seeking geothermal resources

Last Aug. 24-28, a workshop on 'geothermal methods applied to detection, delineation, and evaluation of geothermal resources' was held in Snowbird, Utah. Snowbird Resort, at the blue-sky altitude of 2,470 m in the Wasatch Mountains, is a 30-minute drive from Salt Lake City. There, rented condominiums amidst pine, quaking aspen, and granite provide a restful atmosphere for workshops. Also, the cuisine in Little Cottonwood Canyon, in which Snowbird nestles, is superb.

Given these ethereal surroundings and the unpronounceable acronym of GMADDEGR, 51 participants and observers energetically immersed themselves in the program. The guidelines called for morning sessions that would provide an inventory of current knowledge of applications and identify known problems and points of controversy. Each session chairman would give an overview, and others would contribute differing viewpoints; discussion and individuality in the design of each session was encouraged.

For afternoon sessions, participants were divided into 6 groups, with members chosen at random. Each group would elect its group leader who then would debate with his group the morning session, identify problems and controversies, forecast future developments, and give a 10-minute viewgraph presentation that evening.

Each chairman and group leader wrote a summary of his session, and Donald L. Klick and L.J. Patrick Muffler summarized the evening discussions. From those reports I have drawn these observations:

Models of geothermal systems are still very much in the conceptual stage. There are not, at this writing, any unifying concepts that tie together models for any of the known geothermal systems. It appears, however, that necessary ingredients for continental convection-dominated systems include a shallow young (less than 1 million years?) silicic intrusive to serve as a source of heat, a fracture-dominated reservoir, a caprock or a self-healing fracture system, and adequate recharge. Where regional heat flow is exceptionally high, such as might exist in the Basin & Range physiographic province, a shallow intrusive may not be necessary if the fracture system and convection within it both extend to sufficient depth. The above two models were the basis for most of the discussion at the workshop, with only brief reference being made to hot dry rock, warm water, geopressured-interplate melting anomaly, and spreading-ridge systems.

A hot dry rock system is one through which fluid would be circulated to form a heat exchanger. Los Alamos Scientific Laboratory has drilled into Precambrian gneiss and amphibolite just west of the Valles caldera, Jemez Mountains, New Mexico. At depths of 2,750 m permeabilities are very low and temperatures are near 200°C. LASL clearly has found hot dry rock but the technology for fracturing and heat extraction has not been demonstrated.

The Energy Research & Development Administration (ERDA), in cooperation with the U.S. Geological Survey, is attempting to develop in the Raft River Valley, Idaho, a heat exchanger in a low-temperature (147°C) convective hydrothermal system with a very strong artesian flow of water.

Geopressured systems, with the diagnostics of excessive pore fluid pressure, temperatures higher than normal, and methane dissolved in the fluids, offer a unique possibility for energy development, particularly in the Gulf Coast.

The Hawaiian intraplate melting anomaly offers recent volcanoes and molten magma at shallow depth as sources of heat.

The Icelandic oceanic spreading ridge has long been exploited for central heating.

The design of optimum geological/geochemical/geophysical exploration sequences suited to detection, delineation, and evaluation of convective geothermal systems stirred much debate. There were as many approaches to exploration as there were participants in the workshop! However, a typical phased-exploration sequence is shown in an accompanying table. Flexibility in such a modular exploration sequence was stressed. Given such a broad array of geological, geochemical, and geophysical modules to be used, it is important to understand what each module contributes. There was general agreement on the contributions listed in the second table. Beyond the methods listed in that table, detection of Earth noise and remote-sensing techniques were believed to offer little at present. It was noted that the areal distribution of microearthquakes relative to a geothermal resource was usually not simple nor easily understood. No agreement could be reached on the 'best' method or the best combination of methods for obtaining a 3-dimensional resistivity distribution in a geothermal environment. Considering the variety of techniques available—such as bipole-dipole resistivity, dipole-dipole resistivity, active

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ectromagnetics, AF-AMT, and tellurics—and considering the difficulty of obtaining objective comparisons, I am not at all surprised at this result of the workshop. The self-potential method received divided support.

Geophysical problems clearly identified for further research included **1** establishment of realistic models of coupled hydrothermal—magma systems, **2** systematic collection of worldwide case histories, **3** determination of permeability and temperature at depth from surface measurement, **4** increased emphasis on quantitative evaluation of the various electrical methods, **5** means for assessing the relative importance of salinity, porosity, alteration, and temperature in producing resistivity lows, **6** laboratory determination of physical properties under geothermal conditions, **7** development of logging techniques in deep wells where temperatures exceed 200°C, **8** multiple data-set inversion, **9** means for direct detection of partly molten or molten magma chambers, **10** evaluation of seismic attenuation in geothermal areas, **11** analog and numerical studies of Earth noise and micro-earthquake generation, **12** the meaning of the Curie-point isotherm, **13** more published studies on seismic techniques, both active and passive, **14** research on the self-potential method as a possible specific indicator of geothermal resources, **15** gravity and leveling surveys to determine percentage recharge of a reservoir, **16** nature of fractures and depth to which they extend, **17** interpretation of high regional heat flow, **18** quantitative enhancement of signal to noise in remote sensing, and **19** the importance of refraction in conductive heat flow.

The most important comment heard at the end of the workshop was 'I learned a lot.' We hope so, for there is much to be learned.

Stanley H. Ward
Department of Geology & Geophysics
University of Utah
Salt Lake City, 84112

The program was designed (casually, on purpose) by a steering committee consisting of David M. Boore (Stanford), Jim Combs (UTD), William M. Dolan (Amax), B. Greider (Chevron), Don R. Mabey (ex officio, U.S.G.S.), H. Frank Morrison (UCB), and Stanley H. Ward as general chairman. The U.S. Geological Survey financed the workshop; the University of Utah (with Ward as principal investigator) handled organization. Participation was restricted to 47 persons selected by the steering committee and 4 observers chosen by the Survey. Balanced representation between industry, government, and academia was stressed at every turn.

exploration architecture

Phase I	• Office study • Age dating of silicic intrusives & extrusives • Geologic reconnaissance • Collection and analysis of thermal-water samples • Thermal-gradient measurements in available holes • Assessment of ground-water recharge • Aeromagnetic survey
Phase II	• Drill about 20 thermal-gradient holes to 40m • Measure thermal gradients & calculate heat flow • Telluric survey • Resistivity survey • Detailed geology • Alteration studies on cuttings from drilled holes
Phase III	• Micro-earthquake monitoring for 30 days (minimum) • Determine mercury in soils • Gravity survey
Phase IV	• Drill model-testing holes to 600m • Temperature log • Measure pressures • Determine chemistry of water • Study alteration of cuttings • Describe lithology • Estimate fracture porosity
Phase V	• Production test

geophysical methods	**contribution in the convective geothermal environment**
Gravity	• Delineation of structural framework • Detection of hot intrusive • Delineation of self-sealing silica deposit
Magnetics	• Delineation of structural framework • Delineation of zone of magnetite destruction • Location of igneous rocks related to heat source • Mapping Curie isotherm within intrusive serving as heat source (magma chambers?)
Micro-earthquake monitoring	• Direct mapping of active zones of fracturing • Seismic delay mapping of bodies of anomalous velocities (magma chambers?) • Stress distribution from fault-plane solutions
Resistivity	• Fluid salinity, rock porosity, alteration, & elevated temperatures all tend to produce resistivity lows in a geothermal environment
Heat flow	• Anomalous thermal gradients and heat flow can be detected readily in shallow drill holes using thermistor probes