AN INTEGRATED APPROACH TO CONCEPTUAL MODELING OF GEOTHERMAL RESERVOIRS

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Optimum use of a geothermal reservoir can be best achieved by using a conceptual hydrogeologic model of the reservoir as a guide to development. The conceptual model defines the geologic structures and/or stratigraphic units which form permeable zones within the geothermal system; the source of fluid and the direction of flow within these zones; and the location of the reservoir with respect to the main elements of the geothermal system, including the upflow zone, outflow zone and heat source. As such, the conceptual model forms the basis for the development of a quantitative numerical model.

A detailed and accurate conceptual model can only be developed by integrating and interpreting all applicable geologic, geophysical, geochemical and engineering data. Although interpretation of data from each of these various disciplines is made by separate groups of individuals with appropriate expertise, all data must ultimately be compatible with one comprehensive model. The obstacle to achieving such an integrated model is the separate interpretation of individual data sets without reference to other data sets; this frequently results in the development of several, often incompatible, models for the same geothermal reservoir.

Recognition of the inherent relationships between different types of data is crucial to the integrated approach. GeothermEx's experience with geothermal development worldwide has revealed several fundamental examples of data which are rarely integrated. As examples:

- Surface geologic mapping typically emphasizes identification of individual formations or units based on relative age or similarities in mineralogy or texture,. etc., while the hydrogeologic characteristics of these units are overlooked. From the point of view of developing a conceptual model, knowledge of the hydrogeologic properties of the mapped units can be critical if these same units are encountered in the subsurface.

- Steeply-dipping faults mapped on the surface should be identifiable in drilling data, and conversely, major faults inferred from subsurface data should be identifiable on the surface. However, well site geologists rarely coordinate their interpretations with the geologists who have mapped the surface.

- Geophysical surveys are often interpreted on a "stand-alone" basis. "Anomalies" identified in this way may or may not be associated with a geothermal reservoir; conversely, a geothermal reservoir may not have a readily identifiable anomaly. For example, electrical anomalies can reflect variations in pore-fluid salinity, temperatures, rock type, pore fluid saturation (above the water table), etc. Knowledge of the subsurface distribution of lithologies and fluid types can be used to identify those anomalies which are related to the geothermal system.

- The significance of temperature gradient data may be misinterpreted in areas where natural downflow of cool groundwater is occurring, or where perched, cool aquifers overlie a deep hot water zone. These are common situations in volcanic terrains, and temperature gradients cannot be correctly interpreted without information on the near-surface movement of cool groundwater.

- The analysis of temperature and pressure profiles from wells is often difficult. These profiles should be interpreted to determine the stabilized temperature and pressure profiles as well as to identify permeable zones and fluid condition in each well, with allowances made for: conductive cooling during mud circulation, cooling due to mud loss, cooling due to injection of cold water into the well, cooling due to pressure drop caused by production from two-phase zones, heating of the upper part of the hole due to production, interflow between two or more aquifers open to the well and existing at different potentials, effect of dissolved solids on vapor pressure, and effect of non-condensible gases on vapor pressure.

- Integration of subsurface geochemical and temperature gradients with stratigraphic/structural data is one of the most important methods used to develop a conceptual model. Variations in fluid geochemistry can be used to locate possible heat sources and define the direction of fluid flow. Similarly, information on temperature distribution and geologic features can be used for the same purpose. Together, these data can define upflow zones, mixing zones, hydrologic barriers and recharge and discharge areas to the reservoir.

- Geomorphological analysis can be combined with age-dating, geologic mapping and geophysical studies to identify or eliminate possible heat sources. Geomorphology can also be integrated with gravity studies, remote sensing data and air photo analysis to identify potential permeable or bounding structures; these can then be correlated with structures inferred from drilling results or subsurface temperature distribution.

- The analysis and interpretation of well test data has often been carried out separately from geological or geochemical studies. While that may be acceptable in terms of quantifying reservoir properties in the immediate vicinity of the well field, the well test data become more valuable when integrated with the conceptual model. Reservoir boundaries and anisotropy, identified from the analysis of well interference test data, can be critically reviewed based on the reservoir geometry and boundaries which have been inferred from geology, geochemistry and geophysics. Using both data sets to characterize the reservoir will improve the conceptual model, the numerical model and the resulting long-term predictions of reservoir behavior.

In summary, all data must be integrated on both a regional and local scale in order to develop a valid conceptual model of the geothermal reservoir and to determine the relationship of the geothermal system to the surrounding area. This conceptual model not only serves as a development guide, but forms the basis for a realistic numerical simulation model which can be used to determine the optimum production scenario for the geothermal field.