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Reservoir Permeability Assessment of the Mindanao Geothermal Field, Philippines

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ABSTRACT

The distribution of reservoir permeability in the Mindanao geothermal field varies generally for each sector (Matingao, Marbel and Sandawa). Steam bearing fractures are either low-angled or high angled with a random to semi-random orientation. The low- angled fractures may be confined to specific strata bounded by steep high-angled fractures which are represented by faults mapped at the surface. Most dominant strike of such sub-vertical to vertical faults trend NW (Marbel Corridor) and NNE in the Marbel-Sandawa interface. A lithologic break between the Upper sequence and Lower sequence of the Apo Volcanics defined by a clay-stone horizon also contributed to a field-wide permeability.

Introduction

The exploitation of a geothermal field requires vital target structures that would yield productive pay zones for steam production or good permeability for an ideal injection sink. During exploration drilling, these targets are mainly based on field mapping of faults with surface indications. In developmental drilling however, where there are numerous data already, such technique may be obsolete as some permeability could be attributed to fractures that are not manifested in the surface. It will not be reliable to establish a consistent, field-wide, and synoptic models of reservoir permeability of a specific geothermal field based on surface fault data only.

By utilizing a computer file containing the horizontal and vertical coordinates of wellbores and any steam entries encountered, a three-dimensional distribution of steam bearing fractures was analyzed so that a field-wide model was developed for The Geysers field (Beall and Box, 1989). The predominant orientations of steam-bearing fractures can also be estimated by statistical comparisons of steam entry frequency with wellbore

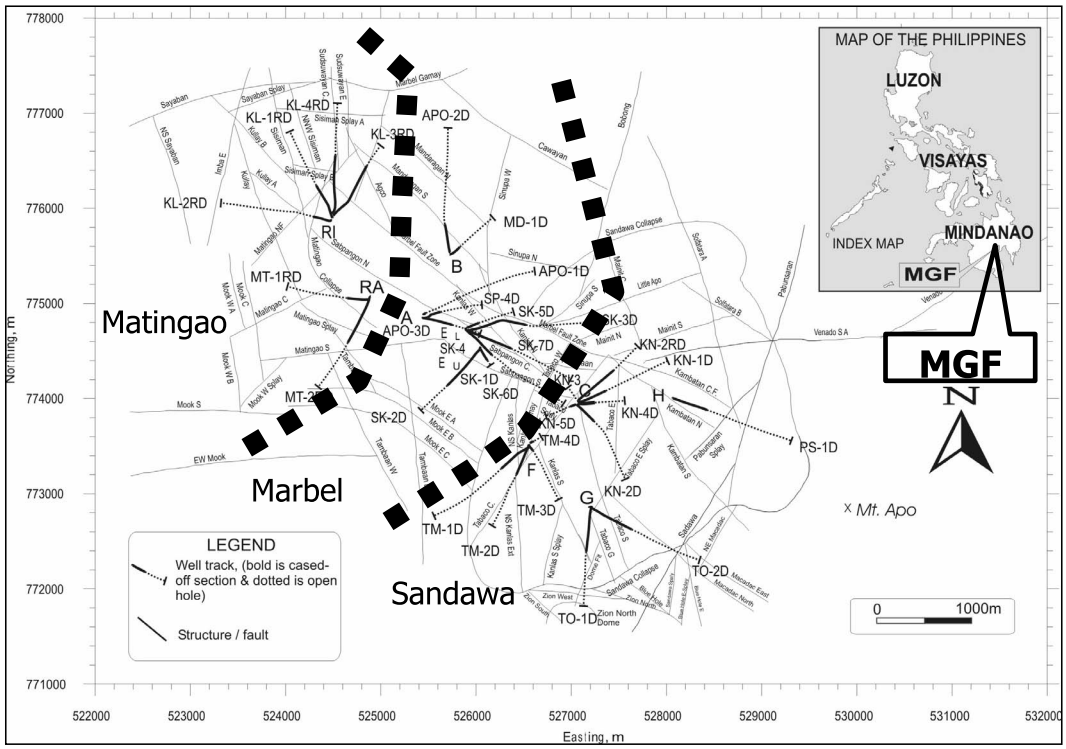

Figure 1. Location map of Mindanao geothermal field showing structures, welltracks and sectors.

inclination angle and with wellbore direction (azimuth). At The Geysers, correlation of steam entry frequency with respect to wellbore inclinations and azimuth bear a striking dependence on reservoir rock types (Thompson and Gunderson, 1989).

The objective of this study is to discretize the reservoir characteristic of each sector in the Mindanao geothermal field by analyzing the distribution and occurrence of permeable zones encountered in the wells. Another aim is to determine a large-scale planar steam- bearing fracture or fracture sets with preferred orientation that would allow deviated wells to intersect the most number of payzones, thus, coming up with the optimum total depths of make-up production and reinjection drilling, as well as, setting depths of production casing shoes.

Overview of the Mindanao Geothermal Field

The Mindanao geothermal field is located in the northwest flanks of Mt. Apo in the southwest central part of the island of Mindanao, Philippines (Figure 1). It has an area of about 30 km^2 with two power plants with a combined installed capacity of 104MWe (52x2).

The geology of the geothermal system is dominated by rocks belonging to the Apo Volcanics (AV) with the young AV found east and south of the Mt. Apo, while the old AV to the northwest and western side of Mt. Apo. Only rocks belonging to the old AV are encountered by the drilled wells. This formation is composed of two sub-units namely: the Upper Old Apo Volcanics (uOAV) and the Lower Old Apo Volcanics (lOAV). The upper member is composed of hornblende andesite, dacite and minor pyroxene andesite lavas, tuff breccias and hyaloclastites. Basaltic andesite to basalt and minor pyroxene andesite lavas, tuff breccias and hyaloclastites comprise the lower member that is separated from the upper sequence by a hematized claystone layer. The deepest well (KN-3) intersected the quartz monzodiorite Sandawa Intrusive (SI) in the southeast central portion of the system with a contact metamorphic aureole of highly altered rocks along its margins called the Contact Metamorphic Zone (CMZ) (Figure 2) (Sambrano, 1998).

Faults trending NW-SE predominate in the area having greater than 3-km. long surface traces. Another structural feature, the Sandawa Collapse, is found in the southeastern vicinity of the field. This structure cuts the northwest rim of Mt. Apo.

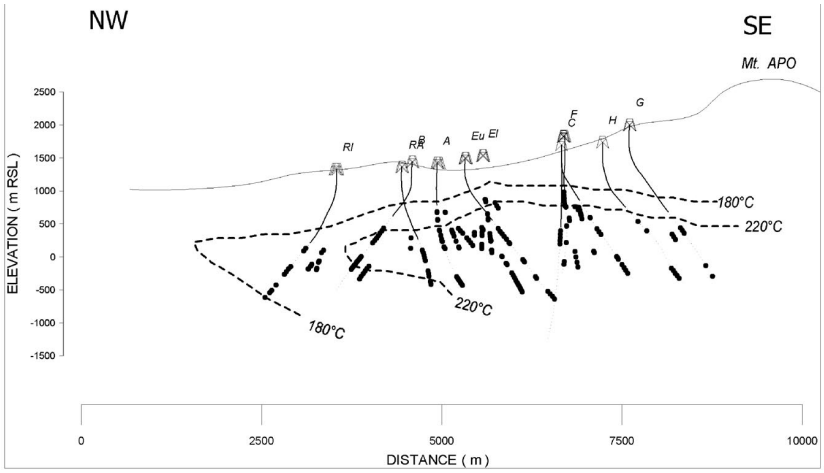

Figure 3. NW-SE section across the Mindanao geothermal field showing permeable zones (dark dots) and the 180° and 220°C isotherms (dashed lines). G, H, C, F, etc. are pad locations with some welltracks. (elevation is in meters reduced to sea level).

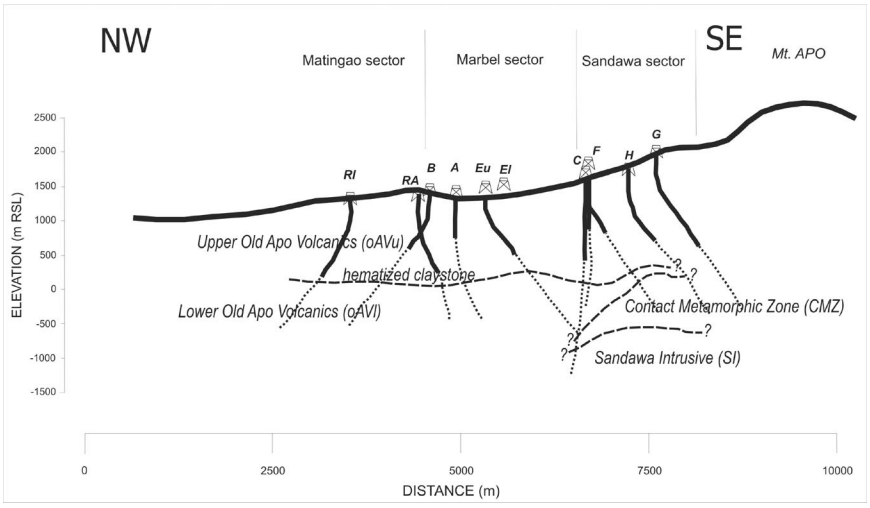

Figure 2. Subsurface stratigraphy of the Mindanao geothermal field along a NW-SE section. RI, RA, B, A, etc. are well pad locations. Bold lines from pads are cased-off sections while finer dotted lines indicate open-hole sections of the welltracks. Dashed lines indicate stratigraphic boundary as obtained from drilling data. Elevation is in meters reduced to sea level (after PNOC-EDC, 1994).

Data and Methodology

The reservoir permeability assessment of the Mindanao geothermal field is first undertaken by dividing the reservoir into three areas that correspond to the traditional sectoral division. These are the Sandawa and Marbel, which comprised the production sectors and the Matingao reinjection block (Figure 1). A field-wide view is illustrated in Figures 3 and 4 showing the NW-SE and SSW-NNE sections respectively. Also shown are the permeable zones intersected by the wells which were obtained from pre-exploitation completion tests or temperature, pressure, and spinner (TPS) surveys and were representative of the baseline permeability of the field. The top of the reservoir is indicated by the 180°C isotherm which is approximately ~1000 mRSL*. Beginning from 1000 mRSL down to –1000 mRSL (deepest well penetration), ten 200-m thick reservoir slices are arbitrarily delineated to generate histograms and statistically analyze the distribution of permeable zones per geothermal field sector (Delfin and Pioquinto,

* All elevation values mentioned are in meters reduced to sea level.

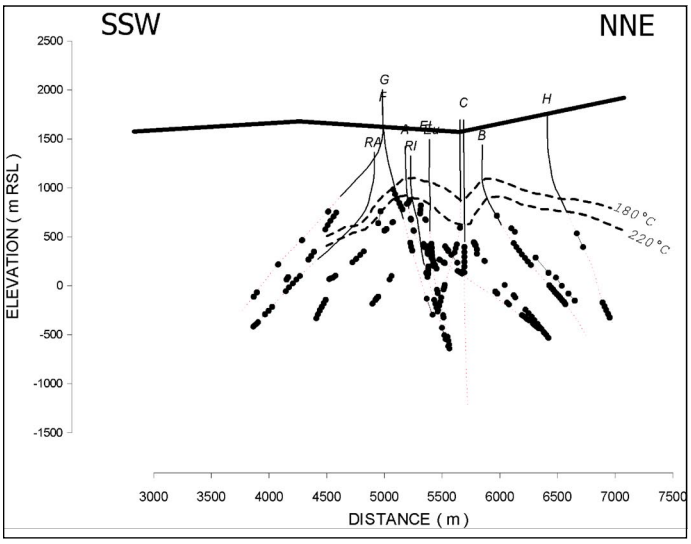

Figure 4. SSW-NNE section across the Mindanao field showing permeable zones (dark dots) and the 180° and 220°C isotherms (dashed lines). G, H, C, F, etc. are pad locations with some welltracks. (elevation is in meters reduced to sea level).

1999; Esberto, 2004; PNOC-EDC, 1994).

In order to determine if there is a large-scale planar fracture zone or fracture sets with preferred orientation that are influencing the occurrence of the permeable zones, a circular graph is utilized to plot the inclination and azimuth of the wellbore at each data point. The circular graph is used in a manner similar to a stereo-net to represent the orientation of lines in three-dimensional space. Following the method of Beall and Box (1989), a vertical wellbore would be located at the center of the diagram while a 60° wellbore would plot on the outermost circle. The azimuth of a wellbore is given by its angle from 0° to 360° around the periphery of the diagram. A zone of N-S striking vertical fractures intersected by wells deviated to the east and to the west would have the steam entry points concentrated on each opposite side from E to W. An east dipping N-S fracture zone would have its steam entry locations concentrated ideally on the western side (Figure 5) (Beall and Box, 1989).

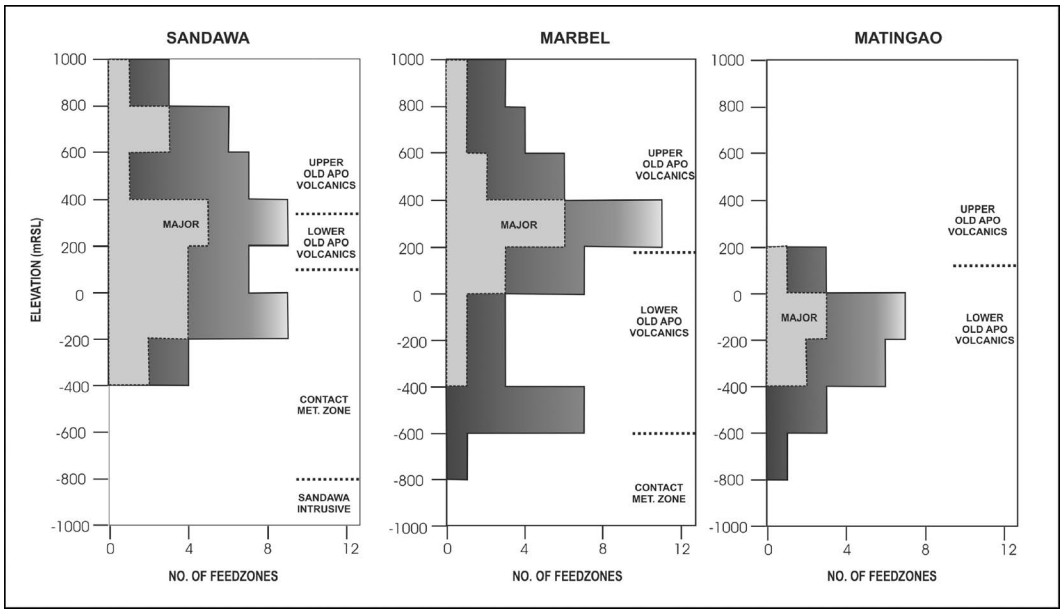

Figure 6. Histograms showing number of permeable zones in each reservoir slice for each sector in the Mindanao geothermal field. Elevation of formational contacts are averaged values. All elevations are in meters reduced to sea level. (updated after Delfin and Pioquinto, 1999).

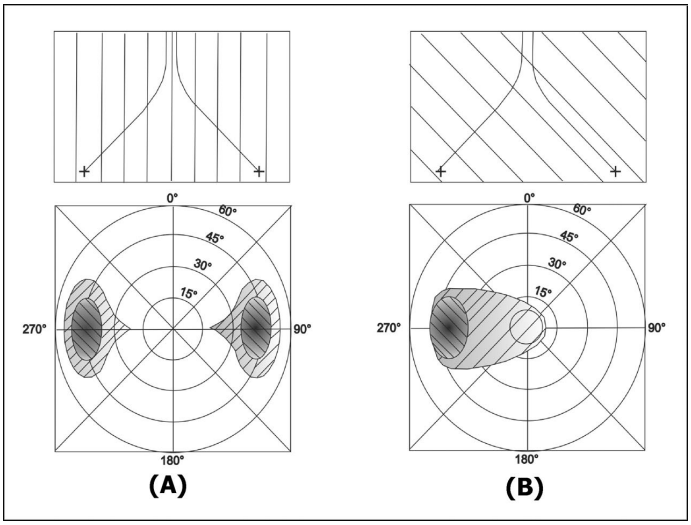

Figure 5. Plot of steam entries of deviated wells to the east and west with fracture zones (A) N-S striking vertical fractures and (B) N-S striking, east dipping fractures. (Beall and Box, 1989).

Results and Discussions

Permeability Distribution

The number of permeable zones encountered per 200-m slices in each sector of the Mindanao geothermal field is presented by histograms in Figure 6. The generalized stratigraphic sequence is also included in the figure to outline the permeability variation within each rock formation. The contact between the Upper and Lower sequence of the Old Apo Volcanics does not vary much between the three sectors. However, the boundary between the Lower Old Apo Volcanics and the Contact Metamorphic Zone (CMZ) vary as much as 200m especially in the Sandawa sector. From Figure 6, the Matingao reinjection block is characterized by a concentra-

tion of permeable zones at 0 to -200 mRSL. The deeper setting of production casing in this area results in an apparent absence of shallow permeability and the preferred occurrence of permeable zones within the Lower Old Apo Volcanics. Meanwhile, the distribution in the adjacent Marbel sector exhibits a strongly unimodal peak at 400 to 200 mRSL which is somewhat coincident with the contact between the Upper and Lower Old Apo Volcanics. This contact is indicated by a claystone horizon, which suggests that the layer has good permeability or is strongly fractured. In the Sandawa sector, the distribution is bimodal with the upper permeable horizon from 600 to 200 mRSL and the lower horizon at 0 to –200 mRSL. The lower part is hosted both by the Lower Old Apo Volcanics and the Contact Metamorphic Zone (CMZ). Well KN-2D produces largely from within the CMZ but all other wells encountered only minor pay zones attesting to the unit's variable permeability or rather less fractured characteristics at some depths (Delfin and Pioquinto, 1999).

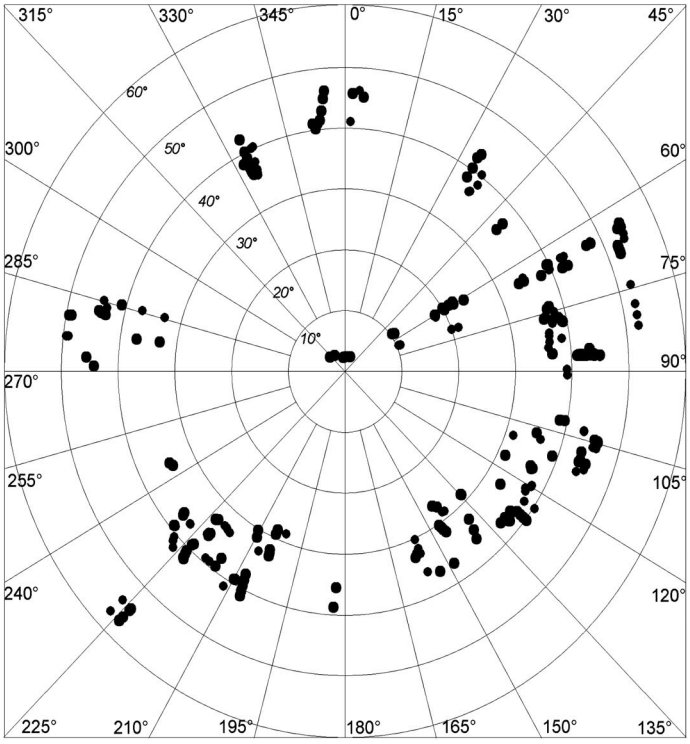

Figure 7. Circular graph showing distribution of permeable zones in the Mindanao geothermal field at each wellbore inclinations indicated by the concentric circles.

Fracture Orientation

Figure 7 is the circular graph plot of the wellbore orientation (azimuth and inclination) of each permeable zone in the whole Mindanao geothermal field. The noticeable concentration of data points within the 30°-45° inclination suggests that the number of deviated wells in the field intersected the permeable zones at the average drift angles attained in the open hole section. No obvious fracture trend is evident in the graph, but only an apparent hint of northwesterly (327°-335° azimuth) structures which dip NE as some points plot at 10° to 50° inclination at the 57°-65° portion of the circular graph. Such interpretation is constrained maybe due to scarcity of data, but it could also correspond to the existing faults in the area that show surface manifestations especially in the Marbel sector. These have generally a NW-SE trend, such as the Marbel Fault Zone and the Sabpangon series of faults with predominantly NE dips. The general pattern, however, presented in the graph is random to semi-random which suggests that the permeable zones intersected by the wells are attributed to (1) gently to steeply dipping fractures which are either shallow or extend down at depth, (2) deep-seated vertical to subvertical fractures and (3) to subhorizontal fractures which are influenced by lithologic contacts. The plot of wellbore inclination of each permeable zone against elevation (Figure 8) corroborates the above interpretation.

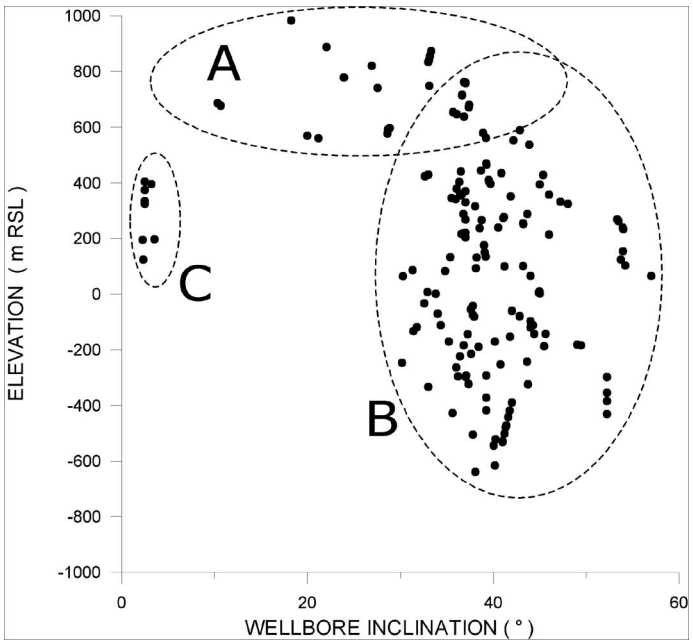

Figure 8. Graph showing wellbore inclinations for each permeable zones (black dots) encountered by the wells in the Mindanao geothermal field. (A) Probable permeable zones attributed to gently to steeply dipping fractures. (B) Probable permeable zones attributed to vertical to subvertical fractures. (C) Probable permeable zones attributed to horizontal to subhorizontal fractures or lithologic breaks. Elevation is in meters reduced to seal level.

A 3D surface model of the permeability distribution in the geothermal field is shown in Figure 9. The model is based on the contour plots of permeable zones which have known easting and northing coordinates, as well as specific elevations reduced to sea level. Here, there is a seemingly NNE trending control of permeable zones between the Marbel and Sandawa sectors or within the vicinity of the Marbel-Sandawa interface. This NNE orientation could be attributed to subvertical fractures associated with the trace of the Tabaco series of faults. This fault zone could be deep-seated and may serve as channel for upflowing hot, neutral pH fluids being tapped in the Sandawa sector. As evidenced from geochemical parameters particularly the contours of quartz geothermometer tempera-

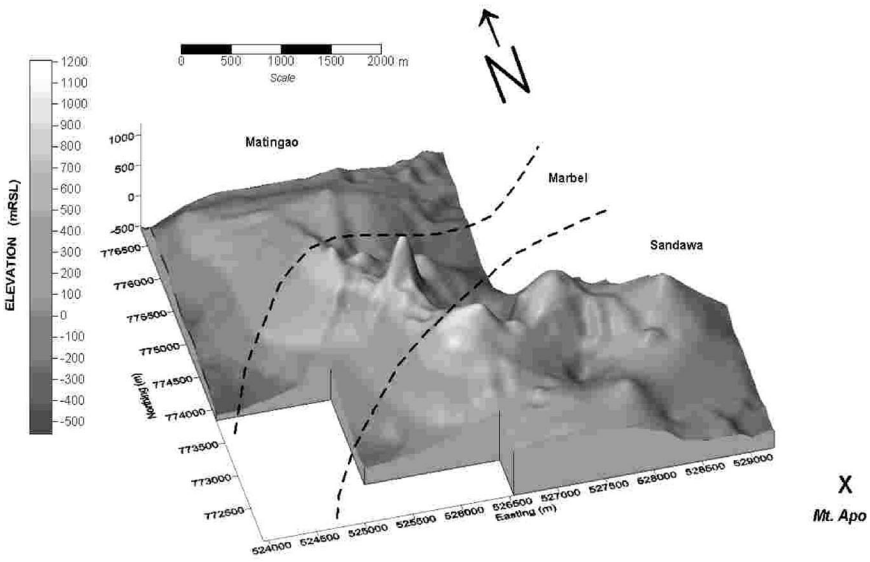

Figure 9. Three-dimensional model of the top of the permeable zones in the Mindanao geothermal field. Note the NNE trending distribution near the Marbel-Sandawa interface aside from the prominent NW-SE orientation. Elevation is in meters reduced to sea level.

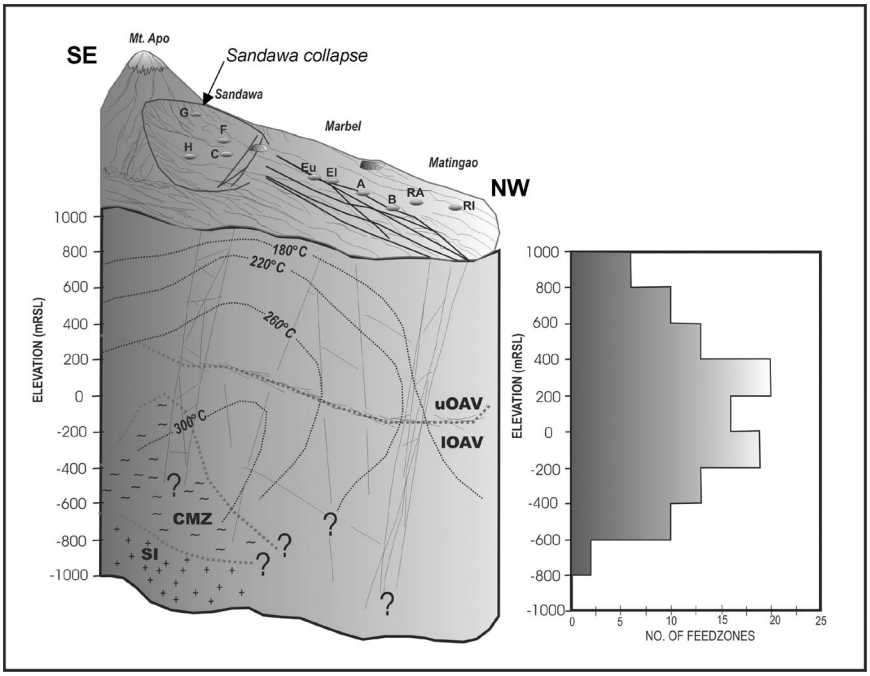

Figure 10. Conceptual permeability model of the Mindanao geothermal field showing prominent NW-SE and NNE-SSW faults in Marbel and Sandawa sectors respectively, the stratigraphic boundaries (dotted lines) and the isothermal contours. G, H, Eu, etc. are well pad locations. At right is the histogram distribution of the total no. of feedzones at corresponding elevations. (all elevation values are in meters reduced to sea level).

ture, there is indeed an apparent barrier of high-temperature (~260°C) fluids that seemed to emanate from a region between the Marbel-Sandawa sectors and which is holding off lesser temperature fluids coming from the Marbel sector (Aragon, pers. comm., 2005).

Summary and Conclusions

The distribution of permeable zones in the Matingao reinjection block of the Mindanao geothermal field peaks at around 0 to –200 mRSL with an apparent absence of shallow permeability due to the deeper setting of production casing shoes (PCS) in this sector. A unimodal distribution is described for the Marbel sector with concentration at around 400 to 200 mRSL. This depth also corresponds to the claystone horizon which marks the lithologic contact between the Upper Old Apo Volcanics and Lower Old Apo Volcanics. Meanwhile in the Sandawa sector, a bimodal distribution is defined by the data cluster at around 600 to 200 mRSL and at 0 to –200 mRSL.

Generally, this study shows an over-all picture of a random to semi-random fracture network for the whole Mindanao geothermal reservoir. There is though a hint of NW-SE trending fracture sets with northeasterly dip directions. Such pattern may correspond to the NW striking Marbel-Sabpangon fault series in the Marbel sector. Another fracture orientation with NNE strike is defined in the Marbel-Sandawa interface as observed from the 3D model of permeable zones (Figure 9). This may coincide with the high-angled Tabaco fault series in the Sandawa area. These faults channel hot upflowing geothermal fluids and form a barrier between the Sandawa production sector and the relatively lower- temperature fluids of the Marbel sector.

The conceptual permeability model of the Mindanao geothermal reservoir with associated fracture network and structural controls that was developed is given in Figure 10.

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