data as outlined in following sections.

2) Quartz is locally abundant in zones of acid alteration within the interpreted vadose zone. The controls of quartz formation in low temperature acid environments is not well understood.

The influx of abundant quartz at the chloride reservoir level along with anhydrite and/or calcite is interpreted to occur in response to quenching of hot reservoir fluid by mixing with cool sulphate and/or bicarbonate fluids from the vadose zone.

(iii) Mineralogy 150m to -900m rsl

(a) Clay Minerals

Smectite is the predominant clay mineral within the interpreted vadose zone although vermiculite has been reported. The 14.5Å Ca-smectite is the main species, although the 12.5Å Na-smectite is locally abundant as well. Within the chloride reservoir, there is a prograde sequence of clay mineralogy presumable dependent on reservoir temperature, (Leach and Harvey 1982), with smectite occurring down to -200, illite-smectite at -200m to -500m rsl (150-230°C), and illite below approximately -500m rsl (> 230°C).

This distribution of clay minerals is complicated by the persistence of I-Sm and I at shallow levels where the current formation temperature is at least 60-80°C below the minimum thermal stability limit for those minerals (from Leach et al, 1383) as indicated in Fig.4. Sm and I-Sm are also found in abundance, at depths where the formation temperatures exceed the maximum stability limit of the minerals (e.g. Sm occurs in **Pal-3P.D** to 1000m rsl at 260°C). The former are probably remnants of a hotter regime at shallow elevations, whereas the latter are relicts of cooler fluid conditions at depth.

(b) Epidote

Epidote is first encountered in the groundmass in productions wells between 150m and -100m rsl where the current formation temperatures are at least 100°C lower than the minimum thermal stability temperature of 240-250°C for epidote formation (Leach et al 1983, Reyes and Tolentino 1982). Epidote occurs sporadically below this depth altered to a nondescript mineral. In many production wells, epidote is locally abundant below -500 to -700m rsl.

(c) Vein Mineralogy

Quartz, anhydrite and calcite are the main hydrothermal minerals both as alteration products and as fracture fillings in the upper 1000m of the chloride reservoir. It is interpreted that the precipitation of these minerals in fractures is a result of the mixing of cool sulphate, sulphate-bicarbonate and bicarbonate fluids from the vadose zone, with hot quartz saturated reservoir fluid. This mixing has produced anhydrite-quartz, anhydrite-quartz-calcite and quartz-calcite vein assemblages. This fracture sealing persists down to at least -700m rsl, well into the chloride reservoir. It is postulated that the cool fluids have moved deep into the reservoir by re-opening of fractures by fault displacements.

(iv) Acid Mineralogy

Distinct zonation of acid mineralogy with depth is observed throughout the Bac-Man field. This zonation is shown in Fig. 4 and may be summarized as follows:

1) Alunite + Opal + Kaolinite between 400-600m rsl (rarely with pyrophyllite). This zone has been discussed in section (i) and is interpreted to mark the site of formation of acid sulphate fluids due to the necessity to oxidize H_2S in an excess oxygen environment. (Schoen et al 1974, Frank 1983). The pH of fluids in equilibrium with alunite at temperatures below 100°C is reported to be 2.5-3.0 (Slansky 1975, Frank 1983).

2) Alunite + Kaolinite ± Jarosite ± Pyrophyllite between 100 to 250m rsl is interpreted to originate from the downward movement of acid sulphate fluids from the above alunite zone. Jarosite (the Fe-equivalent of alunite) is probably the product of acid. alteration of abundant pyrite observed at these depths.

3) Alunite + Pyrophyllite and/or Diaspore (± Kaolinite) between 100m and -350m rsl.

4) Pyrophyllite and/or Diaspore between -100m and -1100m rsl.

From pH-silica activity diagrams involving the phases alunite, diaspore and pyrophyllite (Fig. 5), the transition from alunite to alunite + diaspore + pyrophyllite to diaspore + pyrophyllite with depth is indicative of a change from low pH (-2.5), low silica activity (*i.e.* low temperature) conditions, to moderate pH (3.5-4.0), high silica activity (i.e. high temperature) conditions. This approach is limited due to the need to fix the activities of SO_4^{2} - and K+, to omit the role of Na^+ in alunite formation, and to assume the immobility of Al^{+3} (the controls of which in acid environments are poorly understood, I Bogie pers comm). Nevertheless it

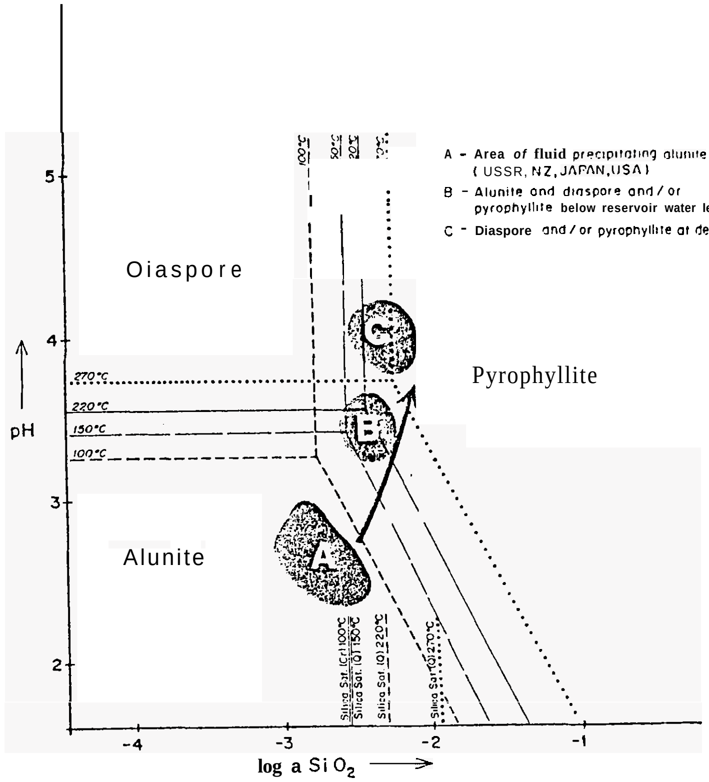


Fig. 5 : Mineral stability diagram for acid mineral assemblages at Bac–Man in terms of pH and log activity SiO_2 at saturated water vapour pressure. Activities of K^+ + SO_4^{2-} are fixed at 6.1 x 10^{-3} and 2.2 x 10^{-5} respectively. (Modified from Aniceto 1982 and Ruaya 1982; area "A" from Slansky 1975 and Frank 1983).

does suggest that the above zonation of acid minerals at Bac–Man is consistent with the downwards migration and accompanying progressive neutralization and heating of acidic fluids.

This mechanism may still be continuing since low pH, low Cl^-, high SO_4^{2-} feed zones have been encountered in some of the Bac–Nan wells.

Fluid Inclusions

Histograms of fluid inclusion homogenization temperatures in anhydrite, from the production well, Pal-13D, are compared to the stable downhole temperature profile in Fig. 4. If a boiling point for depth curve (b.p.c.) with a water level at about 250m rsl (at the influx of abundant quartz) is super-imposed on this diagram, the homogenization temperatures lie between the b.p.c. to just below the downhole temperatures. It is interpreted that the fracture filling mineralogy of anhydrite, calcite and quartz was deposited over a period of cooling, from previous boiling point conditions with a higher reservoir water level than currently observed, to the present formation temperatures. The thermal stability ranges of I-Sm, I and Ep, at the depths these minerals are first encountered, are also illustrated in Fig. 4. The stability ranges of these minerals are at a higher temperature than both the current downhole temperatures, and the b.p.c. at the current water level (as approximated by the well water level). This indicates that this relict mineralogy was also formed when reservoir conditions were at or near boiling with significantly higher water level than at present. The linear downhole temperature profile from near surface to approximately -600m rsl is postulated to reflect a conductive profile suggesting relatively impermeable country rock. The temperature profile below -600m rsl is convective in nature indicating permeability in the formation (Clotworthy 1982).

Primary fluid inclusions that homogenized close to the linear temperature profile down to -600m rsl were all single liquid phase; however those from depths below -600m rsl contain vapour, liquid. and gas, and homogenized at temperatures close to the convective temperature profile. Furthermore primary inclusions below -600m rsl are generally two-phase and gas rich whereas secondary inclusions were observed to contain a single liquid phase and at a slightly lower temperature than the primary inclusions.

Gas rich two-phase feed zones have been observed to originate at shallow levels below the production casing shoe (-300 to -600m rsl) in many production wells but not Pal -13D. It is interpreted that the gas rich liquid-vapour zone is capped by the anhydrite, quartz and calcite which has sealed fractures at depths from the chloride water level (150 to 300m rsl) down to approximately -400 to -600m rsl. The lack of a good correlation between the thermally conductive interval and the distribution of vein filling minerals reflects the difficulties of sampling open fractures. Below this "cap" epidote and chlorite are relatively abundant and unaltered indicating the presence of a hot neutral chloride reservoir fluid. The single phase secondary inclusions below -600m rsl indicate that these fluids have mixed with the two-phase, gas rich fluids.

Hydrological Model

Near boiling point with depth conditions existed in the epithermal region of the Bac-Man field sometime in the past, depositing the typical prograde mineral zonation observed in many Philippine geothermal fields (Leach et al. 1983). Boiling resulted in the release of H_2S, CO_2 and steam which condensed, and the H_2S and CO_2 locally oxidized, in the vadose zone to form acid sulphate and neutral sulphate-bicarbonate fluids. Upon cooling of the geothermal system the reservoir water level progressively dropped and the cool acid sulphate and sulphate-bicarbonate fluids moved downward along fractures into the deep reservoir. The mixing of these cool SO_4^{2}-HCO_3 fluids with hot quartz saturated reservoir fluids caused the precipitation of quartz, anhydrite and calcite, thus sealing fractures. This mineral precipitation has formed an 800m impermeable sealed cap on the current geothermal system. This cap has trapped local two-phase gas rich zones. Renewed movement along faults have re-opened fractures, permitting deeper penetration of the vadose zone fluids. These fluids have been detected at production depths in several Bac-Man wells.

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