SGP-TR-151-30

PROCEEDINGS

TWENTY-FIRST WORKSHOP GEOTHERMAL RESERVOIR ENGINEERING

January 22-24, 1996

Stanford Geothermal Program
Workshop Report SGP-TR-151

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PROCEEDINGS, Twenty-First Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 22-24, 1996
SGP-TR-151

FRACTURE PERMEABILITY IN THE MATALIBONG-25 COREHOLE, TIWI GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

The Tiwi geothermal field is located in southern Luzon on the northeast flank of Mt. Malinao, an andesitic volcano that was active 0.5 to 0.06 Ma. Matalibong-25 (Mat-25) was drilled through the Tiwi reservoir to investigate lithologic and fracture controls on reservoir permeability and to monitor reservoir pressure. Continuous core was collected from 2586.5 to 8000 feet (789 to 2439 meters) with greater than 95% recovery. The reservoir rocks observed in Mat-25 consist mainly of andesitic and basaltic lavas and volcaniclastic rocks above 6600 feet depth (2012 meters) and andesitic sediments below, with a transition from subaerial to subaqueous (marine) deposition at 5250 feet (1601 meters). The rocks in the reservoir interval are strongly altered and veined. Common secondary minerals include chlorite, illite, quartz, calcite, pyrite, epidote, anhydrite, adularia and wairakite. An $^{39}Ar/^{40}Ar$ age obtained on adularia from a quartz-adularia-cemented breccia at a depth of 6066 feet (2012 meters) indicates that the hydrothermal system has been active for at least 320,000 years. Fractures observed in the core were classified as either veins (sealed) or open fractures, with the latter assumed to represent fluid entries in the geothermal system. Since the core was not oriented, only fracture frequency and dip angle with respect to the core axis could be determined. The veins and open fractures are predominantly steeply dipping and have a measured density of up to 0.79 per foot in the vertical well. Below 6500 feet (1982 meters) there is a decrease in fracture intensity and in fluid inclusion temperatures.

INTRODUCTION

The Tiwi field is located on the northeast flank of Mt. Malinao, an eroded and extinct Quaternary stratovolcano located along the Bicol arc of southern Luzon, Philippines (see inset of Figure 1). Discovered initially in the 1960's by the Philippine Commission on Volcanology, and later developed by Philippine Geothermal, Inc. as a contractor to the Philippine National Power Corporation, the field now has an installed capacity of 330 megawatts, and averages a 78% capacity factor. Case histories of the field and data on field performance are presented in Alcaraz, et. al. (1989), and Gambill and Beraquit (1993).

Well Matalibong-25 (Mat-25) was completed on March 15, 1992, as a vertical slim-hole through the reservoir in the western part of the Tiwi field (Figure 1). The interval above the reservoir was drilled by conventional rotary methods and completed with 7 inch (17.8 cm) casing cemented from the surface to 2563 feet (781 meters). The well was then continuously cored, with CHD-134 core collected from 2586.5 to 5000 feet (789 to 1524 meters) followed by CHD-101 core to the targeted depth of 8000 feet (2439 meters). Core recovery was greater than 95%

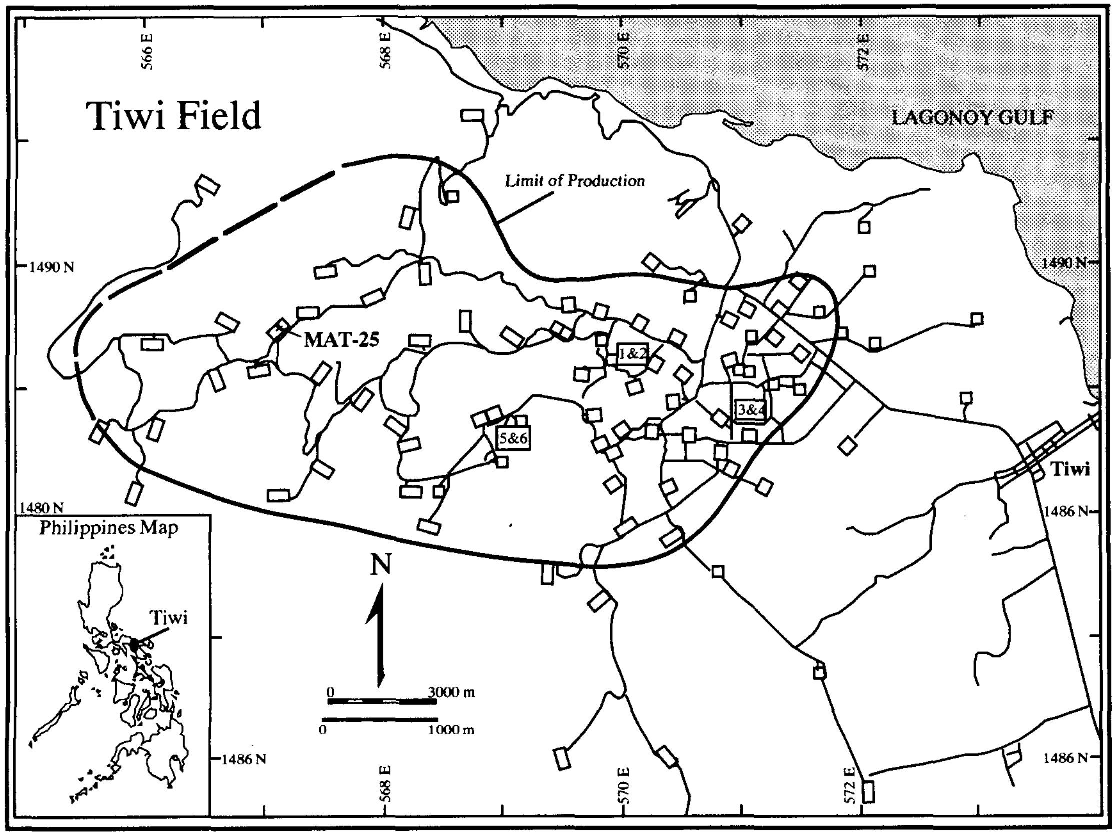


Figure 1. Map of the Tiwi geothermal system showing roads and well pads. Numbered boxes are power plants.

on average, and the corehole remained near vertical, increasing in deviation from 2 1/4 degrees at 2546 feet (776 meters) to 7 1/2 degrees at the bottom of the hole. The well was completed with 5 inch (12.7 cm) slotted liner to 5000 feet (1524 meters) and 3.5 (8.9 cm) inch slotted liner to total depth.

In this paper, we present the initial results of US DOE-sponsored studies being conducted on the core at the Earth Sciences and Resources Institute (ESRI) at the University of Utah. These results pertain principally to the significance, distribution and relative orientation of the veins and open fractures encountered in the well, but include some initial results from alteration and fluid inclusion investigations, as well. Together, these data present a complex picture of an evolving and relatively long-lived geothermal system.

GEOLOGY

Figure 2 presents a summary log of the cored section of the well, based upon macroscopic examination of the core, augmented by spot petrographic and XRD analyses. Columns are given for primary lithology, alteration intensity, veining intensity, and vein mineral abundances. Depths are given relative to the kelly bushing elevation of the drilling rig, which is 1112 feet (339 meters) above sea level, and 28 feet (8.5 meters) above ground level at the drill site.

The core is dominated by basalt and basaltic andesite lavas, flow breccias and volcaniclastic rocks, suggesting a prolonged and nearly continuous episode of arc volcanism. At 5250 feet (1601 meters), the depositional environment of the section makes a transition from subaerial to subaqueous. Paleosol horizons, which are common in the upper section of the core, give way to intervals of poorly-sorted pebbly sandstones. Below 6600 feet (2012 meters), the core becomes almost entirely sandstone. An argillaceous limestone, which appears to be correlative with a regional Miocene limestone formation, is found below the volcanic section in deep Tiwi wells further to the east, suggesting a probable Plio-Pleistocene age for the volcanic section. Ages of samples from Mt. Malinao and associated basaltic cones range from 500,000 to 60,000 years (Gambill and Beraquit, 1993)

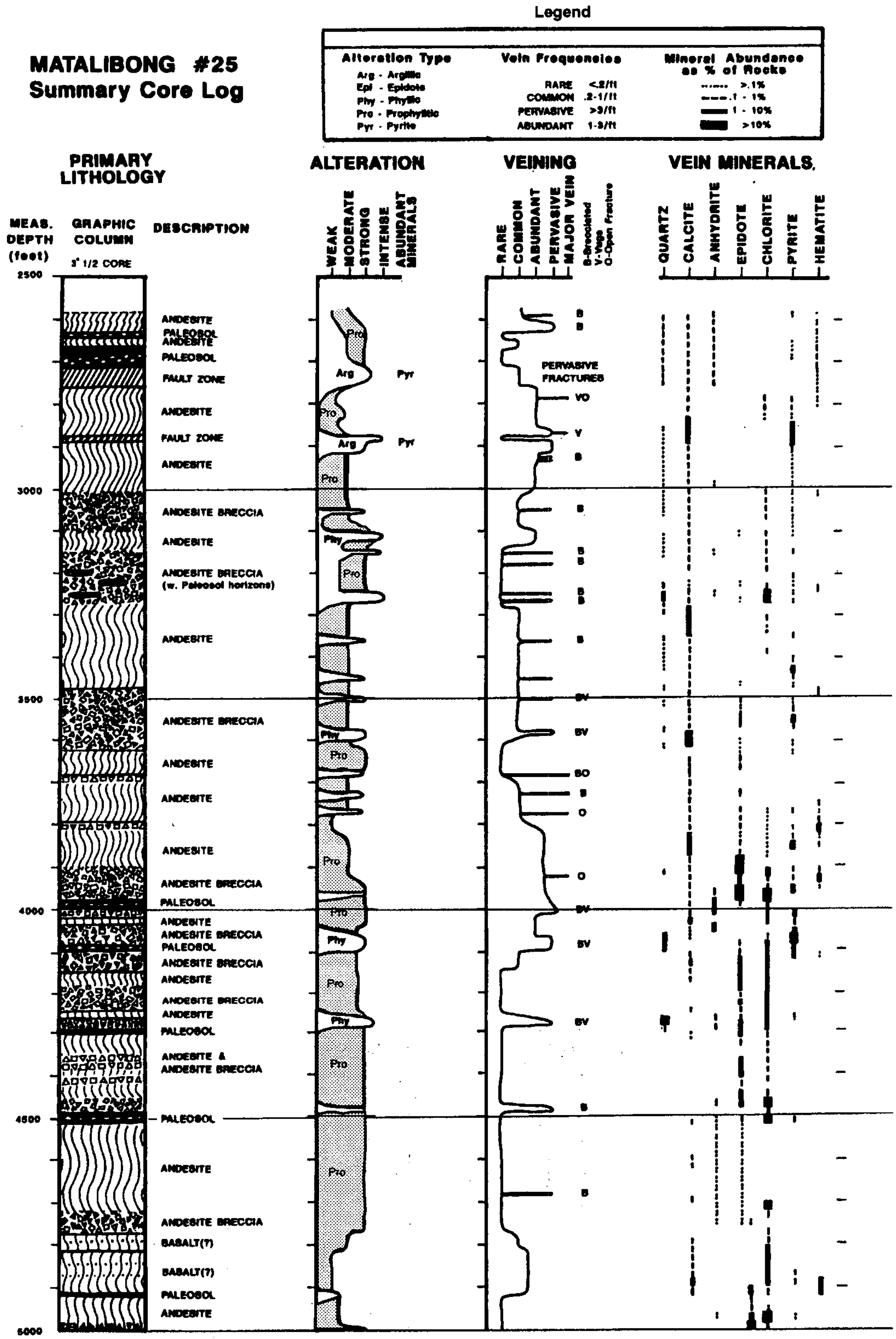
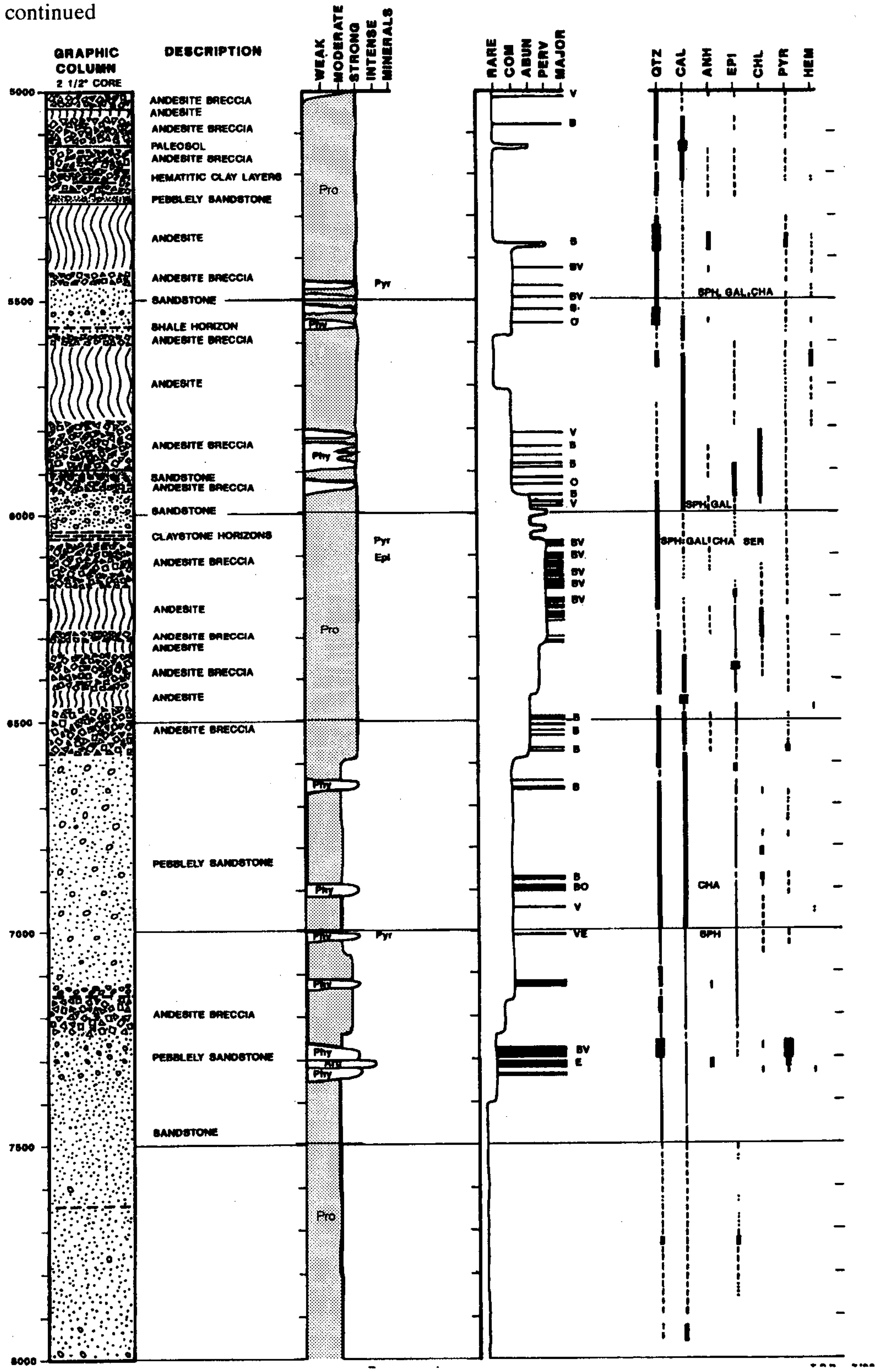


Figure 2. Distribution of lithologies, extent of hydrothermal alteration and veining, and occurance of vein minerals in Matalibong 25.

Figure 2. continued



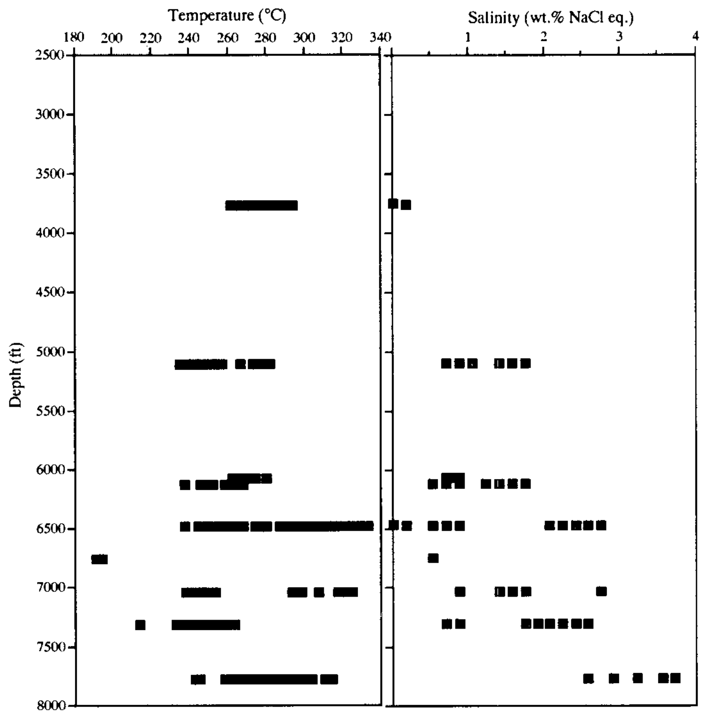


Figure 3. Homogenization temperature and salinity as weight percent NaCl equivalent (wt. % NaCl eq.) measured in fluid inclusions in the Mat-25 core.

The hydrothermal reservoir is characterized by alteration assemblages containing various proportions of chlorite, illite, quartz, calcite, pyrite, epidote, anhydrite, adularia and wairakite. Epidote, which is characteristic of propylitically altered rocks, first appears near the top of the core at depths of approximately 3000 feet (914 meters). With the exception of a few short intervals above 5000 feet (1524 meters), alteration intensity is uniformly high throughout the core.

Veins are common and widespread. They can be divided into two types: assemblages characterized by various proportions of calcite, anhydrite, quartz, epidote, and wairakite, and vein assemblages dominated by illite, quartz, and pyrite. Cross-cutting relationships in the upper part of the well suggest that the illite-rich veins are younger than those dominated by calcite. Two steeply-dipping fault zones, which are the foci of intense pyrite-rich argillic alteration, are found above 3000 feet (914 meters) and may have served as conduits for the downward migration of supergene waters from above the reservoir and the upward movement of steam condensate. Several faults were observed in the core. The orientation of the fault plane and slickensides demonstrate that faulting is predominantly normal.

Veining intensity and the distribution of brecciated, vuggy or open fractures appears to delineate two separate intervals of fluid circulation: one from the top of the core to 4100 feet (1250 meters), and one from 4600 to 7400 feet (1402 to 2256 meters). Comparison with the lithologic logs suggests that rock type exerts little control over vein intensity and the distribution of major veins. Furthermore, there is no change in lithology that might explain the dramatic decrease in vein intensity below 7400 feet (2256 meters).

FLUID INCLUSIONS

Fluid inclusions are common in vein quartz, calcite, and anhydrite in the Mat-25 core. In support of the geologic studies, fluid inclusion salinities and homogenization temperatures from selected intervals between 2986 and 7778 feet (910 and 2371 meters) were determined, with preliminary findings reported here (Fig. 3). Homogenization temperatures within this interval ranged from 195° to 325°C, although most were above 240° to 250°C, while the salinities ranged from 0.0 to 3.7 weight percent NaCl equivalent. Examination of the data demonstrates a close relationship between the composition and temperature of the inclusion fluids and depth within the well.

Above about 6100 feet (1860 meters), where volcanic rocks dominate, the maximum homogenization temperatures range from about 280° to 300°C. Salinities in this interval are less than about 1.7 weight percent NaCl equivalent. In contrast, maximum temperatures in samples from the lower part of the well where sandstones dominate typically exceed 300°C while salinities are greater than 2.5 equivalent weight percent NaCl. The highest recorded temperatures are found at a depth of 6474 feet (1974 meters).

These relationships suggest that the veins were deposited by two different fluids. We suggest that the lower salinities in the upper two thirds of the well, where the rocks were deposited in a subaerial environment, represent thermal fluids that were dominantly meteoric in origin. The higher salinities in the lower third of the well are more typical of sea water. Thus, these deeper fluids may represent mixtures of sea water trapped within the sediments and meteoric waters from above. The lowest salinity fluids, near 0.0 weight percent NaCl equivalent are interpreted as originating as condensate.

Age dating results have been obtained on a sample from approximately 6065 feet (1849 meters) depth. The sample is strongly mineralized with open-space fillings of quartz, adularia, pyrite, and base metal sulfides. Pseudoseconday(?) fluid inclusions in the quartz have homogenization temperatures that range from 262° to 280°C and average 270°C. $^{40}Ar/^{39}Ar$ spectrum dating was conducted on the adularia to determine the age of this mineralization and its thermal history. This dating has yielded several interesting results. First, they show that if the homogenization temperatures also represent the approximate temperature of adularia deposition as we suggest, then vein deposition occurred at 320,000 years ago. If temperatures were higher, then this is a minimum age. In addition, the data suggest that temperatures were no hotter than the fluid inclusion temperatures during the last 250,000 years. Some argon loss is suggested by the age spectra, however, but this may have occurred between 250,000 and 320,000 years ago, in response to thermal transients not observed in the fluid inclusion data.

FRACTURE ANALYSIS

The core from Mat-25 was not oriented and there were no imaging logs run in the well that would allow the orientation of fractures, faults and bedding. Since the hole had an inclination of only about 7 1/2° from vertical at total depth, it is assumed in the analysis that the well is vertical throughout its length. Features in the core were classified as either veins sealed by hydrothermal mineral precipitation, veins with macroscopic porosity, or as faults. We assume that the fractures with macroscopic porosity are probably fluid entries within the reservoir.

Development experience at Tiwi has found that production correlates with subhorizontal zones between wells and does not appear to correspond to the projection of high-angle geologic structures, such as faults (Gambill and Beraquit, 1993). This led to the suggestion that reservoir permeability might be principally controlled by some type of subhorizontal permeability features, such as bedding contacts or certain primary rock types. The findings of this study, however, show that all open fractures identified in the core are associated with fracturing and faulting. Primary lithologic features, such as geologic contacts, which may have been permeable following deposition of the lavas and associated volcaniclastic rocks, have been sealed by alteration processes and do not contribute to geothermal fluid production.

Hydrothermal veins and open fractures were logged over the total length of the core using a protractor to measure the dip angle with respect to the core axis. The data include 906 measurements of sealed veins and 190 measurements of open fractures, that were then compiled in a spreadsheet to expedite statistical treatment. In a number of instances, the same features were sampled by the core over a distance of several feet. In order to provide a statistical representation of their distribution, they have been noted on a footage basis. In other words, if a vein follows the core for three feet, the dip is input at three consecutive footages. The following diagrams were generated from these data.

Figure 4a and b are plots of the dip angles of open fractures and veins as a function of depth. In general, these two features have similar populations. Figure 4 shows that the dip angles can be divided into several different domains. Above about 4200 feet (1280 meters) there is a relatively large population of open fractures with relatively low angles, less than 45°. Below about 7200 feet (2195 meters), there are no additional open fractures and the veins dip at angles of 60° and greater. Other wells in the area confirm that this depth of termination of observed open fractures is the depth of the bottom of the hydrothermal reservoir.

Figure 5 is a cumulative frequency plot comparing the dip angles of both veins and open fractures. The two

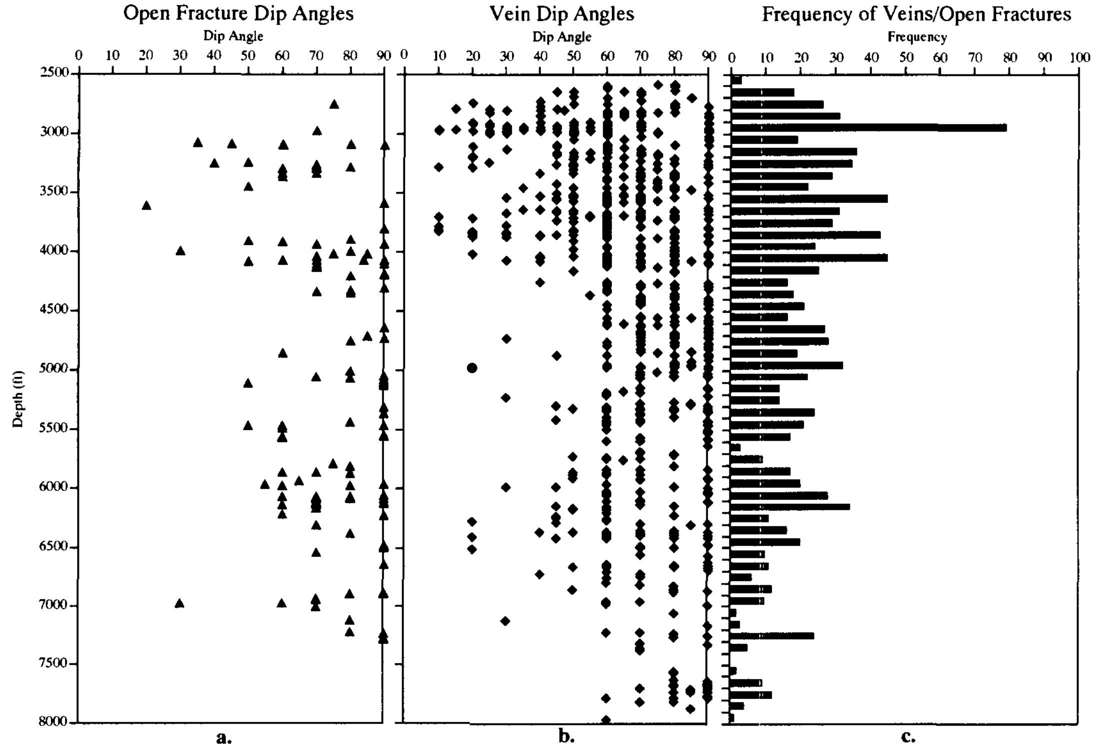


Figure 4. Dip angles of open fractures (a.) and veins (b.) in the Mat-25 core measured with respect to the cone axis. Frequency distribution of veins and open fractures (c.) is compiled on 100 foot intervals.

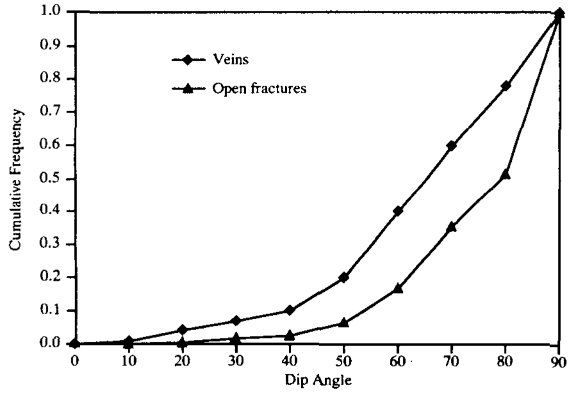


Figure 5. Cumulative frequency plot of veins and open fractures in the Mat-25 core.

populations are generally similar. It is important to note, however, that both veins and apparent entries are predominantly steeply dipping. The median dip of the veins is about 65°, and the median dip of the open fractures is about 80°. One must also be aware that a nearly vertical hole, such as Mat-25, will preferentially sample features with low dip angles; and features with high dip angles will be statistically under-represented (Barton and Zoback, 1992). When the distribution was corrected for the hole being vertical, fracturing in the reservoir is found to be almost exclusively high-angle.

The frequency of veins and open fractures as a function of depth, derived by summing the features within 100 foot depth intervals is shown in Figure 4c. The diagram illustrates the predominance of fracturing in the upper portion of the cored section, and the gradual decrease in fracturing with depth. The maximum density of veins and open fractures is 0.79/foot (2.59/meter) and occurs between 3000 and 3100 feet (914 and 945 meters).

CONCLUSIONS

The Mat-25 core confirms that the Tiwi reservoir is hosted by a sequence of lavas, flow breccias and volcanigenic sediments of andesitic to basaltic composition. The control of primary lithology on alteration mineralogy is relatively minor, with two distinct vein assemblages recognized throughout the core. Only in the case of fluid inclusion salinities does any part of the primary lithology, in this case the chemistry of formation water trapped during deposition, influence the hydrothermal system.

Primary lithology appears to have no influence on permeability in the Tiwi reservoir. Contrary to development drilling experience, which suggested that reservoir permeability was controlled by horizontal features likely related to bedding in the andesitic reservoir rocks, open fractures, that probably represent the principal permeability in the reservoir, are steeply dipping and appear to have been generated by faulting. Primary lithologic features are sealed, and vein intensity has no apparent correlation with lithology. The base of the reservoir is marked by an abrupt absence of open fractures that could serve as fluid entries.

The $^{40}Ar/^{39}Ar$ age of at least 320,000 years reported for a sample of vein adularia from the core suggests a relatively long life for the Tiwi hydrothermal system, and one with a remarkably stable temperature during a period of local volcanism. Additional fluid inclusion studies, now underway at ESRI, should help answer some of the mysteries of this mature and dynamic geothermal system.

Acknowledgements. The authors would like to thank Philippines Geothermal, Inc. and the Philippine National Power Corporation for their support in undertaking and publishing this work. This project was partially supported by the U. S. Department of Energy under contract number DE-AC07-95ID13274. Ken Williamson and Mitchel Stark provided valuable editorial comments.

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