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THE AWI 1-2 CORE RESEARCH PROGRAM: PART I, GEOLOGIC OVERVIEW OF THE AWIBENGKOK GEOTHERMAL FIELD, INDONESIA

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ABSTRACT

The Awibengkok geothermal system is hosted by a thick volcanic section consisting primarily of andesitic rocks, and floored by marine sedimentary rocks of Miocene age. The volcanic sequence is capped by Quaternary rhyolitic domes and related tuffs that form a NNE-trend across the eastern part of the field. A complex network of N to NNE-trending extensional faults linked with ENE- and NW-trending accommodation faults provides high permeability. Phreatic explosion breccias exposed at the surface date back at least 8,400 years. Shallow argillic alteration at Awibengkok gives way with increasing depth and temperature to an argillic-phyllic zone (smectite and illite/smectite) to a propylitic zone (epidote, chlorite, and illite), which accounts for the bulk of the system's production.

Awibengkok is a high-temperature (220-315^{o}C), liquid-dominated reservoir, averaging about 1.3% total dissolved solids (TDS) and low to moderate gas content. The principal deep upflow zone (~315^{o}C) is in the western part of the field. Ascending fluids are locally confined by low permeability, clay-rich ash deposits on the west, but move up along one or more N- or NNE-trending structures that breach these barriers in the central and east-central parts of the field. Fluids in the central part of the reservoir are very uniform in composition and temperature, representing the mixing of upflow and convective reflux. Fluids ascend and flow laterally to the shallow top of reservoir in the eastern area near Awi 1-2 (250 to 270^{o}C). This sector of the geothermal system has had a complex history related to episodic volcanic eruptions, faulting, and hydrothermal venting.

1. INTRODUCTION

Commercial operations at Awibengkok, Indonesia began at 110 MW in 1994 (Murray et al., 1995), and field expansion to 330 MW was completed in late-1997 (Soepardjadi et al., 1998). In 1995 the U.S. Department of Energy (US DOE) and Unocal Geothermal Indonesia (UGI) obtained >1 km of continuous core from the eastern portion of the Awibengkok geothermal field (Fig. 1). US DOE-sponsored research on this core is now underway, providing an excellent opportunity to enhance our knowledge about the processes that formed the largest producing geothermal field in Indonesia. This paper provides a geologic framework for the core research program by highlighting pertinent aspects of the geologic setting, stratigraphy, structure, hydrothermal alteration, and fluid geochemistry of the field as documented by Unocal geoscientists. It describes a simplified conceptual model for the field, focusing on aspects of the model important to further study of Awi 1-2. It also touches on aspects of the stratigraphy and alteration encountered in Awi 1-2, which are discussed in more detail in the companion paper that follows.

2. GEOLOGY AND ALTERATION

The Awibengkok geothermal field is located within the Gunung Perbakti-Gagak volcanic complex of western Java. The complex is part of the active Sunda volcanic arc, which extends from Sumatra to Flores (Hamilton, 1979; Hutchinson, 1989). This arc-trench system marks the convergent boundary between the Eurasian plate to the north and the Indo-Australian plate to the south (Fig. 1). Plate convergence is nearly perpendicular to the arc front in central Java, but becomes increasingly oblique towards the Sumatran arc segment. Some regional tectonic studies indicate that strain is partitioned into normal (extensional/ compressional) and shear (left-lateral strike-slip) components in Sumatra, with increasing shear to the north (McCaffrey, 1991). Estimates of the plate convergence orientation for Java range from N3^{o}W (McCaffrey, 1991) to N11^{o}E (Tregoning et al., 1994), nearly perpendicular to the ridge axis. Stress indicators (earthquake focal mechanisms, borehole breakouts, mapped or inferred surface faults and folds in western Java) reveal that the maximum horizontal stress is directed approximately N, parallel to convergence in this area (Shemeta, 1994).

The Awibengkok geothermal system is located in a rugged, mountainous area ranging in elevation from about 950 to 1500 m asl. The highest peaks are the inactive andesitic volcanoes of Gunung Salak, Gagak, Perbakti, and Endut. These peaks border the development site on the north, east, and south, and give way to lower hill country around the Cianten Caldera on the west. The surficial geology of the Salak prospect area has been mapped in reconnaissance by Unocal geologists and consultants, with heavy reliance on aerial photographs due to dense vegetation and rough terrain. Based on K-Ar and $^{40}Ar/^{39}Ar$ dating, the major peaks of the Awibengkok area were built from 0.86 to 0.18 Ma (Fig. 2). There may have been an important edifice collapse at Kiaraberes prior to 0.42 Ma based on geomorphology, but this is poorly known. Tuffs and lavas dated from 0.28 to 0.36 Ma have partially filled the open Kiaraberes collapse crater and flowed downslope to the west and southwest. The youngest volcanic rocks in the Awibengkok reservoir area are silicic domes, lavas, and related tephra sequences that form a NNE trend across the eastern portion of the field. These rocks, dated from 0.24 to 0.04 Ma, overlie the dominantly andesitic sequence described above, and range in composition from dacite to rhyolite.

The youngest volcanic unit is an extensive tephra known as the "Orange Tuff". This rhyolitic tuff closely mantles topography in most of the Awibengkok development area, attesting to its young age. Maximum pumice size suggests that this unit was erupted from a vent in the young eastern volcanic trend between Awi 1 and Awi 14 (Fig. 2). The Orange Tuff is partially covered by hydrothermal breccia deposits, which have been dated by ^{14}C on a log at 8,400 years B.P. This brackets the age of the Orange Tuff from 40,000 to 8,400 years B.P. An earlier reported ^{14}C age of 2,000 years B.P. on the Orange tuff conflicts with the 8,400-year age on the overlying breccia, and is thought to be in error. Hydrothermal breccia deposits resulting from intermittent phreatic explosions have accumulated over at least the last 8,400 years. These deposits are centered south of Kawah Cibeureum (Powell and Santosa, 1994), varying in thickness from 4 to 10 m near Awi 2 (Fig. 2). Based on areal extent and clast-size distribution, this unit was likely erupted from vents between Awi 2 and Awi 5. An older phreatic breccia deposit underlying the Orange Tuff near Awi 14 suggests that vigorous hydrothermal activity in this area preceded deposition of that unit as well. Hydrothermal and phreatic activity continues through recent times including small historic eruptions in this same area.

The youngest volcanic vents form a NNE trend cutting across the eastern part of the production area (Fig. 2). This vent trend appears to be structurally controlled, as in other chains of silicic domes such as Coso (Bacon, 1982) or Inyo domes (Bursik and Sieh, 1989). As discussed below, this trend is similar to the dominant trend of major fractures measured in boreholes by image logging (Shemeta, 1994, 1995), further supporting the case for structural control. Subsurface lithologies have been inferred mainly from description of cuttings from 55 wells, supplemented by spot core from 11 wells, and the 1067 m of continuous core from Awi 1-2. The Awi 1-2 core clarified many features which were not evident from cuttings and spot core, such as the importance of lahars, and the nature of clay-rich layers called "paleosols". Borehole image logs also provided constraints on major lithologies, and are the only means of obtaining lithologic data in sections of wells that were drilled with total circulation losses. A stratigraphic column showing the typical thickness of the major formations is shown in Figure 3. It can be seen that each major volcanic formation is further subdivided into a lower andesitic section, and an overlying rhyolitic or dacitic section. These formations most likely represent deposits from three distinct or partially overlapping volcanic episodes, each of which became more silicic with time. Facies analysis of the Awi 1-2 core also suggests that epiclastic sediments such as lahars typically mark the end of each episode (see Hulen et al., this volume). Thinly-bedded to massive, clay-rich ash and lapilli tuffs are present throughout the sequence. Groups of these important marker beds have been described from some wells, and some have been correlated from well to well. Two prominent layers were encountered in Awi 1-2 from 786 to 797 m and from 1151 to 1171 m MD.

The stratigraphic section can be divided into four major formations, thought to represent discrete periods in the evolution of the Javanese arc segment (Fig. 3 and Table 1). The oldest rocks are mainly shallow-marine carbonates and epiclastic sediments (mudstones and sandstones with abundant volcanic clasts and waterlain tuffs that probably represent ash turbidites). Most of these units are very different from the overlying and interbedded volcanic rocks by virtue of their composition, lower porosity and permeability, and less-intense alteration. Fossil assemblages are characteristic of shallow-shelf environments of Early to Late Miocene time.

An andesitic to basaltic volcanic formation overlies and is interbedded with the Miocene sedimentary section. These volcanic rocks probably represent the first major episode of calc-alkaline magmatism in the immediate area, and the transition from marine to subaerial deposition. This formation consists mainly of lavas and breccias (hyaloclastite), but has a widespread sequence of silicic tuffs and flows at its top. It is believed that this silicic sequence represents the terminal phase of the first major episode of stratovolcano formation in the area. The Middle volcanic formation is another sequence of andesitic to dacitic lavas, tuffs, and debris flows, representing either the earliest phases of construction of the present stratovolcanoes, or earlier cones which they overlie. This sequence is thought to have formed primarily by subaerial deposition. It makes up the dominant portion of the Awibengkok geothermal reservoir in the eastern portion of the field, and is well represented in the Awi 1-2 core; the western portion of the reservoir is dominated by the underlying volcanic formations. The Upper volcanic formation consists of another andesitic sequence overlain by dacitic to rhyolitic rocks. This sequence includes surficial deposits described above.

Intrusive rocks have been encountered in several wells, including Awi 1-2, but no large intrusive complexes are known at drilled depths. The intrusion in the corehole has been described as a quartz diorite (Hulen and Lutz, 1999). The texture and distribution in Awi 1-2CH and ST indicate that this intrusion is a sill. It is generally less altered than the surrounding rocks, probably due to its low permeability. An intrusion in Awi 2-1 is present in core taken near the bottom of the well (2139 m MD). It is a porphyritic silicic rock consisting mainly of feldspar and quartz. Based on the relatively coarse grain size of this intrusion, it may be either a dike or the top of a larger granitic body with a texture similar to the microgranite porphyry carapace of the Geysers Felsite (Hulen et al., 1997). A coarse-grained granitic fragment about 1 m in long dimension was collected from tuffs associated with the Upper rhyolite (Fig. 3). Hornblende and biotite separated from the granite yielded concordant $^{40}Ar/^{39}Ar$ ages of about 0.113 ± 0.004 Ma, which are thought to reflect complete "thermal resetting" and therefore, the age of the eruption. An intrusion in Awi 4-1 consists of devitrified to glassy rhyolite with sparse phenocrysts of quartz, plagioclase, pyroxene, hornblende, and biotite, and probably represents a feeder to the young rhyolitic dome or related lavas that form a NNE trend in this area. It is largely unaltered, suggesting that it was impermeable to reservoir fluids, or that cooler fluids were moving downward along its margin.

2.1 Geologic Structures

Mapping confirms that surface structures cut the young tuffs that blanket the Awibengkok development area. Most are high-angle faults that have <1 m of displacement and N to N15^{o}E, ENE, and NNW strikes. Considering the regional structural setting and local fault orientations discussed above, there likely is a conjugate set of faults in the Awibengkok development area consisting predominantly of: (1) normal faults with N to NNE orientations, and (2) normal and strike-slip accommodation faults and joints trending NW and NE to ENE. Some extension in the area may have been taken up by recent dike injection along the NNE trend of vents described above (cf. Bursik and Sieh, 1989; Hackett et al., 1996).

Borehole Televiewer, Formation MicroScanner^{TM} (FMS) and Formation MicroImager^{TM} (FMI) logs have been used to better understand the distribution and orientation of fractures in the subsurface at Awibengkok (Shemeta, 1994, 1995). The logs show a detailed view of the formation, where fractures and lithologic changes are clearly seen. Image logs show that, overall, large fractures display N to NNE orientations with steep dips in all wells, although Awi 9-4 displays more easterly trends than other wells (Fig. 4).

2.2 Alteration Zones and Mineralogy

The Awibengkok reservoir hosts argillic, propylitic, and phyllic zones; no advanced argillic alteration has been identified within the high-temperature reservoir. The system is capped by a zone of intense argillic alteration, which is dominated by smectite and smectite-illite mixed layer clays, with accessory pyrite, silica, hematite, calcite, anhydrite, zeolite and chlorite. This assemblage typically corresponds to temperatures of <200^{o}C. The argillic alteration shows a transition to propylitic alteration with increasing depth, which can span hundreds of feet. In Awi 1-2, the bottom of the argillic alteration is marked by 20-meter thick andesitic fallout tuff, which is massively altered to illite-smectite and chlorite-smectite clay. Hulen and Lutz (1999) classify this alteration assemblage as argillic-phyllic. Because of its high smectite content, this rock appears to have been altered at much lower temperature than measured today. Thus, this unit represents an effective seal to the underlying propylitically altered reservoir section.

The propylitic alteration zone is dominated by epidote, illite, and chlorite but also contains albite, adularia, calcite, wairakite, pyrite and titanite. This alteration assemblage corresponds to reservoir temperatures between 220 and 270^{o}C. Rare occurrences of garnet, biotite, and amphibole occur at deep levels, and may indicate higher temperatures of deposition near intrusions. In the Awi 1-2 core, crosscutting hydrothermal veins and breccias containing quartz, epidote, adularia, pyrite, anhydrite, wairakite, and sericite are common, and are discussed in greater detail in Hulen et al. (this volume). Phyllic alteration is present in the more silicic rocks (dacites and rhyolites). This alteration assemblage corresponds to reservoir temperatures of 260-290^{o}C and is dominated by illite, sericite, adularia and quartz, with lesser epidote and chlorite.

3. FLUID CHEMISTRY AND CONCEPTUAL MODEL

Awibengkok is a liquid-dominated, high permeability geothermal system with benign fluid chemistry. Fluid salinity is approximately 1.3 wt. % and NCG content of steam is <1 wt. % except for the shallowest zones. Reservoir pressure conditions show that the system is underpressured with respect to the ground surface. In the vicinity of Awi 1-2, boiling point conditions occurred at about 560 m above sea level, allowing the local development of a gas-rich steam cap. Subtle variations in fluid chemistry allow the field to be subdivided into three distinct cells: West, Central and East (Molling and Rohrs, 1996). In addition, wells located on the periphery of Awibengkok reservoir have distinct chemical signatures of "edge" wells. The key chemical features of each cell and the edge wells are summarized below (Figure 5 and Table 2). The West cell, which includes the Awi 9 wells, has the highest measured temperatures and chemical geothermometry. Measured temperature attains 312^{o}C, while NaKCa and quartz geothermometers are up 316^{o}C. Compared to other regions of the reservoir, the gas composition is depleted in H_2, CH_4, N_2, and Ar, and enriched in CO_2 and H_2S, reflecting a stronger magmatic influence.

The Central cell is characterized by wells on the Awi 7, 8, 10 and 11 locations, where chloride concentrations range between 6500 and 6900 ppm. Compared to the West, the Central cell has higher chloride and lower gas contents. Furthermore, chemical modeling suggests that the Central cell gas is enriched in H_2S and NH_3 and depleted in H_2. These chemical features suggest that the Central cell has experienced gas loss as a result of long-term convective processes and associated boiling. The east cell, which includes wells on the Awi 1, 2, 13, and 16 locations, is distinguished by dilution (Cl from 5100 to 6400 ppm) and higher NCG concentrations. The pattern of dilution, which runs NNE from the Awi 16 to Awi 13 locations suggests structural control related to the young NNE volcanic and hydrothermal vent trend. A mass-balance calculation reveals that the fluid contains relatively high Mg concentration and significant amounts of SO_4^{2-}, HCO_3^- and NH_3. This fluid is interpreted to be steam-heated meteoric water (Figure 5). The higher NCG in this cell is a feature of the shallow reservoir top. During the evolution of the reservoir, gas accumulated in this shallow portion of the system in response to boiling and condensation. A productive steam cap is currently forming in this area in response to mass withdrawals. Most of the edgewells show outflow characteristics and influence from deep marginal air-saturated ground water. Awi 5 and some Awi 14 wells located in southeast Awibengkok show relatively high concentrations of chloride and low chemical geothermometry, indicating an outflow origin. Outflow to the north of Awi 3 is supported by the distribution of surface thermal features.

3.1 Conceptual Model

A simplified fluid-flow map of the Awibengkok geothermal system is shown in Figure 6. Flow patterns include upflow, re-circulation, outflow, and influx. Deep upflow occurs in the West cell. Ascending fluids are locally confined by low-permeability clay-rich tuffs on the west, but move up along one or more N or NNE-trending structures that breach these barriers in the central and east-central parts of the Central cell. Fluids ascend to the top of reservoir in the East cell and boil under the Cibeureum fumaroles. Some portion of the boiled fluid outflows at shallow depths towards Awi 5, another portion moves down into the Awi 14 area, and some re-circulates to the base of the Central cell. Other outflows occur deep to the west of Awi 9 and north of Awi 3. Outflow to the west is indicated by a deep temperature reversal in the western-most well. Influx of steam-heated meteoric water occurs in the East cell, as indicated by dilution in that area. Minor influx or mixing also occurs in edgewells from deep marginal air-saturated meteoric water, as indicated by gas compositions.

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Table 1. Major lithostratigraphic sequences of the Awibengkok reservoir.

Formation	Dominant lithologies	Approximate Age	Possible Origin and Significance
Upper Volcanic	Andesite to rhyolite	Pleistocene to Recent (0.86 Ma to present)	Modern cone construction/destruction and parasitic silicic volcanism. Near-source rhyolitic tuffs and lavas and domes.
Middle Volcanic	Andesite to dacite	Pliocene to Pleistocene	Pre- to Early-modern cone construction stage; includes numerous distal to proximal fallout tuffs
Lower Volcanic	Basalt to rhyolite (silicic tuff sequence at top)	Late-Miocene to Pliocene	Main arc stage; terminated with deposition of the rhyodacite marker bed. Transition from marine to subaerial conditions.
Sedimentary Basement	Carbonates, ash turbidites, and volcaniclastic rocks	Early to Late-Miocene	Marine sedimentary sequence (pre- and syn-volcanic sediments). Includes some lavas and intrusive rocks.

Table 2. Average chemical characteristics of Awibengkok reservoir chemistry cells and edge wells.

	West	Central	East	Edge
Cl (ppmw)	6270	6700	6000	6850
NaKCa (°C)	288	266	252	260
Quartz (°C)	304	277	238	267
Mg (ppmw)	0.07	0.12	0.30	0.15
NCG in TF (ppmw)	1230	1190	2380	870
CO_2/H_2S (mole ratio)	13	14	32	18
CO_2/CH_4 (mole ratio)	466	105	82	95

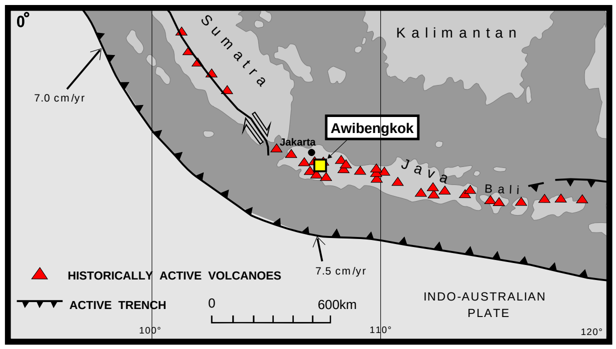

Figure 1. Regional Tectonic Setting

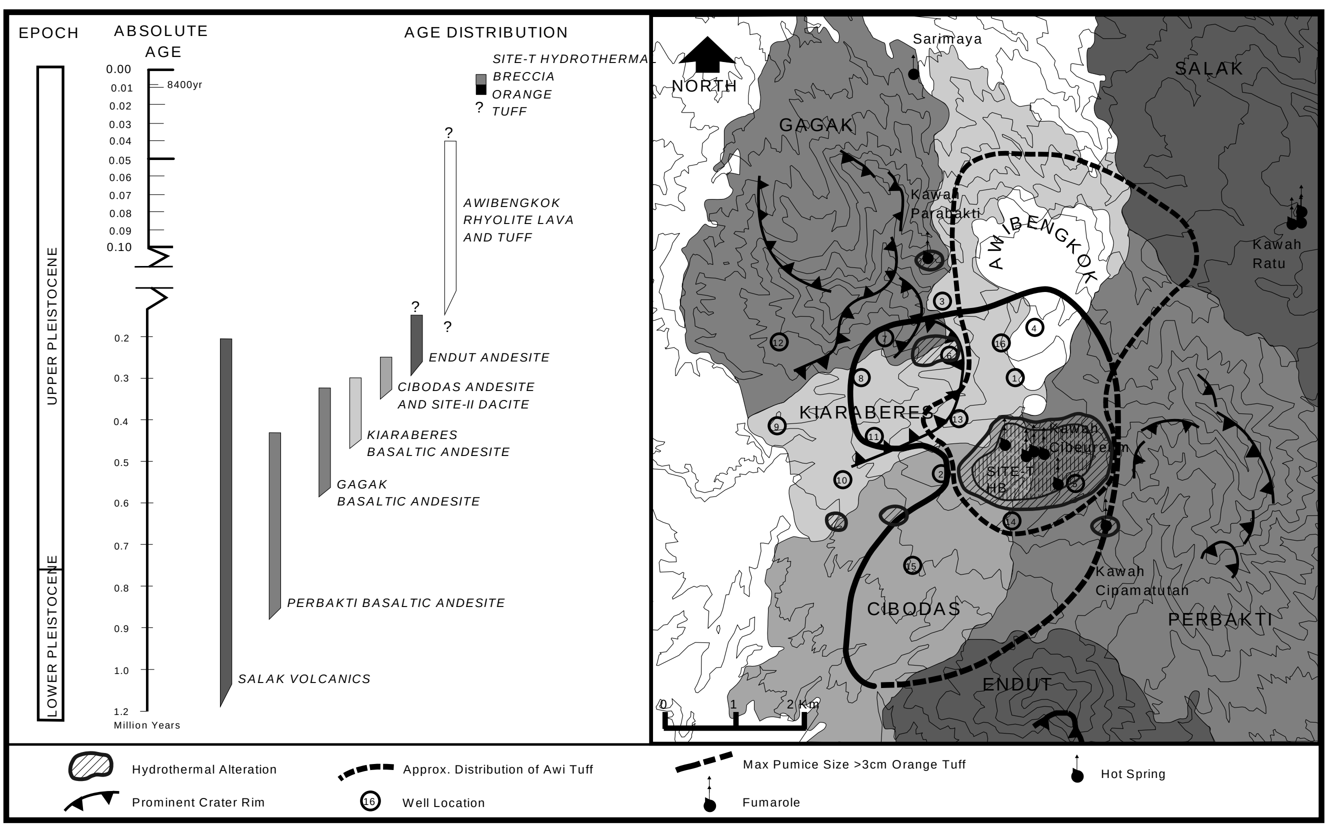

Figure 2. Geology of the Awibengkok Area

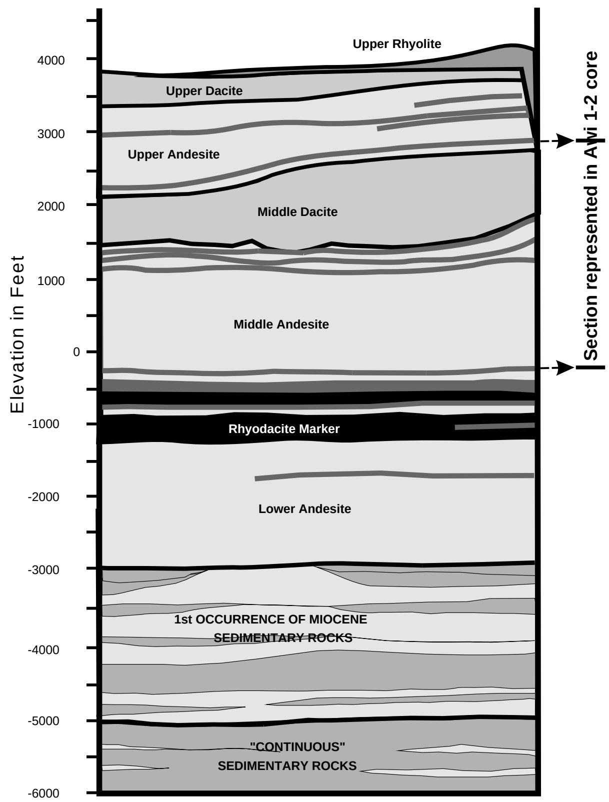

Figure 3. Idealized stratigraphic section

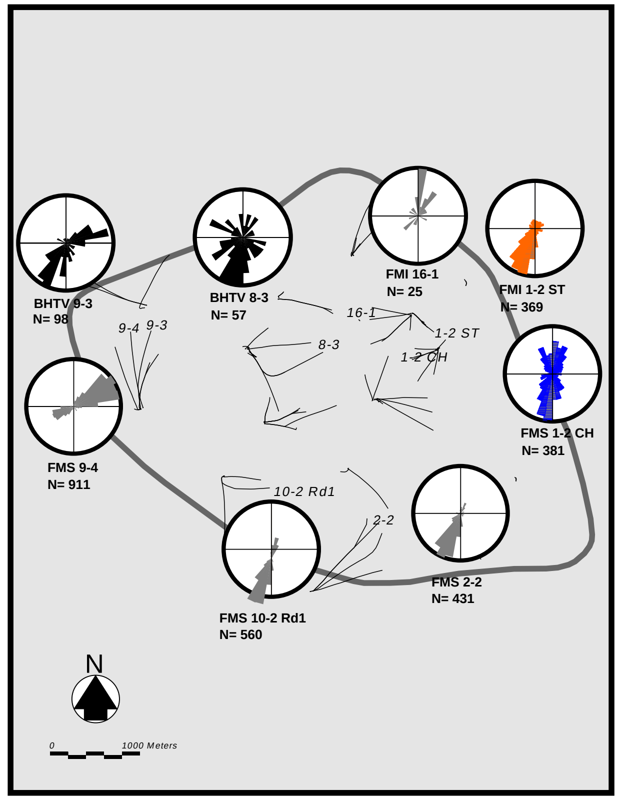

Figure 4. Fracture Strike Direction determined from Image Logs

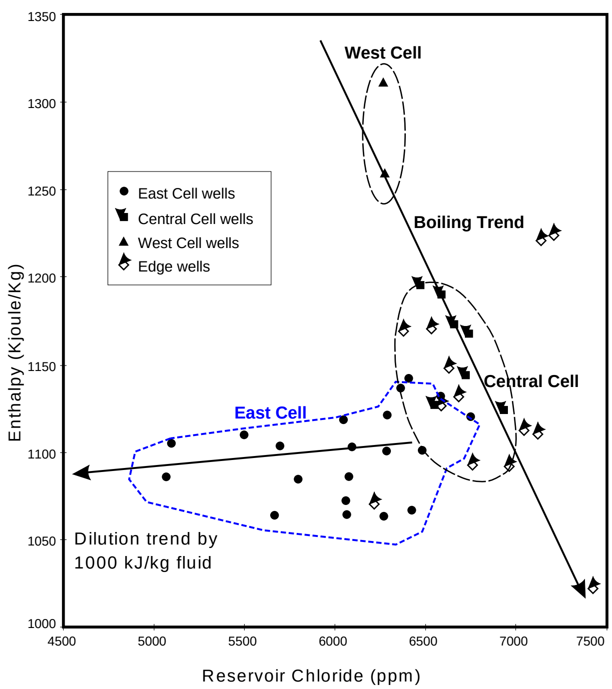

Figure 5. Chloride-enthalpy plot shows the relationships among geochemical cells in Awibengkok reservoir. The central cell is plotted in the boiling trend line of the West cell fluid. The East cell is originated from the Central steam heated meteoric water with enthalpy of about 1000 kJ/kg or 216 degree C.

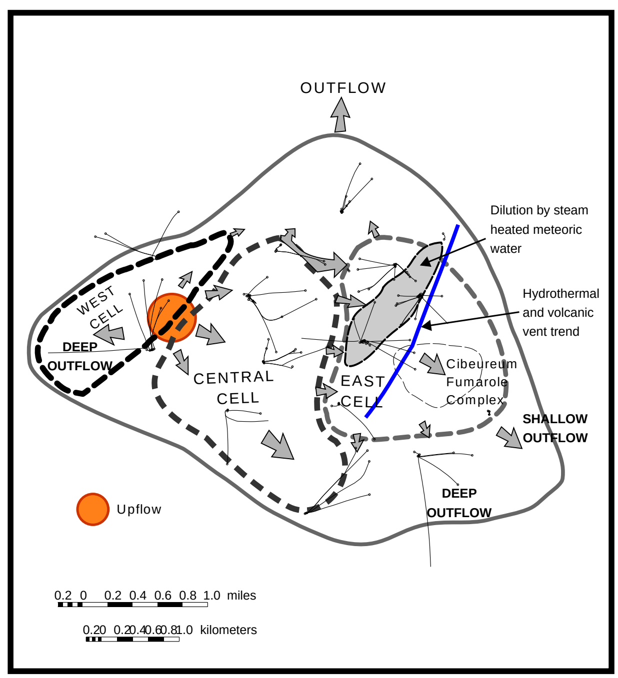

Figure 6. Map of geochemistry and fluid model of Awibengkok geothermal system shows three distinct cells. Upflow occurs in the West side of the field and flows to the East. Outflows occurs in the West, North, Southeast and to the fumarole complex above the reservoir.