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THE AWIBENGKOK, INDONESIA, GEOTHERMAL RESEARCH PROJECT

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ABSTRACT

The U.S. Department of Energy's Office of Geothermal Technology has obtained, from Unocal Geothermal Indonesia, 1.1 km of continuous core from a 1995 research corehole, Awi 1-2, drilled into the large, high-temperature, Awibengkok geothermal system in West Java. The core will be the nucleus of a collaborative research effort designed to expand our knowledge of composite volcanic-hosted ("andesitic") hydrothermal systems, which provide an increasingly large share of the world's geothermal power. Awibengkok, an ideal representative for these systems, is hosted principally by Quaternary-age, intermediate- to felsic-composition volcanic rocks. The research corehole penetrated the shallowest portion of the Awibengkok system, where these young volcanics are pervasively propylitized as well as locally silicified and adularized beneath a clay-rich caprock. Thermal-fluid flow appears to occur and to have occurred along faults, fractures, and open, mineralized veins and hydrothermal breccias. Porosity has been enhanced by hydrothermal dissolution.

Complementing the core for this research effort is an extensive Unocal data set comprising wireline logs; fluid and rock chemical and mineralogic analyses; physical-property measurements; and full-color digital imagery. With the core, this information, and an elite research team, the project is certain to furnish fundamental new scientific insight into the origin, evolution, and configuration of andesitic systems anywhere on Earth. In turn, this new understanding should help U.S. geothermal companies find and develop such systems with greater ease and reduced expenditure.

INTRODUCTION

In mid-1997, the U.S. Department of Energy's (DOE) Office of Geothermal Technology, working through the Energy and Geoscience Institute (EGI), finalized negotiations with Unocal Geothermal Indonesia (UGI) to obtain 1.1 km of continuous core from the heart of the large, high-temperature, Awibengkok geothermal system in West Java, Indonesia (Figs. 1 and 2). The core, with selected logs, analyses, measurements, and imagery provided by UGI, will be the cornerstone of an intensive, multidiscliplinary, DOE-sponsored geothermal research effort during the next several years. The ultimate goal of this project is to, improve significantly our understanding of reservoir controls in andesitic geothermal systems worldwide. The more that is known about these increasingly important systems, the easier they will be to locate and produce at reasonable cost.

The Awibengkok geothermal field was discovered in 1983 by UGI working as contractor to PERTAMINA, the Indonesian National Oil Company. UGI drilled the corehole, Awi 1-2, late in 1995; EGI personnel (J. Hulen and D. Nielson) were on site to monitor the drilling and complete a preliminary description of each 10-m core section as soon as possible after retrieval. The Awi 1-2 core is one of just two from andesitic geothermal systems which is not only of great length and completeness (nearly 100% core recovery by Tonto Drilling Services) but is also currently available for non-proprietary research (the other core is from Unocal's well MAT-25 in the Tiwi system, Philippines).

GEOLOGIC SETTING

The Awibengkok geothermal field is situated in the Salak contract area, encompassing much of the Quaternary-age Salak-Kiaraberes-Gagak-Perbakti volcanic complex (Effendi, 1974; Ganefianto and Shemeta, 1996). These overlapping composite volcanoes are typical of the Javanese sector of the Sunda-Banda volcanic arc (Fig. 1).

The Sunda-Banda arc marks the southern portion of the Eurasian plate where, beginning at the Java trench, it is underthrust by the northward-subducting Indo-Australian plate (Fig. 1, top). The arc is one of the world's richest geothermal resource areas. Eighty-eight of its 177 volcanic centers have active

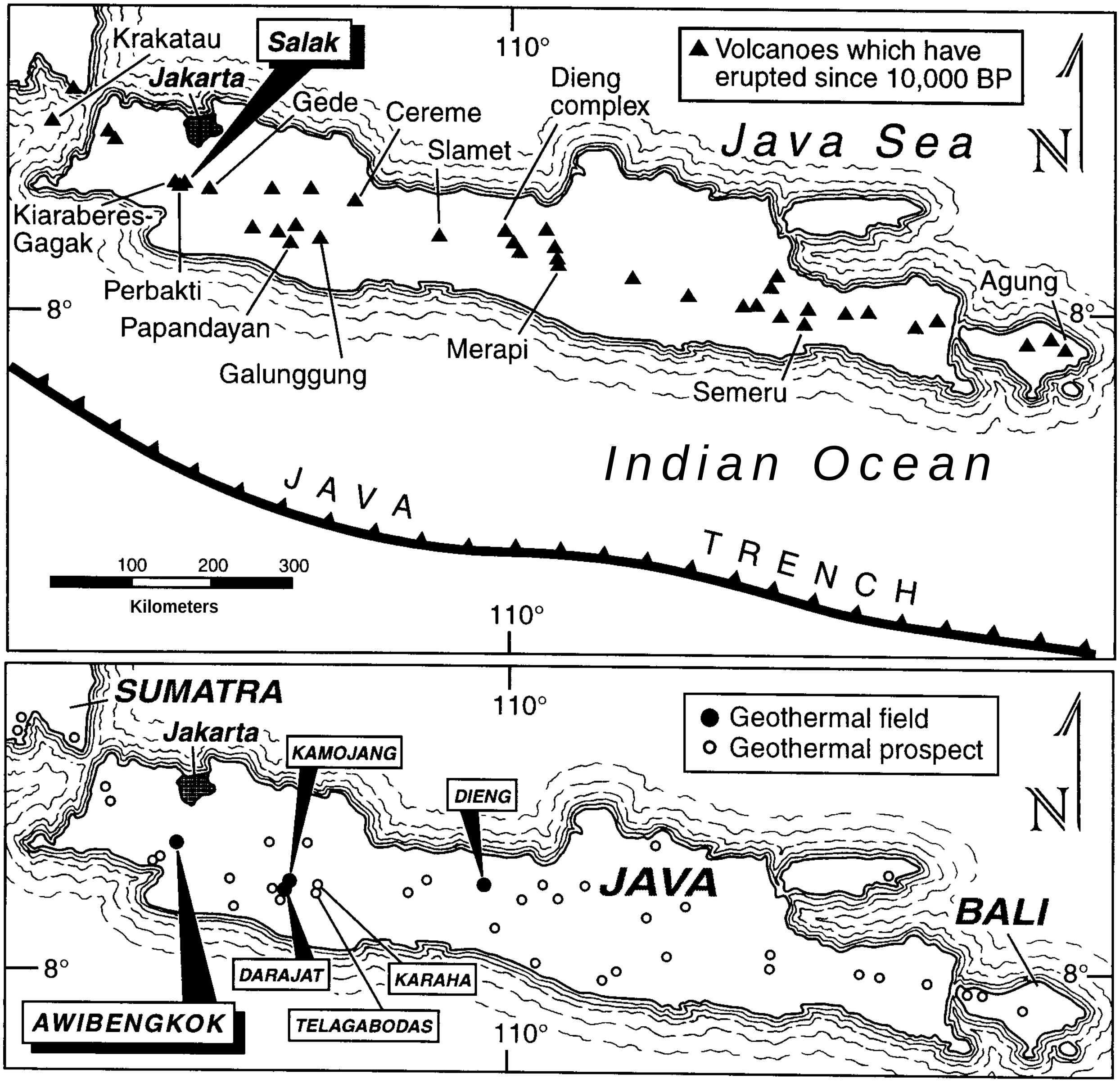

Figure 1. Maps of Java, Bali, and southermost Sumatra, Indonesia, showing (top) volcanoes with documented Holocene eruptions (including hydrothermal eruptions) and (bottom) geothermal fields and prospects. Volcanoes from Simkin and Siebert, 1994. Geothermal sites synthesized from Radja, 1990; Effendi, 1991; Ganda et al., 1992; and Rachman et al., 1995 (site numbers and locations differ slightly among these sources).

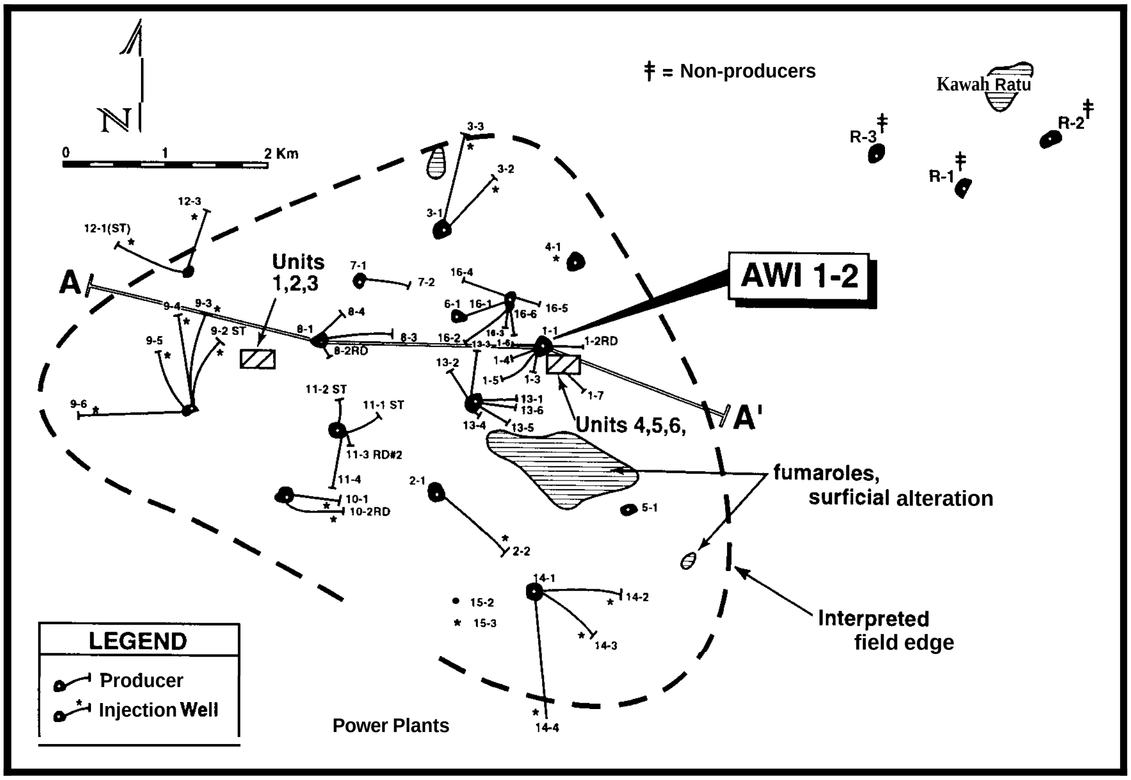

Figure 2. Well map of the Awibengkok geothermal field and Ratu geothermal area, showing'.. location of corehole Awi 1-2. Modified slightly from Unocal et al., 1997.

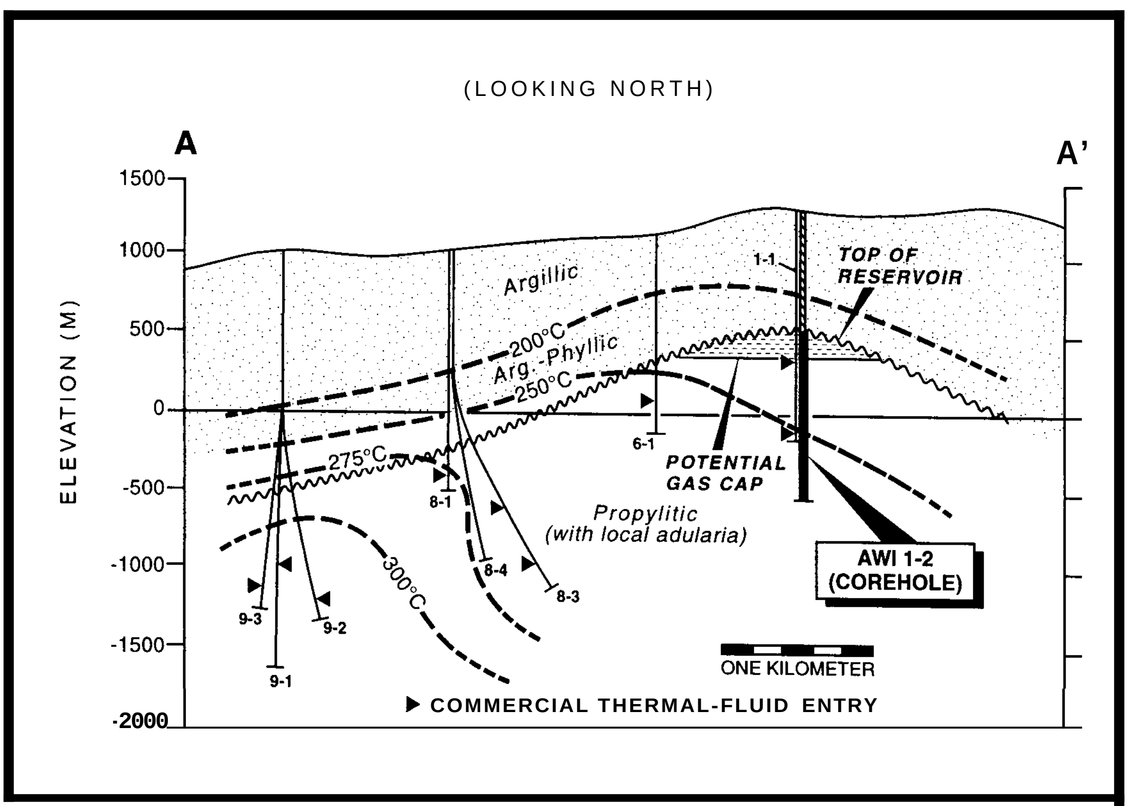

Figure 3. Highly generalized west-to-east cross section through the Awibengkok geothermal field. Modified from Murray et al., 1995; and Unocal et al., 1997.

surface thermal features (solfataras, hot springs, fumaroles, mud pots, and heated ground), and several support producing geothermal systems (Radja, 1990; Rachman et al., 1995).

Large-scale geothermal power production in Indonesia commenced at the vapor-dominated Kamojang field (Fig. I, bottom) in 1983. As of late 1997, Kamojang and the nearby, smaller but similar Darajat field were producing, respectively, 140 and *55* MW of electrical power (David Rohrs, pers. comm., 1998). At 330 MW of installed electrical generating capacity, however, the Awibengkok field is currently Indonesia's largest.

Awibengkok and the Ratu thermal area to the east (Fig. 2) are hosted principally by interstratified, intermediate- to felsic-composition, Quaternary-age flow and dome rocks, lahar breccias, and tuffs locally invaded by chemically similar subvolcanic and hypabyssal intrusive rocks. Of the four overlapping major volcanoes built of these products, only Salak has erupted juvenile magmatic material in Holocene time, having reportedly produced a small-volume pyroclastic flow in 1699 AD (Simkin and Siebert, 1994; L. Siebert, pers. comm., 1998). Other Holocene eruptions from Salak (including Ratu) and from Kiaraberes-Gagak have been phreatic events, yielding localized aprons of unsorted lithic debris.

The Awibengkok field exploits a large but otherwise typical, high-temperature, neutral-chloride, andesitic geothermal system. Reservoir temperatures range from 220°C to more than 300°C, and the produced fluids typically have a TDS content of about 1.3% (Ganefianto and Shimeta, 1996). Corehole Awi 1-2 was drilled in the shallowest portion of the geothermal reservoir, a sort of "cupola", where Murray et al. (1995) postulated there might have been a pre-exploitation gas cap (Fig. 3).

This cupola is somewhat unusual for the field in that it locally encompasses the basal portion of a field-wide argillic-phyllic alteration halo surrounding the reservoir proper (Ganefianto and Shemeta, 1996; Figs. 2 and 3). Within the halo, the volcanic rocks have been partially to near-completely altered to smectite, mixed-layer illite/smectite, and chlorite, with subordinate calcite, quartz, pyrite, and local hematite. As typical for such alteration, the illite content of mixed-layer illite/smectite in general increases with increasing depth and temperature.

The bulk of the Awi geothermal reservoir is hosted by intensely propylitized rocks dominated by the secondary-mineral assemblage epidote, chlorite, and calcite; adularia, quartz, pyrite, sericite "leucoxene" (sphene-anatase mixture), anhydrite, and wairakite are also present in varying amounts and combinations.

The cored portion of Awi 1-2 penetrated the depth interval 762-1830 m (Fig. 4). Beneath an upper andesitic lahar breccia, the hole encountered, in sequence: a thin dacite ash-flow tuff; a thick zone of dacite flow-dome (?) rocks (with prominent quartz phenocrysts); another thin andesitic lahar breccia; a wholly altered andesitic tuff complex; and a relatively thinly bedded sequence of flow rocks, lahar breccias, and tuffs to total depth. There are many thin andesite and dacite porphyry intercepts in the corehole which conceivably could be subvolcanic intrusives rather than flow rocks, but a microdiorite porphyry at about 1700 m depth is of unambiguous intrusive origin. Hydrothermal breccias are common in the core (Fig. 4), and include pebble dikes and jigsaw-puzzle breccias cemented by black pyritic silica. Open veins with apertures as large as 2 cm occur throughout the core below about 1100 m depth. Adjacent to and between these veins, irregular voids up to several cm in diameter record prior hydrothermal dissolution.

TECHNICAL INFORMATION TO ACCOMPANY THE CORE

An important asset to the Awi 1-2 research program will be an extensive collection of wireline logs and analytical data made available for the project by UGI. The logs, in digital format, include (1) total-count gamma; (2) spectral gamma; (3) injection temperature; (4) caliper; (5) vector magnetic intensity; (6) dual-induction; (7) SP; and (8) full-waveform sonic logs for the corehole and/or the adjacent sidetrack production well. The core was also analyzed at the well site for porosity and density, and for total-count gamma ray intensity at 3294 pts along its full length. Continuous, digital, high-resolution color imagery of the slabbed core, to be distributed in CD-ROM format, will allow investigators to view selected intervals with ease.

Various analyses and measurements obtained for the core by UGI and made available as background for this investigation include: (1) porosity and permeability under ambient and overburden conditions; (2) magnetic susceptibility; (3) whole-rock silicate oxygen-isotope values; **(4)** mechanical properties of

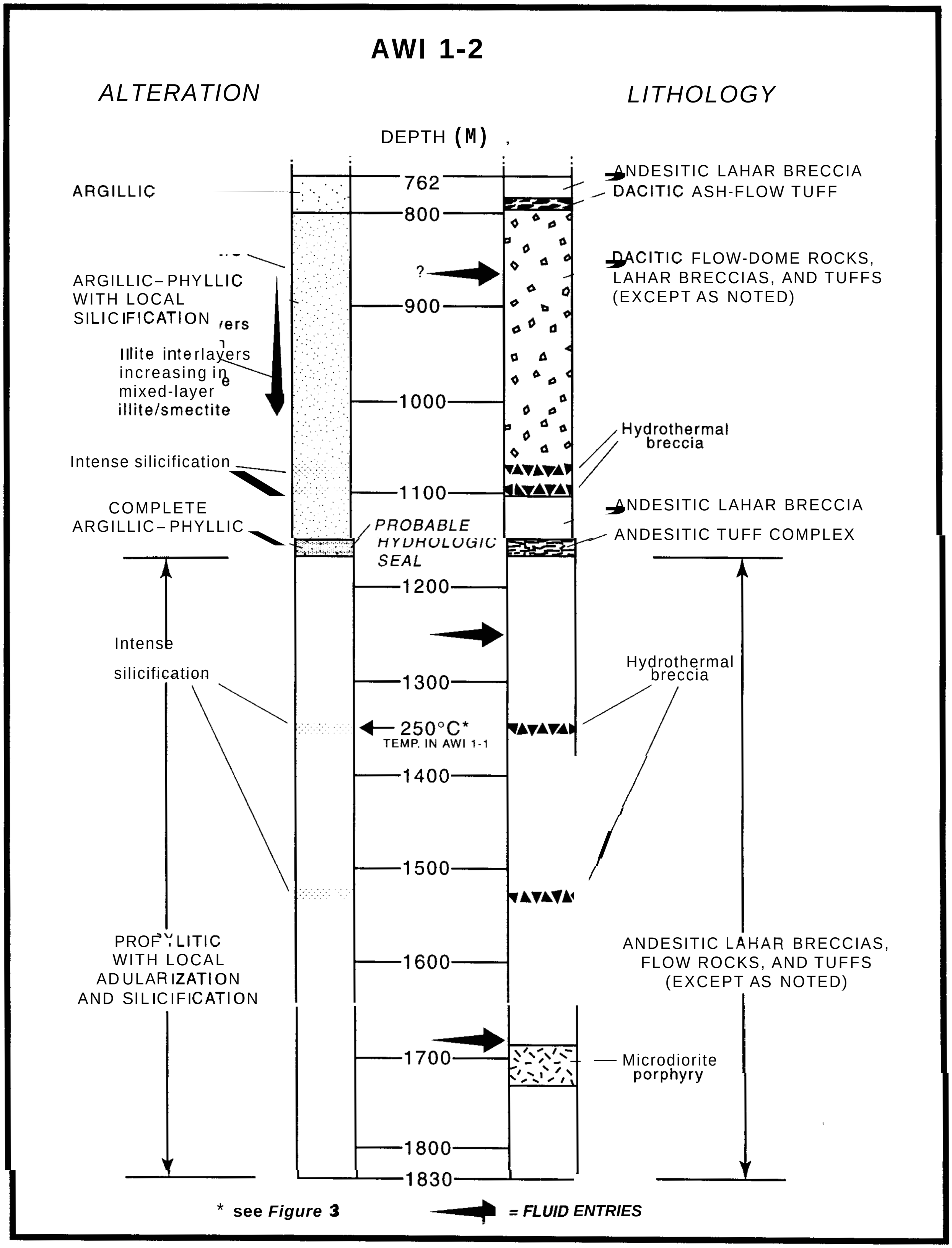

Figure 4. Highly generalized lithologic and alteration columns for corehole Awi 1-2. Simplified and modified from field geologic log prepared in late 1995 by J. Hulen and D. Nielson. Fluid entries inferred from prominent local excursions on UGI injection-temperature-gradient log.

rocks; and *(5)* brine and gas compositions from flow tests of the corehole and an adjacent production well. These data will clearly enhance the value of collaborating investigators' individual and collective research efforts.

SCIENTIFIC OBJECTIVES

The principal scientific and practical goals of this investigation can be stated briefly as follows: (1) Through detailed study of the continuous Awi 1-2 core and accompanying database, significantly improve understanding of reservoir controls in a large but otherwise typical island-arc, andesitic, high-temperature, neutral-chloride, liquid-dominated hydrothermal system. *(2)* Compare and contrast the new information obtained from this study with corresponding data from other such systems, both local and global. (3) Present and publish results promptly so that these systems can be found and developed in all parts of the world with greater efficiency and minimum cost.

Key tasks leading to fulfillment of these goals include but are not limited to the following: 1 -- Determine the origins, measure and map the configurations, and establish the interrelationships of fractures, breccias, dissolution cavities, vesicles, and other voids which singly or in combination serve as geothermal-fluid conduits or storage sites. Develop predictive concepts for the location, character, and quality of permeable zones in andesitic geothermal systems as a class. Study the relative influence of regional vs local controls on development of these features. For example, to what extent are fractures and breccias formed in response to far-field stresses, and to what extent are they products of local forces.

2 -- Ascertain lithologic controls on the geothermal system's key components (for example, caprock vs productive reservoir; aquifers and aquicludes in the reservoir proper). In so doing, establish a detailed volcanic stratigraphy which will be useful for three-dimensional mapping of discordant potential fluid conduits such as fractures and pebble dikes.

3 -- Investigate the effects of igneous intrusions on the geometry of the geothermal system and on the permeability-related compositions and textures of the reservoir rocks invaded by these plutons.

4 -- Map in detail hydrothermal alteration mineralogy and zoning on a reservoir-wide and local scale. Critically examine this information for correlations with other rock and reservoir properties. For example, do certain alteration mineral assemblages and zoning sequences show a systematic relationship to active thermal-fluid conduits? Are impermeable hydrothermal breccias differently altered than their permeable vuggy counterparts? Investigate the utility of secondary-mineral zoning and paragenetic sequences in mapping potentially productive fluid channels.

5 -- Reconstruct the hydrothermal history of the portion of the Awibengkok system penetrated by the corehole. If possible, utilize this information to help predict changes in reservoir characteristics with time and progressive depletion.

6 -- Measure multiple physical and mineralogic properties of the penetrated rocks, not only under ambient conditions but also under simulated reservoir pressures and temperatures. Examine the utility of this information in constraining interpretations of surface- and borehole-based geophysical surveys.

SIGNIFICANCE OF EXPECTED RESULTS

The new information obtained from this investigation will: (1) improve the odds of finding similar andesitic systems anywhere in the world; (2) help reduce costs in exploiting those systems already secured, including Awibengkok itself; and (3) help enable reservoir engineers to prolong the systems' productive lives through more informed long-term development strategies.

The work will also inevitably yield a detailed picture of the system's evolution since inception, especially: (1) the nature and timing of events specifically linked to the creation or modification of porosity and permeability; and (2) fluid sources, volumes, pathways, chemical transformations, and thermal histories. This knowledge will be valuable not only in geothermal exploration and development, but also in the search for and mining of worldwide, volcanic-hosted, epithermal mineral deposits.

APPROACH

The Awi 1-2 core arrived in late January 1998 at EGI's Geothermal Sample Library, where it will be available for examination and judicious sampling by collaborating investigators. To ensure proper archival of the core and the data generated therefrom, sampling activities will be governed by a strict core protocol. For example, each researcher will be requested to furnish raw data generated by his or her research project to EGI within a specified period following sample acquisition. The core itself will be (technically, will have been when this paper is published) the focus of a workshop in Salt Lake City, Utah, during the second quarter of 1998. A site-specific Science Plan for the project will be debated and refined at this gathering, and copies of the Plan will be distributed to all participants within two months of the workshop. Chief Scientist for the project will be J. Hulen of EGI. In order to maximize the project's scientific yield, Hulen will maintain close contact not only with the research team, but with key Unocal personnel most familiar with Awibengkok, especially Unocal's Chief Development Geologist Glenn Melosh, Senior Geologist Jim Stimac, and Research Coordinator Tim Anderson. The Awi research plan as presently envisioned will be a modification and expansion of the one successfully applied on The Geysers Coring Project (e.g. Hulen et al., 1995), but tailored to the geologic, geochemical, and hydrologic setting of the Awibengkok field.

Fundamental studies for the Awi 1-2 project will be those which have proven value in the characterization of high-temperature geothermal systems and epithermal mineral deposits. Some of the investigations scheduled for completion are listed below. **A** more exhaustive catalogue will have emerged from the Awi workshop in Salt Lake City.

1 -- Detailed geologic logging of the core at a nominal scale of 1" = 10 ft. This work will complement the very preliminary logs prepared on site during drilling operations, and will focus more closely on those features critical to the storage and transmission of thermal fluids in the subsurface -- fractures, faults, breccias, veins, vugs, dissolution cavities, vesicles, intergranular pores. Lithologic units will be scrutinized to determine their roles as aquifers and hydrologic seals. A detailed stratigraphy will be established for comparison, ultimately, with the geologic sections penetrated elsewhere in the reservoir. The stratigraphic section and its rock components will be compared with wireline logs so that similar units can be identified with greater confidence from log responses alone.

2 **--** Studies of hydrothermal alteration mineralogy and zoning as well as vein mineralogy and paragenesis will provide detailed information for constraining the hydrothermal history of the Awibengkok system. Methods to be employed in this undertaking include the detailed geologic logging mentioned above; petrographic analysis; X-ray diffraction; X-ray fluorescence and other geochemical analytical techniques; stable-isotope geochemistry; electron-microbeam geochemical analysis of individual minerals; clay-mineral geothermometry; $^{40}Ar/^{39}Ar$ incremental-heating age dating and thermal-history modeling; fluid-inclusion microthermometry and geochemical analysis (especially trapped gases); numerical geochemical modeling.

3 -- Refined characterization and measurement of porosity and permeability at the scale of the core, utilizing an array of precise, modern, imaging and analytical methods.

4 -- Monitoring of changes in permeability, porosity, and other rock properties **of** the core (for example, electrical and acoustic) at various simulated reservoir conditions. This information will be useful in forecasting reservoir behavior, for planning effective injection strategies, and for predicting the responses of various rock units and alteration assemblages during surface- and borehole-based geophysical surveys.

SUMMARY

This outline of the Awibengkok research project, in addition to announcing an unparalleled geothermal research opportunity, is also in effect the project's abbreviated, preliminary Science Plan. The Plan will have been expanded and refined at the Salt Lake City workshop through the efforts of interested investigators from universities, national laboratories, governmental agencies, and other institutions. Component research projects are envisioned to span 1-3 years. Research updates will be given to all interested parties in semi-annual EGI reports, and in talks and discussions at the annual Stanford Workshop and Geothermal Resources Council Meeting. We will further distribute information electronically via the world-wide web.

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*--Illustrations by Ron **Wilson** and Doug Jensen--*

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