IMPROVING EXPLORATION MODELS OF ANDESITE-HOSTED GEOTHERMAL SYSTEMS

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Project Background and Status

Conceptual models provide the framework for essentially all geothermal exploration and development. These models are used to locate and prioritize geothermal systems, site drill holes and predict the characteristics of the reservoir before extensive drilling has occurred. Most of the world's producing geothermal systems are associated with andesite volcanoes. Similar geothermal systems are likely within the Cascades of the western U.S., but this province is still largely untapped and poorly understood.

U. S. geothermal companies specifically requested the investigations being conducted under this five-year program. Our study of Karaha-Telaga Bodas (Indonesia) is a joint effort between the Karaha Bodas Co. LLC (an affiliate of Caithness Energy LLC) while work on Bulalo (Philippines) is a cooperative program with Philippine Geothermal Inc. (a subsidiary of Unocal). Karaha-Bodas Co. LLC has provided more than 4 km of core from 4 coreholes, cuttings from production wells drilled to depths of 3 km, MT and gravity data, downhole pressures and temperatures, gamma-ray surveys, electric image logs, chemical and isotopic analyses of water and gas samples, well-test results and existing petrographic and geologic information. This is the most comprehensive data set currently available from any andesite-hosted system.

Project Objectives

The objective of this project is to develop better exploration models of volcanic-hosted systems through an improved understanding of reservoir geometries, permeabilities, fluid chemistries and evolutions. Meeting this goal will have three important results. First, it will lead to improved exploration strategies within the high Cascades, which holds great potential for geothermal development in the U.S. Second, it will reduce the cost of exploration and development by minimizing the number of wells needed and by improving drilling targets in volcanic-hosted systems. Third, this information will help the U.S. industry remain leaders in geothermal exploration and development.

Approach

The basic premise behind this investigation is that there are common geologic factors that favor the formation and growth of geothermal systems in specific geologic environments. The geologic factors that are most important will become evident through a comparison of detailed studies of individual systems. Downhole temperature, pressure, production and geochemical data are allowing us to characterize the present-day structures of the geothermal reservoirs. Mineralogic and fluid inclusion studies are providing information on their evolutions. Modeling of the geophysical data is yielding insight into their geometries and heat sources. Satellite images of surface structural trends and alteration zones, thin sections of core and cuttings samples, fracture logging of core holes and electric image logs are being used to characterize permeabilities at different scales. Information on the age of the systems and major hydrothermal events is being obtained from $^{40}Ar/^{39}Ar$ and ^{14}C dating.

The results of these investigations are being critically examined in light of concepts generated from studies of other geothermal systems. In this regard, recently completed investigations of Tiwi, Philippines (Moore et al., 2000a) and The Geysers, U.S. (Moore et al., 2000b, 2001a) are particularly relevant. For example, Karaha-Telaga Bodas and Tiwi are associated with young andesitic volcanoes; both display evidence of a magmatic influence, both have wells that discharge highly acidic fluids and both appear to be relatively large systems. However, Karaha-Telaga Bodas has a large vapor-dominated regime, whereas Tiwi does not. Thus fundamental differences exist between the two systems, despite their apparent similarities. In contrast, the presence of vapor-dominated regimes at both The Geysers and Karaha-Telaga Bodas suggests that there may be some similarities in their reservoir properties and evolutions, despite differences in their geologic settings. A generalized conceptual model that can be applied to the exploration and development of andesite-hosted volcanic systems will be developed from these investigations.

Results

Prior to our investigations of Karaha-Telaga Bodas, little was known about this potentially significant resource or about the evolution of vapor-dominated geothermal systems in volcanic terrains. Although vapor-dominated systems are widely sought after because of their high productivities, few are known (e.g. Darajat, Indonesia; The Geysers, California; Larderello, Italy). Thus, our studies of Karaha-Telaga Bodas represent a unique opportunity to evaluate the evolution and characteristics of vapor-dominated systems. Furthermore, few time-temperature-composition histories of geothermal systems have been developed. This information is used to develop natural state models and predict how a system will behave during production.

The Karaha-Telaga Bodas Geothermal System

Exploration at Karaha-Telaga Bodas has focused on a portion of the volcanic ridge extending from Kawah Galunggung to the north (Fig. 1). The fumarole field at Kawah Saat, a shallow acidic lake (Telaga Bodas) and chloride-sulfate-bicarbonate springs occur at the southern end of the prospect. A smaller fumarole field, Kawah Karaha, occurs at the northern end of the prospect. Figure 2 is a north-south cross section of the field based on our interpretation of the downhole measurements and gravity data (Allis et al., 2000; Tripp et al., 2002). The pressure-temperature data indicate that the resource is partially vapor-dominated and that these conditions extend laterally for more than 10 km and vertically to depths below sea level. A liquid-dominated resource with measured temperatures of at least 350°C and low salinities (1-2 weight percent TDS; Powell et al. 2001) lies beneath the vapor-dominated regime.

Mineral parageneses, fluid inclusion systematics and ^{14}C dating indicate that the vapor-dominated regime developed very recently (Moore et al., 2002a). The ^{14}C dating indicates that lakebeds encountered at a depth of 988.8 m were deposited 5910 +/- 76 years BP. The age of the lakebeds is younger than expected. It implies that significant volcano building, high-temperature hydrothermal alteration (>300°C) related to an extensive liquid-dominated system and the development of the modern vapor-dominated regime occurred since the lakebeds were buried. This liquid system appears to have formed in response to the intrusion of quartz diorite emplaced at a depth of <3 km near the Telaga Bodas thermal area.

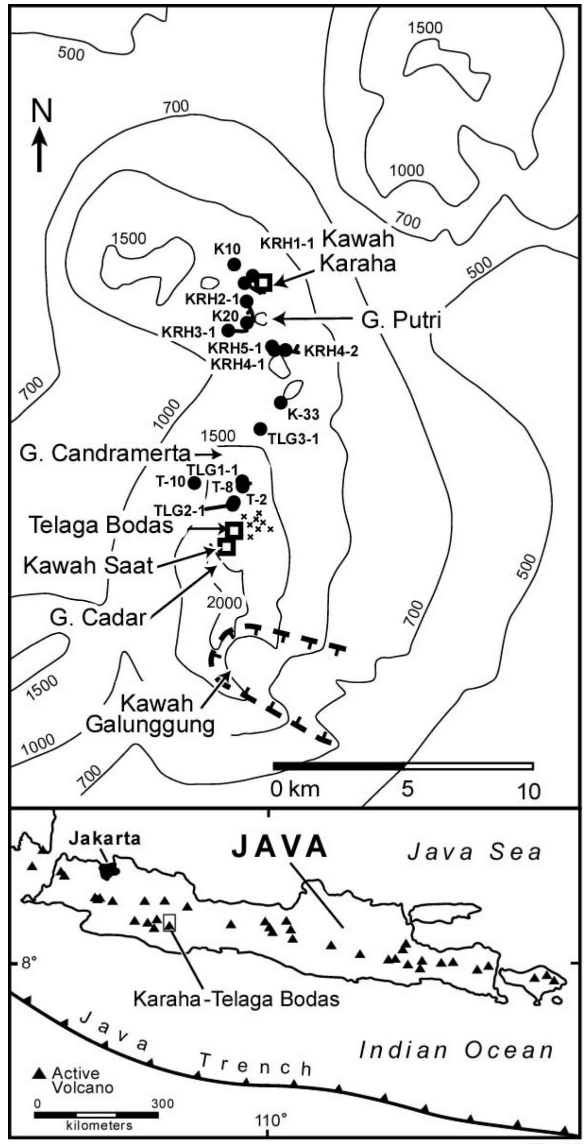

Figure 1. Map illustrating the distribution of volcanic features, thermal manifestations (Kawah Saat, Telaga Bodas, thermal springs (x's) and Kawah Karaha), and geothermal wells (filled circles) at Karaha-Telaga Bodas. Contour lines show surface elevations in meters above sea level.

The transition from a high-temperature liquid-dominated system to vapor-dominated conditions is represented by the widespread deposition of chalcedony and quartz. Fluid inclusions in quartz indicate that the, chalcedony was deposited at temperatures in excess of 250°C. At these temperatures, extreme supersaturation of silica with respect to quartz is required. Continued boiling and

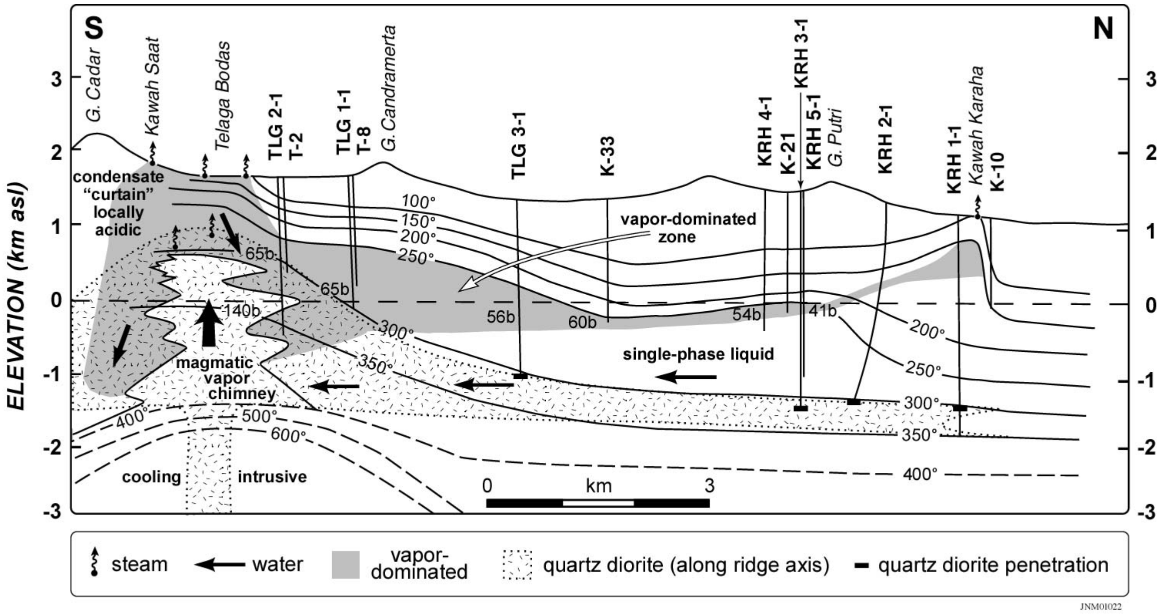

Figure 2. North-south cross section through the Karaha-Telaga Bodas geothermal system. Modified from Allis et al. (2000) and Tripp et al. (2002).

escape of the steam resulted in a progressive increase in the salinities of the residual fluids. Fluids with salinities up to 24 weight percent NaCl-$CaCl_2$ equivalent were trapped in the quartz crystals. Catastrophic depressurization and boiling is required to produce chalcedony at temperatures >250^oC. Depressurization of the liquid-dominated system could have been triggered by massive slope failure of Galunggung Volcano ~4200 years ago (Katili and Sudradjat, 1984).

As the liquid levels and pressures within the reservoir declined, steam condensate percolated downward. Interactions between the condensate and wall rocks produced advanced argillic alteration assemblages and veins dominated by the successive appearance of anhydrite, pyrite, calcite and fluorite (Moore et al., 2002b). Fluid inclusions trapped in anhydrite and calcite suggest that temperatures increased again after deposition of the quartz due to renewed magmatic heating. Boiling off of the descending condensate resulted in a progressive increase in its salinity with depth and eventually the deposition of chemical precipitates consisting of NaCl, KCl, $FeCl_x$ and Ti-Si-Fe. The presence of these precipitates demonstrates that the rocks had dried out prior to drilling. Hypersaline fluids trapped in anhydrite at 300^oC may record conditions shortly before complete dry out occurred.

The waters encountered in the reservoir rocks underlying the vapor-dominated region could not represent residual liquids remaining after deposition of the chalcedony and quartz. These fluids would have had salinities much greater than the 1-2 weight percent of the produced waters. The low salinity waters most likely represent mixtures of meteoric recharge and descending condensate.

The importance of these investigations is perhaps most clearly demonstrated by the willingness of the geothermal industry to initiate and actively participate in studies with EGI, provide access to data and samples that are not in the public domain and to encourage publication of the results.

Future Plans

During the remainder of the award period, our investigations will focus on:

1) Deciphering the evolutions of individual systems through detailed mineral paragenetic and fluid inclusion investigations;
2) The distribution and evolution of reservoir permeability through fracture logging of core holes and interpretation of electric image logs;
3) Determination of fluid sources and reservoir processes (e.g. boiling and mixing) through measurement of fluid inclusion gases (H_2O, CO_2, CH_4, H_2S, H_2, N_2, Ar, and $C_{2\text{-}7}$);

4) The absolute ages of geothermal activity ($^{40}Ar/^{39}Ar$ and ^{14}C dating); and
5) Developing conceptual models of andesite-hosted systems. The model presented by Allis and Moore (2000) will be refined and tested.

Collaborations

Our studies represent collaborative efforts with the geothermal industry and other organizations. The associations we have developed bring a broad range of demonstrated expertise to the project. Key collaborators include: M. Adams (EGI; geochemistry), R. Allis (Utah Geological Survey; temperature-pressure data), P. Browne (University of Auckland; geology and geochemistry), B. Christenson (Institute of Geological and Nuclear Sciences New Zealand; geochemistry), T. DeRocher (Caithness Energy), M. Heizler (New Mexico Bureau of Mines, $^{40}Ar/^{39}Ar$ spectrum dating), S. Lutz (EGI, mineralogy), J. McCulloch (Caithness Energy), D. Mindenhall (Institute of Geological and Nuclear Sciences, New Zealand; palonology and radiocarbon dating), G. Nash (EGI; remote sensing), M. Nemcok (EGI, structural geology), D. Norman (New Mexico Tech; fluid inclusion gas analyses), S. Petty (Caithness Energy), T. Powell (Thermochem, Inc.; geochemistry), I. Raharjo (University of Utah; geophysics) J. Renner (INEEL; mineralogy), J. Stimac (Unocal), A. Tripp (EGI; gravity data) and P. Wannamaker (MT data).

Sixteen technical papers have resulted from the research conducted under this grant. Four were delivered at the 2002 Stanford Reservoir Engineering Conference; one will be presented at the 2002 Geothermal Resources Council meeting. Two (Moore et al., 2001a and Nemcok et al., 2001a) were invited presentations at international conferences. The full citations of these papers are given below.

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