Electrical Logging in Geothermal Reservoirs— Retrospective and Prospectives

A.C. Tripp[1] and Howard P. Ross[2]

[1] Department of Geology and Geophysics
[2] Energy and Geoscience Institute
Department of Civil and Environmental Engineering
University of Utah, Salt Lake City, Utah 84112

ABSTRACT

Early logging effort in geothermal boreholes utilized logging tools developed for petroleum reservoir evaluations and had both temperature limitations and new interpretation requirements. Electric and induction logs proved useful in lithologic identification and fracture detection but a full suite of geophysical logs were required for meaningful interpretations. To improve the identification and characterization of productive fractures, often some distance from the borehole, requires the development of new electrical/induction tools. Ongoing research indicates that a triaxial induction tool can be designed to maximize the resolution of fractures of a wide variety of orientations and petrophysical properties.

Introduction

The history of electrical logging in geothermal reservoirs has been honorable, but has indicated how innovation might lead to significant enhancement of the capabilities of the technique. This paper offers such a retrospective, drawing from the DOE Industry–Coupled Program, and then discusses some modern innovations which draw on lessons from the past.

In 1976–1982, the Department of Energy–Geothermal Division (DOE-GD) sponsored a cost-shared exploration and research program with the young geothermal industry which emphasized systematic exploration followed by drilling (Fiore, 1980; Ward *et al.*, 1981). The DOE Industry Coupled Program resulted in the drilling of 18 new deep thermal gradient holes and exploration wells and the release of lithologic and well log data for more than 30 boreholes. Complementary research programs funded by the DOE-GD supported the development of tools suitable for the new high-temperature wells (Sandia National Laboratories; Veneruso and Coquat, 1979; Norman and Livesay, 1999), and the interpretation of geophysical well logs in geothermal environments (UURI - Glenn *et al.*, 1982). All geophysical well logs were made available to the industry through Rocky Mountain Well Log Service (Denver, CO). Integrated well log suites and interpretations for many wells were reported by UURI (Glenn and Hulen, 1979; Glenn *et al.*, 1982; Glenn and Ross, 1982).

Typical well log suites for these wells included: mud, temperature, caliper, neutron, density, acoustic, electric, SP, gamma ray, dip meter, and directional survey logs. Additional logs in selected wells included special neutron, special acoustic, fracture location, cement bond, temperature injection, spinner, and pressure logs. Table 1 indicates the resistivity and induction tools used in 24 wells. We believe the logging tools are representative of those commonly used at present.

Electric Log Characteristics

Much of the current interest in borehole geophysics is focused on the detection and location of productive fractures which were not intersected by the borehole, and the resistivity and electromagnetic methods have demonstrated the most promise for fracture detection some distance from the borehole. It is useful to review the performance of electric logs in geothermal boreholes indicated in Table 1, overleaf.

Observations and Logging Tool Performance in Geothermal Wells

A brief description of the tools (after Schlumberger, 1972), as presented in Table 1, is useful. The short normal (SN - 16 in.) tool has the shallowest current penetration and was little used, and only in conjunction with deeper penetrating tools. It would typically indicate the resistivity of the mud cake or mud filtrate and possibly lower resistivities in fractures within resistive rocks. The spherically focused log (SFL) provides greater current penetration (10s of cm) than the short normal and is typically used as the short-spacing complement to the deep induction tool. The Laterolog 8 (LL8) is a shallow penetration tool while the other component of the dual Laterolog tools, the LL3, LL7 LLd (deep Laterolog) may provide current penetration of a few meters. The deepest reading devices used were the deep induction devices (Ild, or 6FF40) often as part of the Dual Induction Laterolog (DIL) comibination. These deep induction tools, subject to formation and invaded zone resistivities, unit thicknesses, etc., may indicate bed conductivities a few

Electrical Resistivity/ Induction Logs			
Industry Coupled Geothermal Wells			
Area	Well/TGH	Depth (FT.)	Resistivity / Induction Logs
Cove Fort, UT.	CFS 14-29	2,620	SN,SDI,SFL
	CFS 31-33	5,221	DIL,LL8
	CFS 42-7	7,695	DIL,LL8
Roosevelt H.S., UT.	GPC-15	1,890	LL8,6FF40
	US 14-2	6,100	SN, 6FF40
	US 52-21	7,504	DIL,LL8
Beowawe, NV.	Ginn 1-13	9,551	DIL,LL8
	Rossi21-19	5,686	DIL,LL8
	Beow. 85-18	5,927	SDI,SFL
	Goc- Coll. 76-17	9,005	SDI,SFL
Tuscarora, NV.	TUC. 66-5	5,237	SDI,SFL,DIL
Leach H.S., NV.	USA 11-36	8,565	SDI,SFL
McCoy, NV.	14-7	2,010	SDI,SFL,DIL
	66-8	2,510	SDI,SFL,DIL
Colado, NV.	IGH #1	1,501	LL8
	IGH #2	1,165	LL8
	44 -10	7,965	LL8
San Emidio, NV.	Kosmos 1-8	4,013	SDI, LL8
	Kosmos 1-9	5,367	SDI,SFL
SodaLake, NV.	44-5	5,070	SDI,SFL
	1-29	4,306	SN, DIL,LL8,6FF40
Stillwater, NV.	Debraga #2	6,946	SDI,SFL
	R. Weishaupt #1	10,014	SDI,SFL
Humboldt House, NV.	Campbell E#2	8,061	SFL,DIL
Log Types SN = Short Normal; SDI = Schlumberger Dual Induction;			
SFL = Spherically Focused Log; DIL = Dual Induction Laterolog; LL8 = Laterolog 8; 6FF40 = Schlumberger Deep Induction Log.			

Table 1. Electrical Resistivity/Induction Logs, Industry Coupled Geothermal Wells.

meters beyond the borehole. The combination of shallow focused tools (SFL, LL8, Lls) and deep Laterolog or induction tools, carefully interpreted, may provide a good estimate of formation resistivity. The various logging tools are described in detail in Schlumberger (1972).

Several general observations regarding geothermal well logs have been made in earlier studies (Glenn and Hulen, 1979; Glenn and Ross, 1982; Glenn *et al.*, 1982). Tool selection was often limited by the temperatures encountered in the boreholes, and most holes were cooled by circulation prior to logging. The induction tools are often saturated in resistive carbonate units (marble), in dense metasediments, unaltered intrusive rocks and Precambrian gneisses—a characteristic of these logs when resistivities approach 200 ohm-m. Resistivities are highly variable in volcanic and igneous rock, often varying by two or three orders of magnitude within a meter of hole depth. Electric logs must be interpreted in conjunction with neutron, caliper, gamma ray and density tools to understand many low resistivity zones. Hydrous mafic minerals, graphite, metallic and clay minerals may all contribute to low resistivity without fracture porosity and fluid content.

At Cove Fort–Sulphurdale, Utah all three wells experienced severe lost circulation and poor cuttings returns, and large fractures show as low-resistivity zones (< 5 ohm-m) in all wells. In well 31-33, the drill hole parallels or follows a major fault and fracture zone from 841 to 881 m, as inferred from resistivity and other logs. In well 42-7 the drill hole appears to follow another fault from 620 m to 696 m. More than 15 major faults / fractures which intersect or approach the drill holes are clearly demonstrated by resistivity, bulk density, neutron porosity, caliper, gamma ray, and sometimes temperature, drilling rate, and lost circulation for these three wells (Glenn and Ross, 1982). Electrical resistivities recorded by Schlumberger DIL/LL8 logs to depths of 700 m in wells 14-29 and 42-7 are in good agreement with average resistivities (20 and 100 ohm-m) determined by numerical modeling of dipole-dipole lines near these wells.

At Roosevelt Hot Springs, Utah, wells 14-2 and 72-16 were drilled in quartz monzonite and Precambrian banded gneiss respectively, and both rock types are intruded by other units and cut by fractures (Glenn and Hulen, 1979). The 6FF40 induction log shows many zones of high conductivity (100-300 mhos/m) above 2000 ft. depth (well-fractured rock) and generally much reduced conductivity (10 - 20 mhos/m to saturation) below 2000 ft. Unproductive well 52-21 was drilled in mainly amphibolite gneiss. DIL and LL8 logs show very high resistivity, mainly saturated (≥ 100 ohm-m), with numerous large excursions suggesting conductive cracks and/or veins. Numerous models of dipole-dipole resistivity profiles near these wells show a range of resistivities from 6 to 450 ohm-m, in general agreement with observed borehole resistivity values.

At the Beowawe, Nevada geothermal area, the Ginn-13 and Rossi 21-19 wells are drilled in Tertiary basalts and basaltic andesites which overlay the Ordovician Valmy formation. The Ilm, Ild, and LL8 logs generally follow each other closely throughout a wide range of conductivity (resistivities of 1 to > 100 ohm-m) with frequent saturation in Ginn-13, and high variability throughout the holes. We infer that all three logs reflect the true formation resistivity and that the effects of drilling mud, mud cake, and fluid invasion are limited to the immediate borehole wall (excepting fracture zones) for much of the logged intervals.

Numerous well logs document low resistivity and low variability associated with Quaternary alluvium,valley fill, and fluvial and lake deposits. At San Emidio, SDI and LL8 logs of the Kosmos 1-8 well show a narrow range of resistivity (1-3 ohm-m) to almost 3000 ft depth. In nearby Kosmos 1-9 SDI and SFL logs show good agreement from depths of 500 -2200 ft. where the indicated range of resistivity is 5-30 ohm-m, with relatively low variability. At Colado intermediate depth gradient hole 2 (IGH-2), SFL and SDIL logs record 10 ohm-m at 350ft., then decrease to 1-4 ohm-m at total depth of 1150 ft with little variability. Similar low resistivity, low variability behaviour is recorded at Stillwater (DeBraga 2; SFL and ILd), and Soda Lake (wells 1-29, 44-5: Ild and DIL) logs. In these low-resistivity sediments occasional resistive units may correspond to thin volcanic beds, but young faults and fractures generally have little or no expression.

Our review of several Industry Coupled Program log suites (vintage 1978-1982) provides some useful thoughts relating to the development of improved borehole electrical logging tools and techniques. The deeper penetration induction logs and focused electrode resistivity logs typically recorded resistivity well beyond the invaded zone in a variety of reservoir rock types, such as metasediments, carbonates, intrusives, gneisses, and well-consolidated sedimentary rocks. Fracture zones and faults typically showed lower resistivity or more influence from drilling fluids and muds, and numerous fractures have been interpreted from resistivity / induction logs.

The accurate interpretation of fractures (as opposed to lithology changes , borehole enlargement etc.) is often dependent on confirmation from other logs, especially the caliper, drilling rate, neutron porosity, bulk density, and gamma ray. Acoustic logs allow one to infer the presence of fractures, but provide little information on fracture geometry and transport properties. Bore hole televiewer and microscanner logs provide measurements of fracture orientation, and rough estimates of fracture filling and aperature, for those fractures that intersect the well bore. This latter information can be used to construct statistical models of fracture network geometry based on fracture orientation and frequency, but lack robustness because fracture size and connnectivity must be modeled in an ad hoc fashion. It is clear that the identification of fractures several meters from the borehole, which may be suggested by new induction tools, will require similar multilog interpretations, including those of focused electrode and induction logs in current use. Conductive fractures several meters from the borehole may exhibit a gradual change in conductivity with depth, similar to lithologic changes, and may be partially masked by large resistivity variations similar to those we have observed in this review. The importance of locating productive fractures is great, but the task is not simple!

Prospectives

The DOE-Industry Coupled Program demonstrated detection of fracture systems using electrical and induction logging in a variety of geothermal environments. However, it is necessary to improve the resolution of electrical logging techniques and to the reduce the ambiguity of fracture characterization inherent in present data. Three developments are presently under way which should reduce these difficulties. The first is the development of more accurate petrophysical fracture models; the second is the development of triaxial induction logging; the third is the development of adaptive field focusing for induction logging.

Petrophysical Fracture Models and Triaxial Induction Logging

Fracture zone maps reveal that a large variety of geometries are possible, with pronounced anisotropy in fracture orientation. Furthermore, the physico-chemical environment of a fracture must be considered in developing a model of the electrical response of a fracture zone. Tripp *et al.* (1999) contains a compilation of the literature on this subject. One practical conclusion of this work is that the electrical conductivity for fractured media will be anisotropic and represented by a tensor.

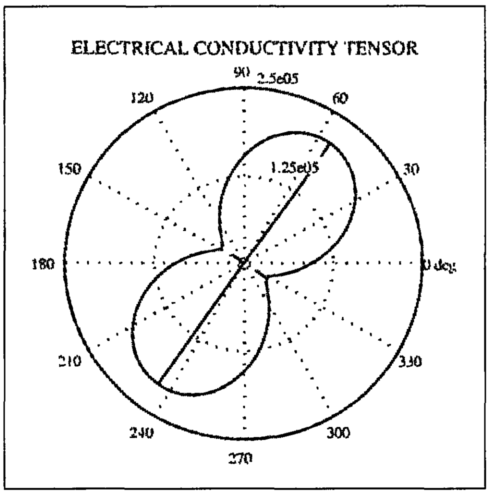

Figure 1. Two dimensional conductivity tensor plot for Dixie Valley Formation.

Estimates for the entries of this tensor are possible given maps of the fracture system and a knowledge of the physico-chemical conditions of the formation. For example, Figure 1, taken from Tripp *et al.* (1999), represents a two dimensional conductivity tensor for a Dixie Valley formation.

Conversely, estimates of the electrical conductivity tensor are informative of the fracture fabric and the physico-chemical regime of the formation. Estimating an anisotropic electrical conductivity tensor requires innovative logging sources, since the geometry of the source fields can restrict resolution of the conductivity tensor. To understand this point, consider Figure 2. This figure assumes that a fracture zone is a perturbation on a whole space. In this case, a uniaxial magnetic dipole source orientated in the z direction will have an electrical current distribution which is azimuthal. Hence, in cylindrical coordinates, it will sample $\Delta\sigma_\phi$, but has no component in the z or the ρ directions. In this case, $\Delta\sigma_z$ and $\Delta\sigma_\rho$ are unresolved. The composition of two sources has no component in the r direction and hence $\Delta\sigma_r$ is unresolved. Only when there are three sources can one hope to resolve a general conductivity tensor. It is for this reason that there has been recent interest in developing triaxial induction tools for delineating fractures in geothermal systems (Sato *et al.*, 1996; Wilt *et al.*, 1997; Wilt, pers. comm.). Tripp *et al.*, (1999) demonstrate that triaxial source–receiver geometries and anisotropic formations should be considered for optimal inductive borehole resolution of fracture systems. Unfortunately, the triaxial geometries and anisotropic formations offer interpretational difficulties which are not encountered in the conventional uniaxial arrays in isotropic materials. One problem is the borehole effect from sources oriented perpendicular to the well axis.

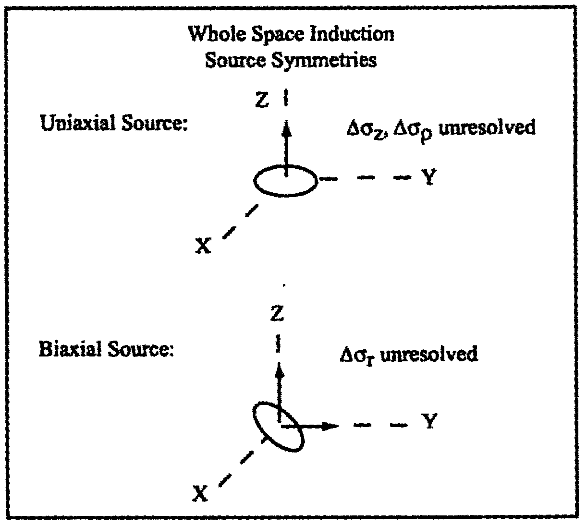

Figure 2. Resolution ambiguities for two source types.

One possible solution to this problem is to focus the triaxial sources and receivers to optimize resolution vis-a-vis a prior conductivity distribution. Such a prior distribution could be a borehole. Cherkaeva and Tripp (1999) have described a theory of inductive focussing which could be used for triaxial sources and receivers. The focusing theory leads to superior resolution even for uniaxial sources and receivers. The efficacy of the method can be illustrated using a computer simulation taken from Cherkaeva and Tripp (1999). Figure 3 illustrates the model which is considered. This model consists of a 1 m fracture zone of horizontal resistivity 100 Ω - m, embedded in a background unit of horizontal resistivity 10 Ω - m. Note that this is a much more difficult target than the regular "conductive fracture" zone model, and could correspond to a case in which a particular lithologic zone has fractures which parallel the borehole. To make the problem even more difficult, we assume that there is an invasion zone of horizontal resistivity 1 Ω - m. Again, all of the units have arbitrary vertical resistivity - the vertical transmitter array shown in the figure has no sensitivity to vertical resistivity components.

In each model, the borehole and bounding media attributes are known, as well as the resistivity and thickness of the invasion zone. The 100 Ω - m zone behind the invasion zone is the target zone and all array optimizations are designed to optimize this unknown region given the knowledge about the rest of the model. The transmitting and receiving dipoles were spaced at 1m intervals, with a total of 15 of each. The locations of some of the transmitting dipoles are shown by the arrows. The receiver locations coincide with the transmitter locations. We assume that all transmitters will fire in-phase with each other

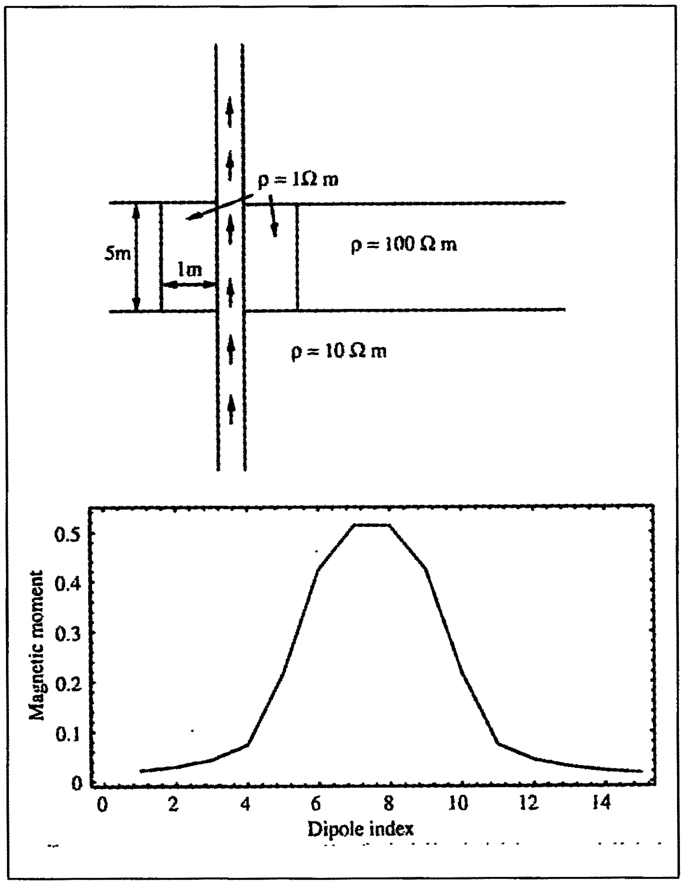

Figure 3. A cross-sectrion of the model (top) and the optimal distribution of the moments of magnetic dipoles (bottom).

and that each receiver will record the response due to each of the transmitters. Alternately, we could represent the measured response as a weighted sum of the responses due to each separate transmitter. In either case, our task is to find the relative transmitter weighting which maximizes the response of the 100 Ω - m zone, assuming an a-priori model where all the other model parameters are known and the 100 Ω - m zone is thought to be 10 Ω - m. The theory for focusing permits arbitrary a-priori models, which may be adaptively changed with borehole depth at the time of logging.

Figure 3 shows the optimal transmitter weighting for Model 1. Obviously, the array weighting is using the invasion zone to "focus" energy into the resistive zone. Figures 4 and 5 illustrate

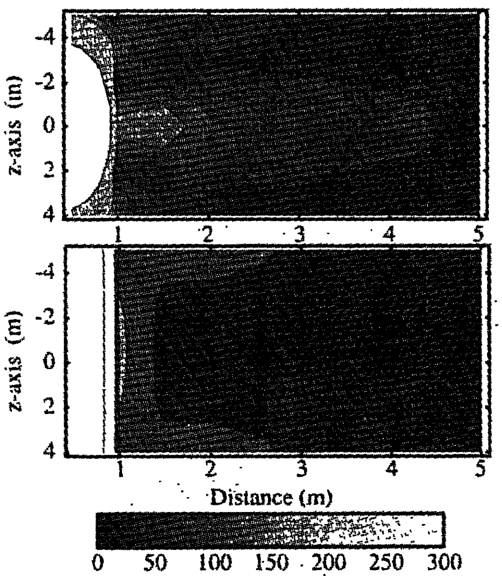

Figure 4. Cross-plots of the amplitude of Hz for the optimal weighting (top) and uniform weighting (bottom). The frequency of excitation is 1 kHz. The contours are in units of .1 milliAmps/m.

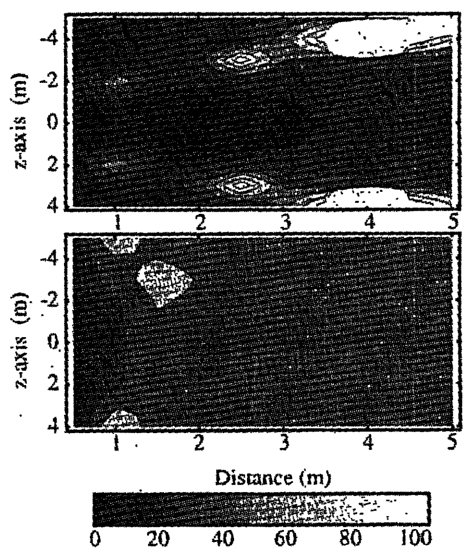

Figure 5. Cross-plots of the phase of Hz for the optimal weighting (top) and uniform weighting (bottom). The frequency of excitation is 1 kHz. The contours are in mrad.

contours of the H_Z (vertical magnetic field) response for the optimized transmitter array and uniformly weighted arrays for an x-y cross-section containing the borehole axis. In all plots it is apparent that the focussing array leads to an improved field concentration in the fracture zone.

Summary

Conventional electric logging in geothermal boreholes detects fractures and may give estimates of formation conductivity, which is a fundamental physical property. Typically, high conductivity values may correlate well with the presence of fractures, a primary permeability control in geothermal reservoirs. Much contemporary research has concentrated on improving fracture detection and characterization. The first step is to define valid models linking fracture geometry and physicochemical environment to the electrical conductivity tensor. The second step is to develop new hardware and software which is designed to give the increased resolution necessary for consistent resolution of fractures of arbitrary inclinations at reasonable separations from the borehole and to improve the radius of investigation. Contemporary research efforts are concentrating on these two steps.

Acknowledgements

Financial support for this study was provided by the U.S. Department of Energy under grants DE-FG03-93ER14313 and DE-AC07-95ID13274. Such support does not constitute an endorsement by the U.S. Department of Energy.

References

Cherkaeva, E. and Tripp, A.C., 1999, "Optimal focussing in inductive logging." *Proceedings of the 24th Workshop on Geothermal Reservoir Engineering.*

Fiore, J.N., 1980, "Overview and assessment of the U.S. Department of Energy's Industry Coupled Geothermal Reservoir Assessment Program." *Geothermal Resource Council Transactions,* v. 4, 201-204.

Glenn, W.E. and Hulen, J.B., 1979, "Interpretation of well log data from four drill holes at Roosevelt Hot Springs KGRA." U. of Utah Research Inst., Earth Science Lab. Report No. 28, DOE/ID/28392-38, 79p.

Glenn, W.E. and Ross, H.P., 1982, "A study of well logs form Cove Fort-Sulphurdale KGRA, Millard and Beaver Counties, Utah." U. of Utah Research Institute, Earth Science Lab. Report No. 75, DOE/ID12079-62, 50p.

Glenn, W.E., Ross, H.P., and Atwood, J.W., 1982, "Review of well logging in the Basin and Range Known Geothermal Resource Areas." *Journal of Petroleum Technology*, May, 1104-1118.

Norman, R.A., and Livesay, B.J., 1999, "New high-temperature electronics for geothermal instrumentation applications." *Geothermal Resources Council Bull.,* v. 28, p. 15 - 20.

Sato, T., Osato, K., Takasugi, S., and Uchida, T., 1996, "Development of the Multi-Frequency Array Induction Logging (MAIL) tool." *Geothermal Resources Council Transactions,* v. 20, 637-642.

Schlumberger, Limited, 1972, Log Interpretation, Vol. 1 - Principles, New York, N.Y., 113p.

Tripp, A.C., Bruhn, R., Jarrard, R.D., and Brown, S., 1999, "Inductive detection of fractures in geothermal systems - Petrophysical aspects and geophysical implications." *Proceedings of the Twenty -fourth Workshop on Geothermal Reservoir Engineering.*

Veneruso, A.F. and Coquat, J.A., 1979, "Technology development for high temperature logging tools." *Proc. SPWLA 20th Annual Logging Symposium,* Tulsa, Paper KK.

Ward, S.H., Ross, H.P., and Nielson, D.L., 1981, "A strategy of exploration for high temperature hydrothermal systems in the Basin and Range Province." *Bull. AAPG,* 65, no. 1, p. 86-102.

Wilt, M., Takasugi, S., Uchida, T., Kasameyer, P., Lee, K., and Lippmann, M., 1997, "Fracture mapping in geothermal fields with long-offset induction logging." *Proceedings of the Twenty-Second Workshop on Geothermal Reservoir Engineering,* Stanford University.