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Review of Well Logging in the Basin and Range Known Geothermal Resource Areas

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Summary

This paper discusses applications and interpretations of well logs to Basin and Range Province geothermal exploration and development. Problems experienced in use of conventional oilfield tools and techniques are reviewed, and methods to circumvent these problems are illustrated. Particular examples focus on log responses and matrix effects in complex lithologies.

Introduction

In 1977, the U.S. DOE's Div. of Geothermal Energy (DGE) initiated the ''industry coupled program'' to accelerate development of high-temperature geothermal resources. There are two key aspects of the program: (1) cost sharing with industry for exploration, reservoir assessment, and reservoir confirmation; and (2) the release of geologic, geophysical, and geochemical data to improve knowledge and understanding of geothermal reservoirs. A third aspect of the program was to evaluate techniques and current methods on a cost-effective basis.

Two regions of high industry interest and high geothermal potential were selected by DGE for procurements within the industry coupled program. The first request for proposals (RFP) resulted in six contracts for work in south central Utah, the second in 12 contracts for exploration and reservoir assessment work in the northern Basin and Range Province. The geothermal resource areas included in the program are shown in Fig. 1.

The range of exploration activities of participating companies and data to be made public through this program are indicated in Table 1. Ward *et al.*[1] studied these data and recommended a generalized exploration strategy for high-temperature geothermal systems in the Basin and Range Province. Fiore[2] provided an overview and status report for the overall reservoir assessment program.

The program's emphasis was direct drilltesting of the geothermal reservoir. At least one deep exploration well has been (or will be) drilled in each reservoir, at costs between \$500,000 and \$2,000,000.[3] The high well costs demand prudent, systematic exploration before siting the well and as much geologic information as possible from each well test. Drill cuttings, geophysical well logs, temperature, pressure and flow test data, and complete well histories for each well drilled are transmitted to the U. of Utah Research Inst.'s Earth Science Laboratory Div. (ESL). ESL reviews and approves the deliverables and makes data available to the public through established open-file procedures. Geophysical well logs are transmitted to Rocky Mountain Well Log Services (of Petroleum Information Corp.), where they are reproduced and distributed at nominal cost. In this manner detailed well data for 29 geothermal exploration wells and deep thermal gradient tests have been made public since 1977. The current status of drilling and the availability of well log data are listed in Table 2. Many thermal gradient holes with only mud and temperature logs are not included in Table 2.

Note that DGE has instituted complementary and supporting programs designed to advance well log interpretation[4] and high-temperature tool development.[5] At ESL detailed well log/lithologic interpretations form an important part of several reservoir case histories and topical studies published or in preparation.[6-11] These integrated interpretations are instrumental to the planning of subsequent well tests and to overall reservoir evaluation.

We describe well log data that have been made available through the industry coupled program. Logging parameters used, data quality, previously published log interpretations, and some results of the ESL log interpretation work are reviewed and discussed.

Well Logging in Geothermal Areas

In many ways the objectives of well logging and well log

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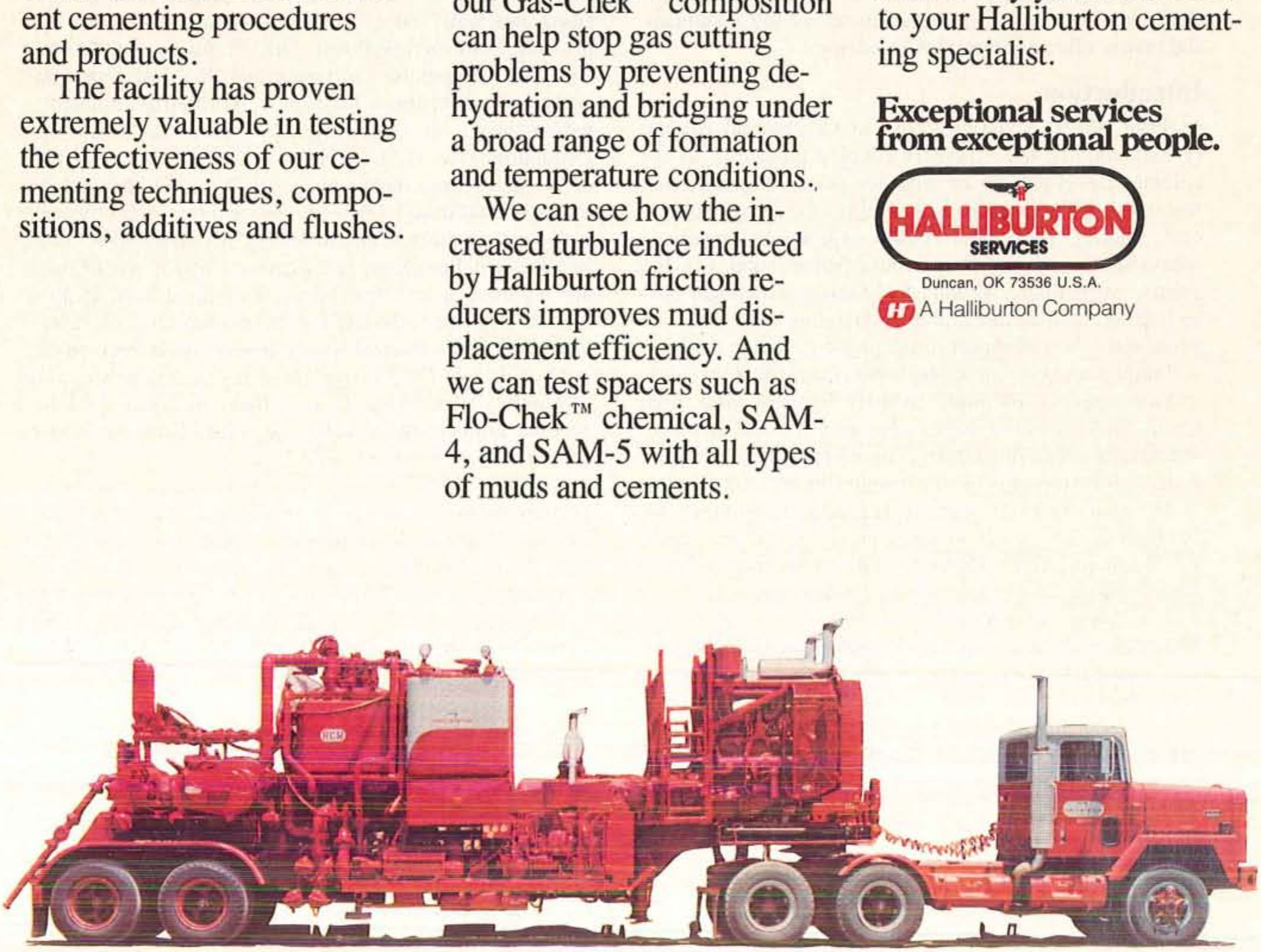

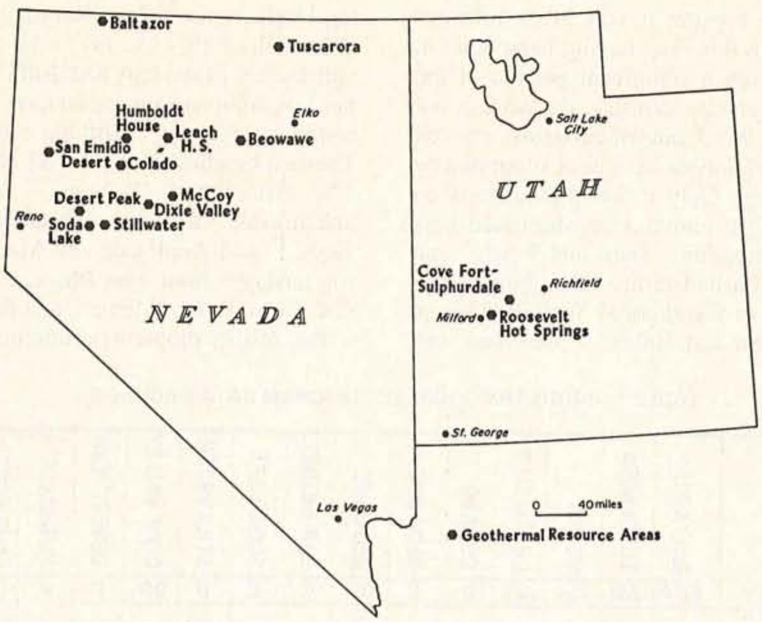

Fig. 1—Location map showing industry coupled program resource areas.

analysis in geothermal investigations parallel those of the petroleum industry and can be regarded in terms of openhole logging, production logging, and cased hole logging. The objective of geothermal resource exploitation is to produce a hot fluid—water and/or steam—from some formation at depth. Hence, there is an obvious parallel to the investigation and the exploitation of petroleum resources.

A parallel also exists to logging in mineral deposits. Hydrothermal resources are current manifestations of a process that in the past has created a large variety of mineral deposits. Hydrothermal fluids introduce new minerals, remove some minerals, and alter other minerals in place. The fluids move primarily along fractures and crystal boundaries. Movement along crystal boundaries must be relatively insignificant in most rocks. Temperatures and pressures are in a range such that alteration or metamorphism is typically low grade. New minerals are largely feldspars, chlorites, epidotes, clays, silica, and calcite, with minor amounts of base metal minerals that tend to be concentrated on fractures (veins) or faults. The mineralogy is complex and highly variable. However, in-depth studies of chip samples of core and well logs are useful in determining the lithology and possible intensely altered zones that may indicate recent or ongoing hydrothermal activity.

Lost circulation is a common, serious problem in drilling geothermal wells. The lost circulation is often difficult or impossible to control and drill chip returns are either lost or extensively mixed. Well log data become the only means to distinguish lithology and structures intercepted by the drill holes.[10] Although standard logs and log interpretation techniques will work in these environments, the applications are not simple. Many of the basic logging procedures and log interpretations are tailored by many years of experience in petroleum resource applications. This experience is recent and short in the geothermal industry; therefore, anyone not familiar with logging by the geothermal industry might believe too many (redundant) logs are obtained or some obviously valuable logs have been omitted from particular log suites. Geothermal well logs commonly are obtained in a harsh borehole environment of high temperature and corrosive fluids. An excellent review of state-of-the-art geothermal well logging and log interpretation can be found in Ref. 12.

We believe a good well logging program should support three important areas of geothermal resource investigation: (1) exploration, (2) assessment, and (3) exploitation. DGE has attempted to develop logging technology that would improve well logging applications in all three areas. As noted in the Introduction, the industry coupled program has focused on exploration and preliminary resource assessment. Hence, well logs obtained under this program are largely openhole logs and have been obtained in wells that could be viewed either as wildcat or as stepout wells.

A summary of well logs, obtained by the industry coupled program and open-filed by ESL or Rocky Mountain Well Log Services, is given in Table 3. (Only those areas containing a well with more than a mud and a temperature log are included.) Well log suites tend to be fairly complete, often including more than two porosity logs, and tend to cover much of the drill hole length. One exception that should be reassessed is the exclusion (often) of logging in near-surface formations. Data obtained in near-surface rocks can prove invaluable in interpreting structure, lithology, and surface geophysical surveys.

Only a few production and/or cased hole logs have been submitted as part of the industry coupled data packages (see Table 3). Holes may be circulated and cooled for openhole logging, but much of the production logging would require flowing the hot, often corrosive, fluid in the well. The environment exceeds most design specifications of available logging tools; hence, production logging applications to geothermal resources lag behind openhole logging applications. The maximum temperature encountered in each hole during openhole logging operations is included in Table 3.

Geothermal openhole logging is still in its infancy, with most of the work in this field having been done in the last 5 years. Although a significant portion of the work has been done by private industry, the work is not in the public literature. Most published results of well logging technology development have been supported by DGE or its predecessors. Only a few publications on well log analysis in the resource areas discussed here have appeared in the literature. Sethi and Fertl[13] and Benoit *et al.*[14] have published results of logging operations and log analysis in Geothermal Well B-23-1 at Desert Peak, NV. Glenn and Hulen[7,8] presented well log interpretations from Roosevelt Hot Springs (RHS), UT, Wells GPC-15, 14-2, 52-21, and 72-16. A detailed study of the logs and drill chips of RHS Well 9-1, the Los Alamos Log Calibration Hole C/T-2, has been completed recently.[9] Hill has discussed logs obtained in Thermal Gradient Holes 11-33 and 63-33 at Soda Lake, NV. Galbraith,[16] Cochran,[17] Sanyal *et al.*,[12] Davis and Sanyal,[18] Littleton and Burnett,[19] Ershaghi *et al.*,[20] Keys,[21] and Applegate and Moens[22] have reported on log analyses from East Mesa, Coso, and The Geysers, CA, Cerro Prieto, Mexico, and Raft River, ID.

Log quality problems commonly reported are those en-

TABLE 1—INDUSTRY COUPLED PROGRAM DATA PACKAGES

AREA	BALTAZOR	TUSCARORA	MC COY	LEACH H.S.	COLADO	BEOWAWE	BEOWAWE	SAN EMIDIO	SODA LAKE	STILLWATER	DIXIE VALLEY	DESERT PEAK	HUMBOLDT H.	COVE FORT-SULPHURDALE UTAH	ROOSEVELT HOT SPRINGS UTAH
COMPANY	EPP	AM	AM	AO	G	G	C	C	C	U	SR	P	P	U	*
DATA															
GRAVITY	E	X	X	E	E	X		E		E		E	E	E	
GROUND MAG.					E	X						E			
AERO MAG.	E	X	X				E				E			E	E
ELEC. RES.					E	X	E	E	E	E				E	X
MAGNETO-TELLURIC		X	X	X	E		E		E	E	E	E	E		
AUDIO MAGNETO TELLURIC					E										
SELF POTENTIAL		X	X				E	E							
SEISMIC EMISSIONS							E	E						E	X
MICRO-EARTHQUAKE	E	X	X				E								
SEISMIC REFL. (weight drop)							E		E					E	
SEISMIC REFL. (CDP 12 or 24 fold)			X	X			X	E	E						X
GEOLOGY	E			E				E			E X	E	E	E	X
GEOCHEMISTRY	E			E							E			E	
SHALLOW TEMPERATURE											X				
SHALLOW THERMAL GRADIENT	E	E X	E X	X	E X	X		E	E	E	E			E	E X
DEEP THERMAL GRADIENT	X	X	X	X	X	X			E X		E X	E		E	X
EXPLORATION WELL ✦	X	X	X	X	X	X	E	E	E	E	X	X	X	E X	E X
FLOW TEST (if appropriate)	X	X	X	X	X	X	X			X	X	X	X	X	X

COMPANY EXPLANATION

EPP – Earth Power Production
AM – Amax Exploration Inc.
AO – Aminoil USA, Inc.
G – Getty Oil Co.
C – Chevron Resources Co.
U – Union Oil Co. of Ca.
SR – Southland Royalty Co.
P – Phillips Petroleum Co.

E = *EXISTING DATA*
X = *NEW PROGRAM*

* Companies at Roosevelt Hot Springs:
Getty Oil Co.
Thermal Power Co.
Geothermal Power Co.
Seismic Exploration Inc.
Geophysical Services Inc.
University of Denver (DRI)

✦ Exploration Wells — Drill cuttings and geophysical well logs provided countered in other resource applications: improper scales and calibration, large borehole washout degradation of tool response, signal attenuation in aerated mud, and tool failure. Tool failure and poor data often result from high temperatures encountered in the borehole. To eliminate the temperature problem, holes are circulated before logging, and tools developed for deep oilwell logging are used when available.[12,13,23]

Well Logs From Basin and Range Known Geothermal Resource Areas

Table 3 contains a summary of well logs obtained in several known geothermal resource areas (KGRA's) by companies participating in the industry coupled program. Not all areas listed in Table 2 appear in Table 3 because deep wells and/or well logging have not been completed yet. Several thermal gradient holes have been drilled in these and other areas, but these holes often have only lithologs and temperature logs. Table 3 is constructed with the openhole logs at the top and production or cased hole logs at the bottom. Obviously, openhole logging suites are the most complete, and nearly all wells have a complete set of logs. Production logs may have been obtained subsequently in some of the wells but are not part of the participation agreements.

Mud logs were recorded on site during drilling in the same manner as done for petroleum wells. Drilling rate, lithology, mud and bit history, and flowline temperature in and out values are recorded in every well. Hydrogen sulfide and carbon dioxide gas are almost always monitored. Flowline pressure in and out, mud density, and methane gas are commonly recorded. Weight on bit (WOB) is recorded in only a few instances. The mud

TABLE 2—LIST OF INDUSTRY COUPLED PROGRAM GEOTHERMAL WELLS (well depth or status as of Jan. 1, 1982)

Area	Well Name	Well Depth/Status (ft)	(m)	Open-Filed Well Logs
Baltazor, NV	unnamed	probably 2 holes, unscheduled		—
Beowawe, NV	Ginn 1–13	9,551	3033	yes
	Rossi 21–19	5,686	1733	yes
	Beowawe 85–18	5,927	1807	yes
Colado, NV	IGH–1	1,500	457	yes
	IGH–2	1,165	355	yes
	Colado 44X–10	7,965	2428	yes
Cove Fort-Sulphurdale, UT	CFS–14–29	2,620	799	yes
	CFS–31–33	5,221	1591	yes
	CFS–42–7	7,695	2345	yes
Dixie Valley, NV	Dixie Federal 45–14	9,022	2750	yes
	Dixie Federal 66–21	9,780	2981	yes
Desert Peak, NV	B–23–1	9,641	2937	yes
Humboldt House, NV	Campbell E–2	8,061	2457	yes
Leach Hot Springs, NV	USA–11–36	8,565	2611	yes
	unnamed	to be drilled in 1982 ?		—
McCoy, NV	unnamed	to be drilled in 1982		—
	14–7	2,010	613	yes
	66–8	2,510	765	yes
Roosevelt Hot Springs, UT	GPC–15	1,890	576	yes
	14–2	6,100	1859	yes
	52–21	7,504	2287	yes
	72–16	1,254	382	yes
San Emidio, NV	Kosmos 1–8	5,367	1636	yes
	Kosmos 1–9	4,013	1223	yes
Soda Lake, NV	1–29	4,306	1312	yes
	11–33	2,000	610	yes
	44–5	5,070	1545	yes
	63–33	2,000	610	yes
Stillwater, NV	DeBraga 2	6,946	2117	yes
	R. Weishaupt No.1	10,014	3052	yes
Tuscarora, NV	66–5	5,237	1596	yes

TABLE 3—TYPES OF WELL LOGS OBTAINED IN INDUSTRY COUPLED DRILL HOLES

AREA	Beowawe				Colado			Cove Fort-Sulphurdale			Desert Peak		Dixie Valley		Humb. House	Roosevelt Hot Springs				San Emidio		Soda Lake				Stillwater		Tusca-rora	Leach H. S.
LOG	GINN 1-13	ROSSI 21-19	BEO. 85-18	COLL. 76-17	IGH 1	IGH 2	COL. 44x-10	CFS 14-29	CFS 31-33	CFS 42-7	R-21 1&2	R-23 1	DF 45-14	DF 66-21	CAMR. E-2	GPC 15	U.S. 14-2	U.S. 52-21	U.S. 72-16	KOS. 1-8	KOS. 1-9	SL 1-29	SL 11-33	SL 44-5	SL 63-33	DE BR. 2	R.W. 1	66-5	U.S.A. 11-36
Mud	X	X				X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X		X			X	X	X
Temp.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Caliper	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X		X		X	X	X	X
Neutron	X	X		X	X	X	X	X	X	X		X	X	X	X		X	X		X	X	X		X		X	X		X
Density	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X		X		X	X		X
Acoustic		X	X	X	X	X	X			X		X		X	X	X	X	X		X	X	X		X			X	X	X
Electric	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X
SP	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
GR	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X
Dip Log Meter	X	X	X	X			X	X	X	X				X						X	X	X		X		X	X		
Direct-ional	X	X	X	X			X	X	X	X		X		X						X	X	X		X		X	X		
Special Neutron				X								X																	
Special Acoustic			X																	X									
Fracture Loc., etc			X									X						X			X								
Spectral Gamma												X																	
Cement Bond			X							X									X										
Temp. Inj.										X			X																
Fluid									X	X											X								
Spinner										X			X															X	
Pressure	X	X	X						X	X									X								X		
Max. Temp. °F	301	393	354	311	216	110	306	198	342	336	390	408	381	366	312	148	406	352	332	187	239	270	NA	220	245	336	353	242	259
Max. Temp. °C	149	201	179	155	102	43	152	92	172	169	199	209	194	186	156	64	208	178	167	86	115	132	NA	104	188	169	178	117	126

logs commonly note amounts of lost circulation and its control, well kicks, and completion history.

Almost all neutron, density, and acoustic logs were obtained with compensated tools. The caliper logs were recorded in most wells with the density tools, in few wells with the acoustic tools, and infrequently with an individual caliper tool. Almost all electric logs were obtained with combination tools comprised of two radii of investigation, focused induction logs, and a shallow radius of investigation electric log, either focused or unfocused. Gamma ray logs were recorded with the neutron and density logs, with acoustic logs or, in a few instances, with both logs. The spontaneous potential (SP) log was recorded most frequently with the electric log and less often with the acoustic log; in one instance, Well CFS-31-33, the SP log was omitted from an otherwise fairly complete set of logs. Of the more popular logs, the acoustic log is the one most frequently omitted. Logs designed to measure formation strike and dip were obtained in about one-half the wells, and logs designed to locate and/or determine strike and dip of fractures were obtained in only four wells. Hole deviation or directional surveys were, with one exception, Desert Peak Well B-23-1, a part of the formation dip logs.

The geothermal log interpretation program, also a DGE program,[4] sponsored neutron lifetime, gamma spectral, and Fraclog™ logs in Desert Peak Well B-23-1. The intent was to investigate the usefulness of these logs in geothermal resource investigations. The interpretation of these logs is included in the reports by Sethi and Fertl[13] and Benoit *et al.*[14]

The logging companies that supplied the logs noted in Table 3 are listed in Table 4. Other logging companies may be used by the geothermal industry in other areas of the country or have been used by industry to obtain logs not included in the industry coupled data packages. We have not examined log quality or tool failure on a company basis but give a general evaluation.

The most popular production logging technique is the measurement of temperature and/or pressure logs during and at set intervals after a flow or injection test in the well. The spinner and fluid-migration tracer logs have been used on only a few occasions.

Log quality parallels that found in any other application of well logging. Log scales and log recording parameters occasionally were stated incorrectly, such as an acoustic log recorded on a 20- to 120-μsec/ft scale when the actual scale was 50 to 150 μsec/ft. Incorrect tool calibration may be suspected often, but this is difficult to confirm, even though logging company personnel are cooperative in trying to resolve these problems. Sometimes it is difficult to determine the borehole environment during the logging operation. Time after circulation, bottomhole and maximum borehole temperatures, borehole fluid type, logging speeds, time constants, and borehole fluid properties such as resistivity are not always recorded. In highly variable lithologies it is frequently difficult to determine on which scale range the log is recorded. Which scale makes sense and is compatible with other logs determines the scale selection. The log trace style or weight are not always clear.

Many of the geothermal wells were drilled in poorly consolidated sediments or badly fractured igneous and metamorphic rocks. Hole caving was a common problem, particularly in upper portions of the wells. Although many tools are compensated and are designed to correct for borehole enlargement, the caving was frequently sufficient to produce obviously incorrect data. Acoustic logs are commonly of poor quality, with cycle skipping over most of the logged interval. Signal attenuation in the low-velocity formations and borehole fluid, and unsteady tool drag in rough holes account for most of the degraded acoustic tool response. Perhaps slower logging speeds (not always a choice) in some instances could improve the acoustic log quality.

TABLE 4—WELL LOGGING COMPANIES SUPPLYING LOGS IN BASIN AND RANGE KGRA'S

Wireline Logging	Mud Logging
Agnew Sweet	Alpha Beta Gamma Assoc.
Dia Log	Energy Well Logging Service
Dresser Atlas	Exploration Logging Inc.
Gearhart-Owen	Geological Engineering Service
Geotex	R.F. Smith
Geothermal Services Inc.	
Mineral Services Co.	
Pruett Wireline Service	
R.F. Smith	
Schlumberger	
Triangle Service	
United Wireline	
Welex	

Since caliper logs were recorded by more than one tool in many wells, it is possible to compare their repeatability while considering the different tools involved. In very few wells do the caliper logs depict the true hole diameter as predicted by bit size. The logs often exhibit drifting that might be attributed to temperature effects. Repeat logs have been several inches (~ 5 cm) apart in measurement of borehole diameter. Since calipers were recorded with other tools, particularly decentralized tools, true hole roughness and cross-section shape are not depicted accurately by the logs. In these situations, correcting logs sensitive to borehole diameter variation is not satisfactory.

SP logs seldom exhibit much variability and, in places where changes occur, they do not appear to be interpretable in the usual way.[8,12] The SP log has very limited use in identifying lithology. The gamma ray log, however, does distinguish several lithologies. Examples can be found in various papers[8,12,22] and later in this paper. Gamma spectral logging was demonstrated to be effective in lithologic studies in Desert Peak Well B-23-1 by Sethi and Fertl.[13]

Many geothermal resources are fracture-controlled systems. Hence the measurement of location and attitude of fractures intercepted by the borehole is an important objective of well logging. Dip logs and Fraclogs have been obtained in several wells in the Basin and Range KGRA's, and good bedding attitude data have been obtained in layered sedimentary sections. Volcanic rocks also have yielded reasonable results. However, in crystalline rocks and where used as fracture logs, the data are at best qualitative. The variable dip and azimuth of several intersecting fractures, a common occurrence, are not distinguished easily on these logs. The acoustic televiewer has the greatest potential for fracture measurements, and its application has been limited to a few areas.[21]

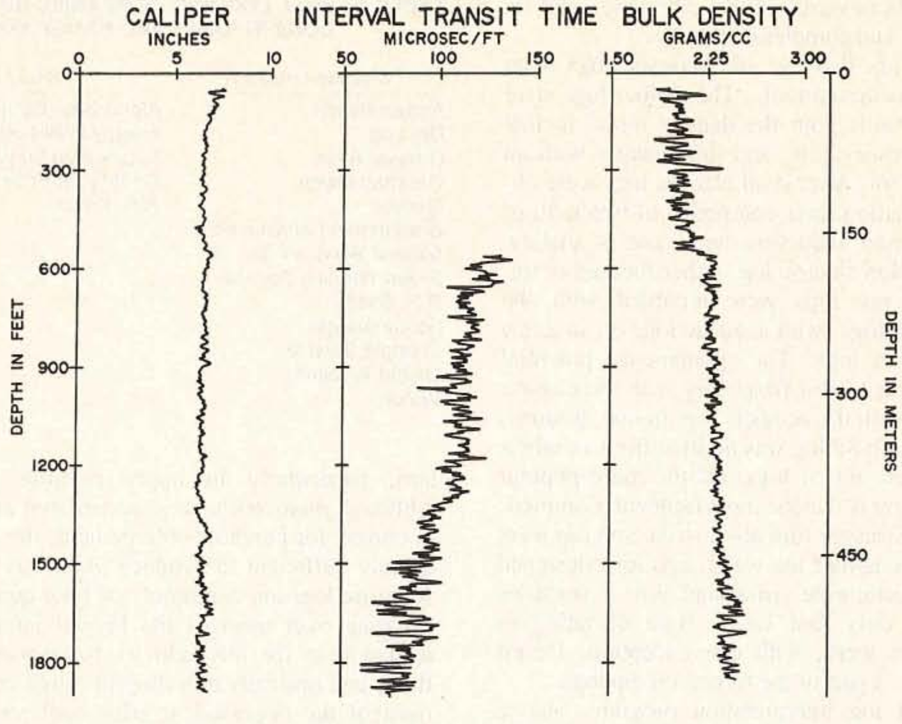

Fig. 2—Selected logs from Geothermal Gradient Hole GPC-15, Roosevelt Hot Springs KGRA, UT.

Lithology/porosity crossplots[24,25] utilizing neutron, density, and velocity log data have proved useful in distinguishing rock types in complex lithologies and in obtaining improved estimates of porosity.[7,12,22] However, log calibration is commonly inappropriate for the lithologies encountered in geothermal wells. The log interpreter must rely on experience, published empirical log responses,[12,26] logging service company manuals, and common sense to interpret logs quantitatively in these environments. Fortunately, a fairly complete suite of logs has been obtained in most geothermal wells, and the wealth of data tends to give the interpreter a better chance to achieve good results.

Examples

Selected logs from several drill holes in Roosevelt Hot Springs and Cove Fort-Sulphurdale, UT, and from Beowawe and Soda Lake, NV, geothermal resource areas are presented and discussed in the following. Glenn and Hulen[7,8] have presented a study of well logs from the Roosevelt Hot Springs KGRA. Glenn and Ross[6] have presented a well log study for the Cove Fort-Sulphurdale KGRA. These logs have been discussed further by Ross *et al.*[10] Examples are taken from these previous studies because some of the results have not been published in the literature. Well log studies for Beowawe, Dixie Valley, Humboldt House, San Emidio, and Soda Lake are in progress. Some preliminary results of the Beowawe and Soda Lake studies are presented.

Roosevelt Hot Springs KGRA

The Roosevelt Hot Springs (RHS) KGRA has been described in some detail[1] and a comprehensive geologic study of the area has been published.[27] The geothermal resource occurs in a faulted block of acidic to intermediate-composition igneous and metamorphic rocks only a few hundred feet (few hundred meters) beneath arkosic alluvium. Porosity and permeability of the reservoir are probably entirely in faults and fractures.

The first log example is taken from Geothermal Power Corp.'s Thermal Gradient Hole GPC-15, which was drilled entirely within the alluvium to a depth of 1,890 ft (576.1 m).

The interval transit time and bulk density logs from Well GPC-15 are shown in Fig. 2. Crossplots of the data from the two logs are shown in Fig. 3. The break in the density log and the termination of the acoustic log at 540 ft (164.5 m) is interpreted as the water table. The bulk density to 450 ft (137.2 m) is variable, 1.8 to 2.4 g/cm^3, but tends to average about 2.05 g/cm^3; between 450 and 540 ft (137.2 and 164.5 m) it is slightly higher, approximately 2.1 g/cm^3. Below 540 ft (164.5 m) the bulk density increases with depth from 2.28 g/cm^3 at 540 ft (164.5 m) to 2.46 g/cm^3 at 189 ft (57.6 m). If we use 2.1 and 2.28 g/cm^3 for the alluvium density above and below the water table and 0- and 1-g/cm^3 density for air and water, respectively, we obtain about 22% porosity for the alluvium both above and below 544 ft (164.5 m). This result tends to confirm the interpretation of the water table at 540 ft (164.5 m).

The crossplot in Fig. 3a illustrates a possible but incorrect interpretation of the data that would result if the crossplot were used without careful review of the logs and without use of common sense. Fig. 3b illustrates an alternate and, we believe, correct interpretation of the data. The Parallel Lines 3 through 4, where the slope $(\rho_g-1)/B$ is constant with depth (ρ_g is grain density and B is a constant), identify four distinct units in the alluvium. This interpretation yields consistent, reasonable values for porosity, matrix travel time, and grain density with depth. The logs indicate that the alluvium is better cemented and less porous with depth.

Further discussion of these results is given by Glenn and Hulen.[8] This example illustrates the usefulness of obtaining well log data in alluvium. The data have contributed to seismic,[28] gravity,[11] and hydrologic studies.

The second RHS example is taken from Getty Oil Co.'s Utah State Geothermal Well 52-21. Selected logs from the interval of 4,500 to 5,500 ft (1371.6 to 1676.4 m) are shown in Fig. 4. The most significant feature here is the correlation of the biotite-hornblende quartz monzonite gneiss to high neutron porosity and bulk density. The acoustic log exhibits insignificant correlation to lithology on the scale of the plot. These logs were obtained with compensated tools. The caliper log is included to illustrate that the log variations are not produced by any borehole effects. Glenn and Hulen[7,8] have demonstrated that the log responses can be explained by variations in the abundance of hydrous mafic minerals such as chlorite, biotite, and hornblende. These minerals are much more dense than the major silicate minerals (quartz and feldspars) in the rock. Hornblende and chlorite may have a neutron porosity of 5 to 40%, respectively. Glenn and Hulen[8] showed a good correlation of neutron, density, and acoustic logs to volume percent of the mafic minerals in the drill chips. This correlation is shown in Fig. 5. The log data were averaged over 10-ft (3.05-m) intervals to correspond with chip sample intervals.

Note that using a nominal grain density of 2.65 g/cm^3

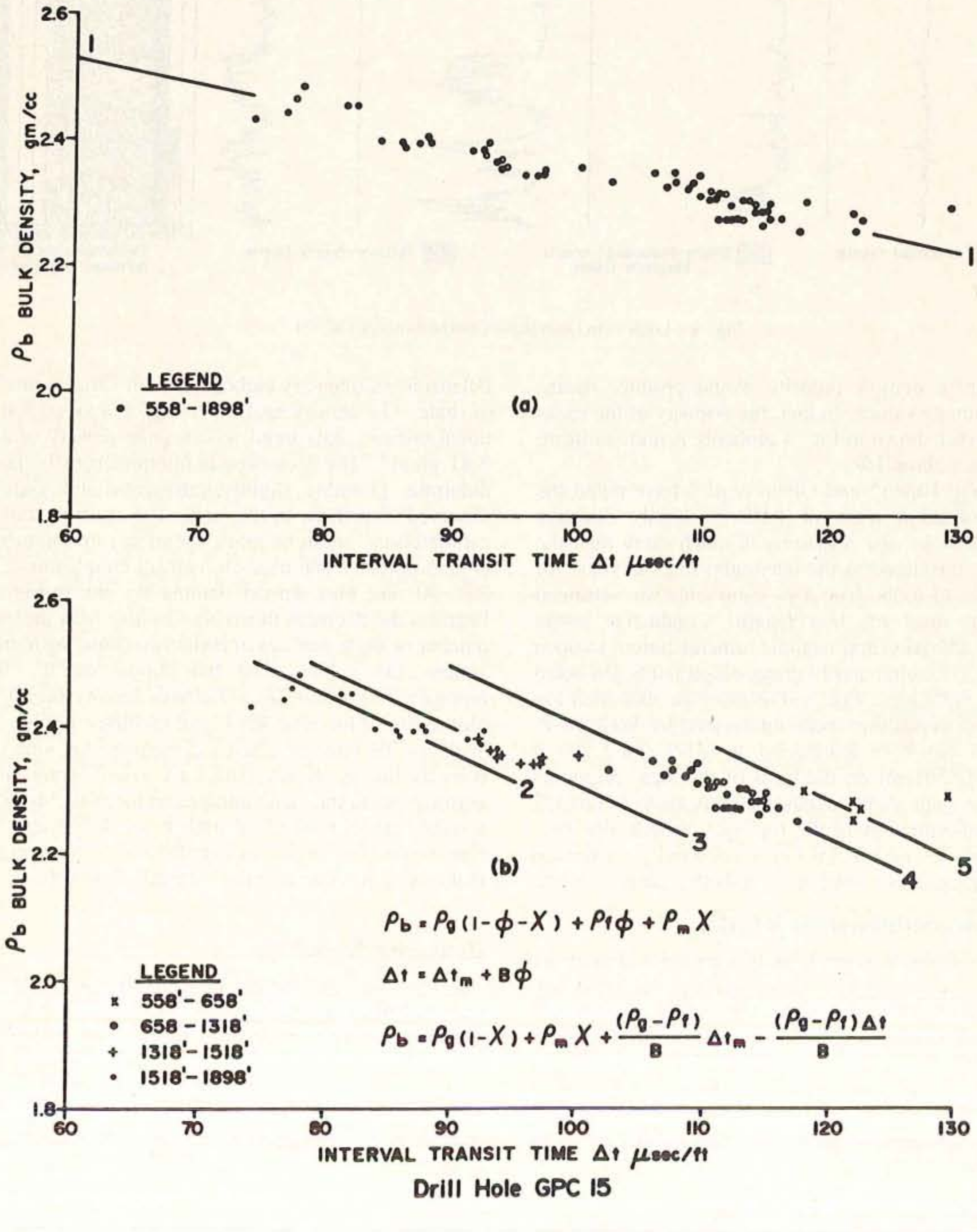

Fig. 3—Interval transit time/bulk density crossplots.

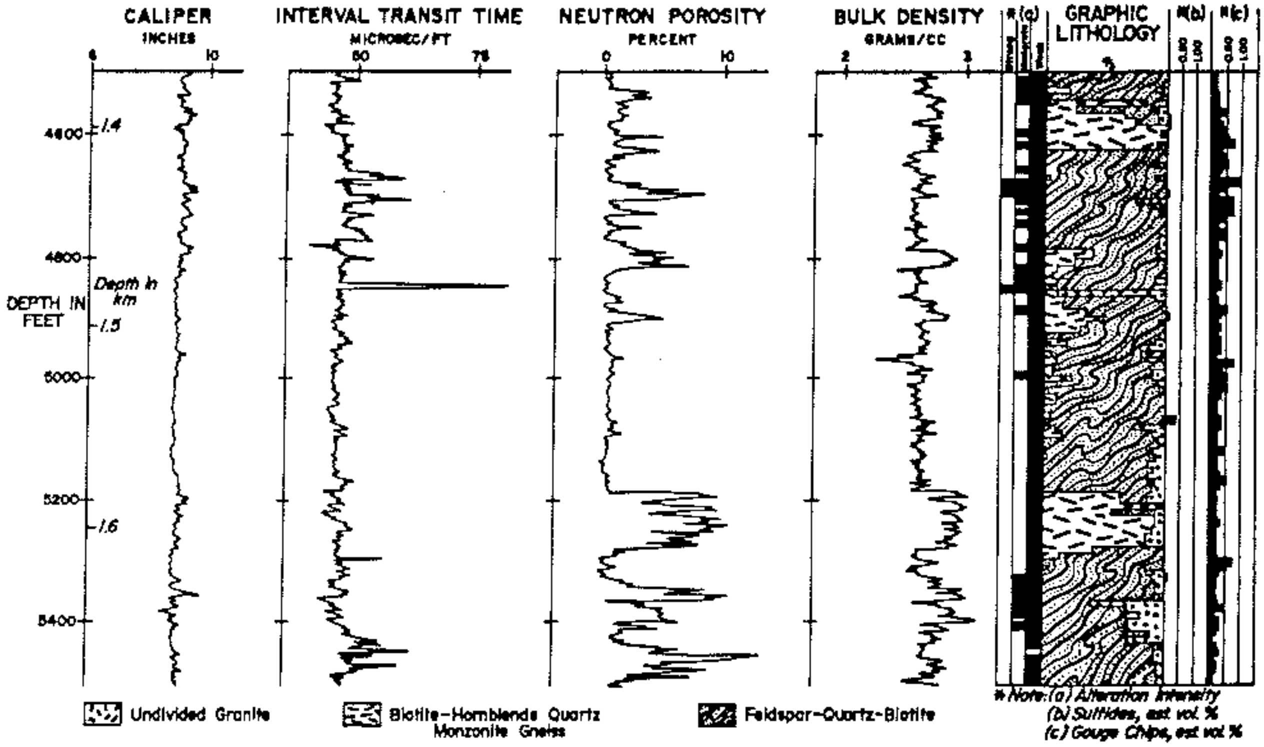

Fig. 4—Logs from Utah State Geothermal Well 52–21.

to compute a density porosity would produce meaningless porosity values. In fact, the porosity of the rocks in the interval shown in Fig. 4 probably is quite uniform and averages about 1%.

Glenn and Hulen[8] and Glenn *et al.*[9] have noted the use of induction tools at RHS in highly resistive crystalline rocks; the resistivity is much more than the 100 Ω-m considered as the maximum reliable value for these types of tools. The logs commonly are saturated throughout most of their length. Conductive zones related to alteration and metallic mineralization, to open fractures and faults, and to gouge-filled faults are noted easily on these logs. Fig. 6 illustrates the induction log response in crystalline rocks intercepted by Well 14–2. A fracture has been interpreted at 5,000 and 5,220 ft (1524 and 1591 m) on the basis of the logs' responses and gouge chips at this depth. There is about 0.5 to 1% sulfide concentration in the fractures, which also contributes to the higher fracture conductivity. Saturated resistivity logs were noted in several other areas as well.

Cove Fort-Sulphurdale KGRA

The Cove Fort-Sulphurdale (CFS) geothermal resource is in highly fractured and metamorphosed Mesozoic and Paleozoic sedimentary rocks. These rocks are buried beneath alluvium and a thick sequence of Tertiary tuffs. The geology of the area is reported in detail in Ref. 29. Ross *et al.*[11] have presented an integrated case study for the area.

Three log data crossplots from Union Oil Co. Wells 14–29 and 42–7 at CFS KGRA are shown in Figs. 7, 8, and 9. Figs. 7 and 8 show bulk density plotted vs. neutron porosity and gamma ray API units, respectively, for the interval of 1,240 to 2,056 ft (378.0 to 626.7 m) in Well 14–29. The interval had only partial returns of Paleozoic sedimentary carbonates with variable amounts of shale. The density neutron crossplot shows a conventional porosity data trend with a grain density of about 2.81 g/cm^3. The rock type is interpreted to be largely dolomite, probably slightly calcareous and shaley as observed elsewhere in the area. The neutron tool was calibrated in limestone units; therefore, to compute the correct porosity one needs to consult Graph Por–13b in Ref. 30. The bulk density gamma ray plot in Fig. 8 illustrates the decrease in matrix density, with increasing number of shale partings or beds corresponding to higher gamma ray values. The line drawn on the figure represents zero porosity. The bulk density transit time plot in Fig. 9 for Well 42–7 is in lithology similar to the Well 14–29 interval discussed earlier. An interpreted porosity line is shown. The 2.81-g/cm^3 grain density corresponds to the value interpreted for Well 14–29, and a matrix travel time of 46 μsec/ft for dolomite is quite reasonable. The scatter of data below the lines suggests that more limestone is in this interval of Well 42–7.

Beowawe KGRA

The Beowawe geothermal resource appears to be fracture controlled and resides in a complex, interbedded sequence of acidic to basic volcanic and sedimentary rocks. The sedimentary rocks, shaley siltstone, bedded chert, and micaceous sandstone are found below 4,500 ft (1371.6 m) in both wells. Ref. 31 is a detailed report on the geology of the Beowawe geothermal resource area. Selected well logs from two Chevron Resource Co. wells, Rossi Well 21–19 and Ginn Well 1–13 at Beowawe, are shown in Figs. 10 and 11, respectively. Only part of Ginn Well 1–13 is shown in Fig. 11; the well is 9,551 ft (2911.2 m) deep.

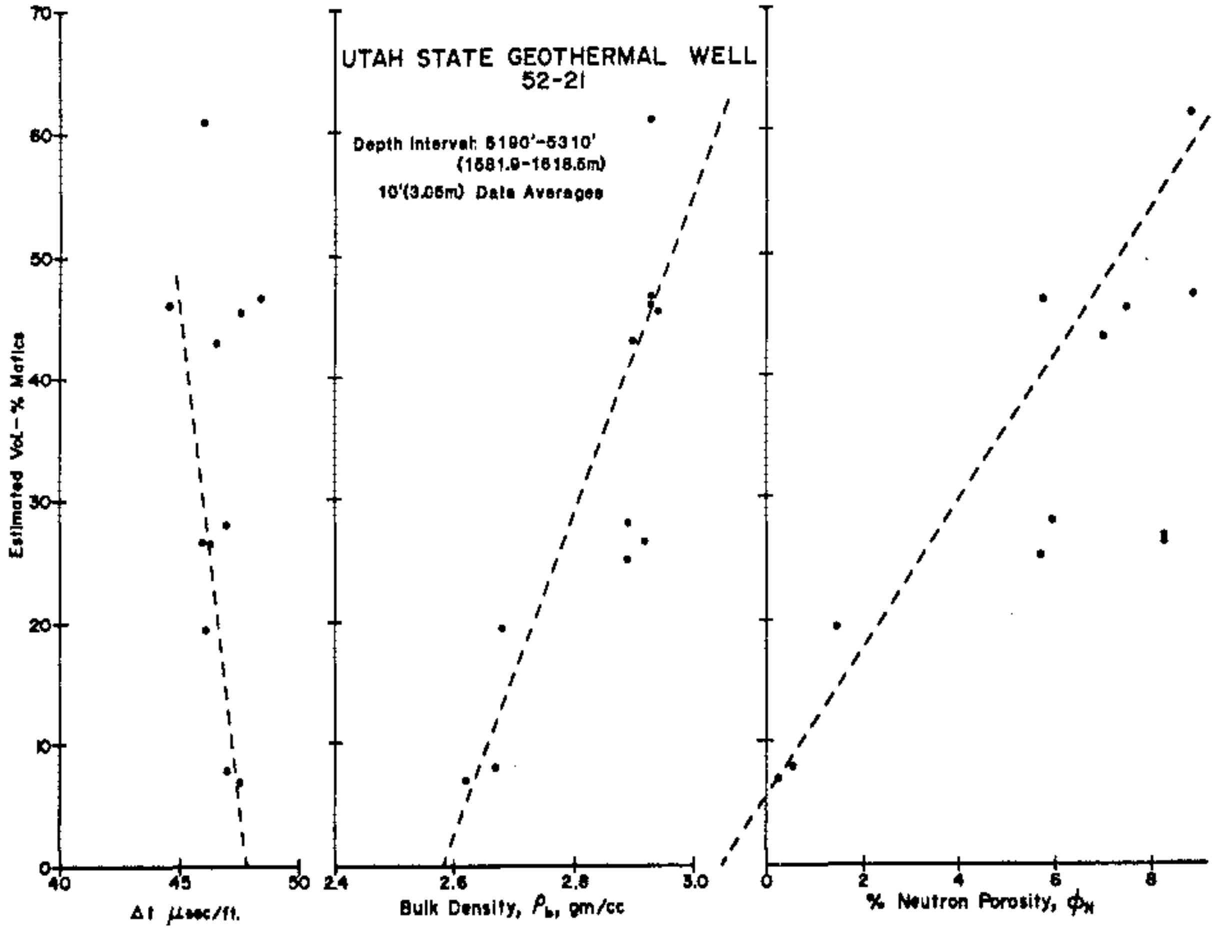

Fig. 5—Correlation of well log data to volume percent mafic minerals in chip samples from Utah State Geothermal Well 52–21.

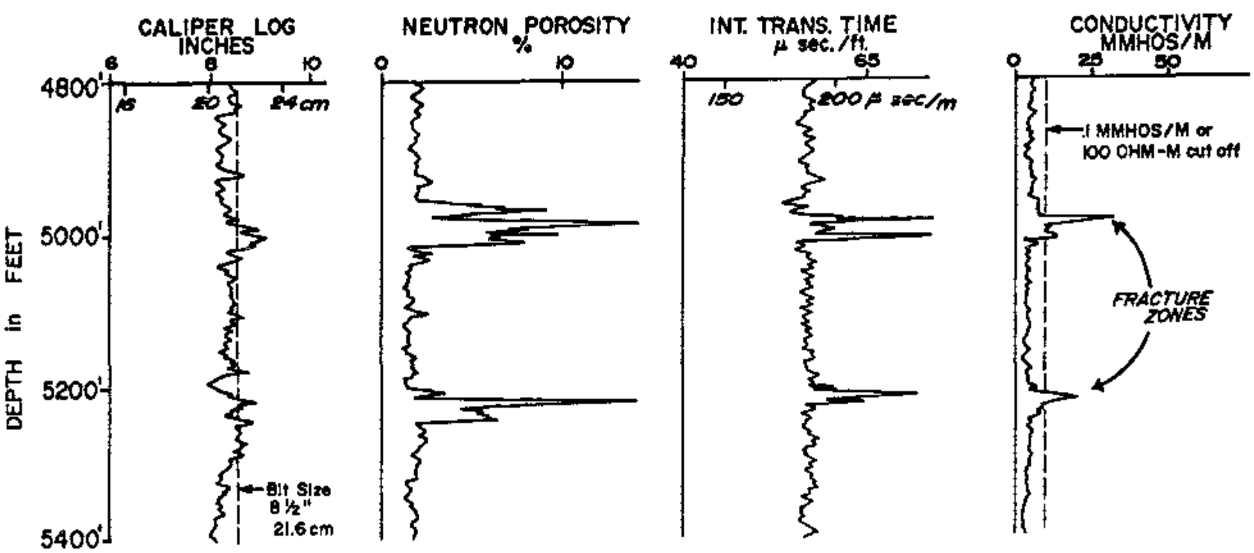

Fig. 6—Selection of well logs from RHS Well 14-2, UT, illustrating induction log saturation and fracture response.

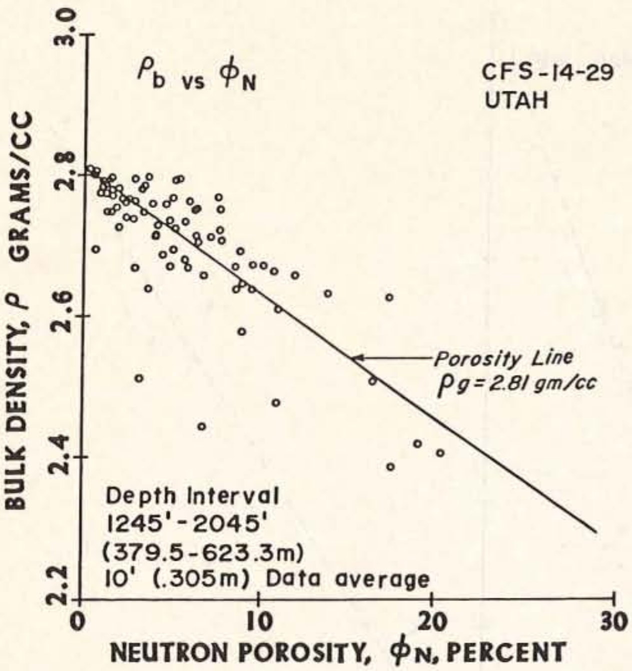

Fig. 7—Bulk density/neutron porosity crossplot from CFS Well 42-7, UT.

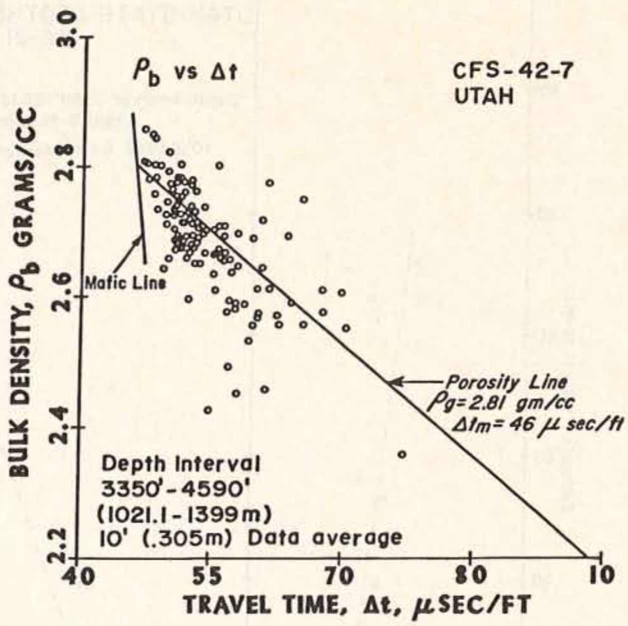

Fig. 9—Bulk density/travel time crossplot from CFS Well 42-7, UT.

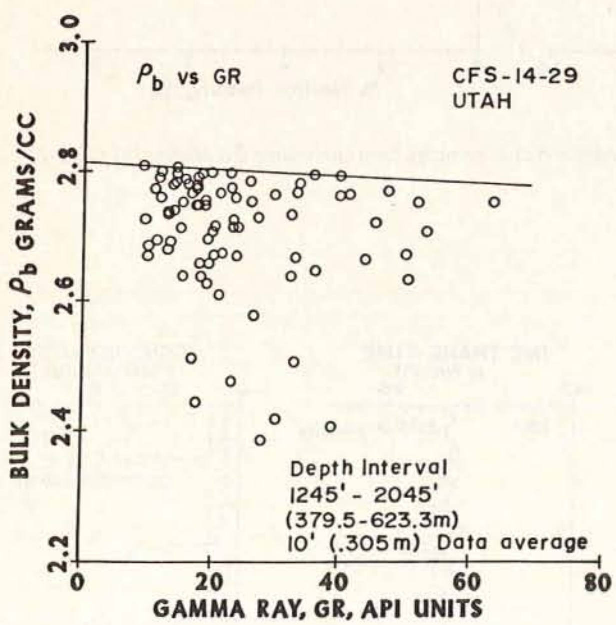

Fig. 8—Bulk density/gamma ray crossplot from CFS Well 14-29, UT.

Several interesting features are evident in Figs. 10 and 11. The three logs shown—bulk density, gamma ray, and deep induction resistivity logs—correlate well between the two drill holes and have distinct responses corresponding to several of the rock types. In particular, the basaltic andesite has a distinct low (approximately 20 to 40 API units) gamma ray response. This result is expected because, in the absence of alteration minerals, basalts characteristically contain very minor amounts of radioactive minerals. In contrast, the dacite aphanite and tuffaceous sedimentary rocks are more acidic rocks and have a high gamma ray response. The tuffaceous sedimentary rocks also are characterized by a low resistivity and bulk density. The rock units below about 5,050 ft (1539.2 m) in Ginn Well 1-13 exhibit less variability on the density and resistivity logs than the rocks above this depth. By contrast, the gamma ray log exhibits the opposite characteristic, which suggests that the sedimentary rocks are probably an alternating section of interbedded volcaniclastic rocks and ash flow tuffs. The lost sample interval below 2,000 ft (609.6 m) in Rossi Well 21-19 can be interpreted to be the tuffaceous sedimentary rocks and basaltic andesite observed at about the same depth interval in Ginn Well 1-13. Both well logs and lithologic logs correlate across this interval.

Crossplots of the log data from the interval of 3,245 to 4,155 ft (989.1 to 1266.4 m) in Ginn Well 1-13 are displayed in Fig. 12. The gamma ray and resistivity data are plotted in Fig. 12a, the resistivity and bulk density data are plotted in Fig. 12b, and gamma ray and bulk density data are plotted in Fig. 12c. As expected from the discussion of Figs. 10 and 11, good correlations exist among these three logs. The interval plotted contains the basaltic andesite. The increasing gamma ray response accompanied by a decrease in resistivity and density

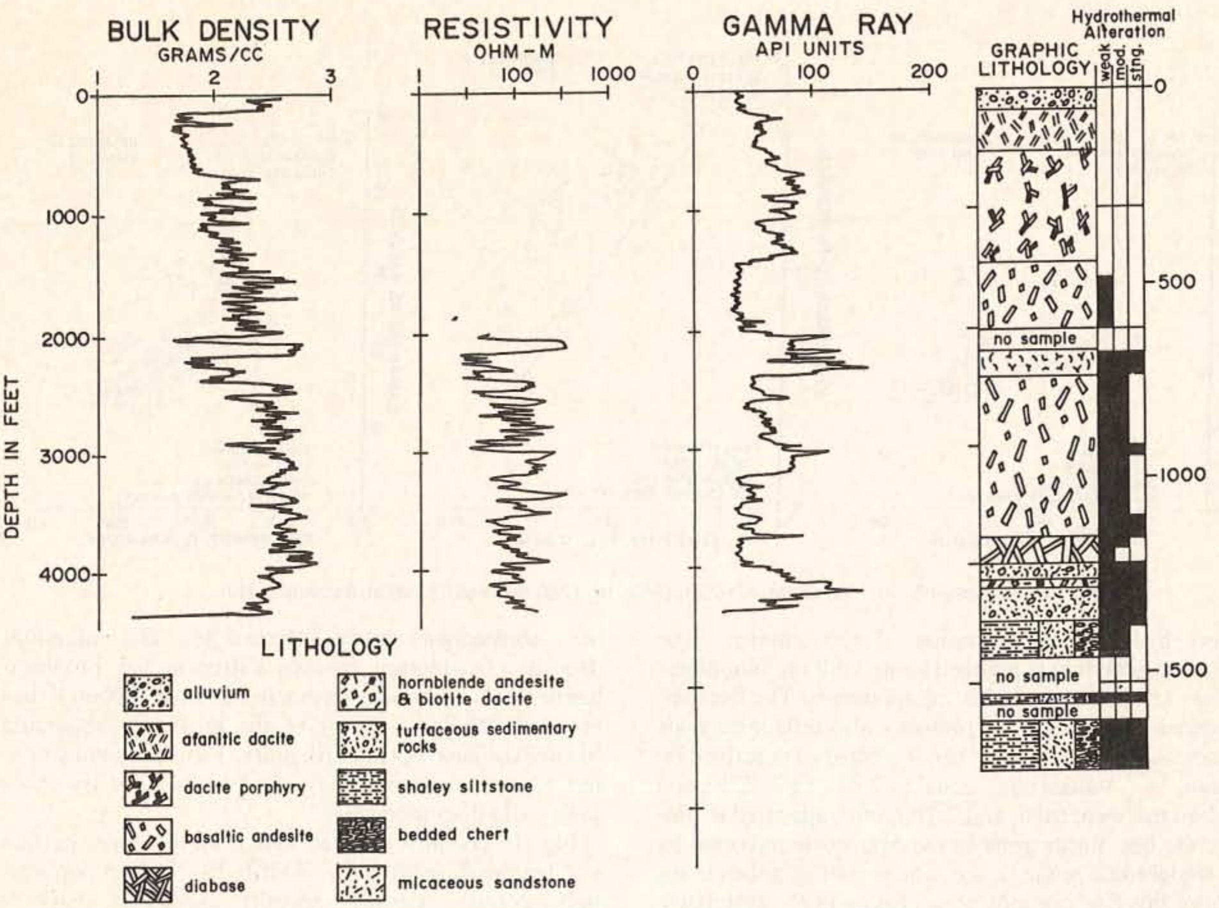

Fig. 10—Selected well logs from Rossi Well 21-19, Beowawe, NV.

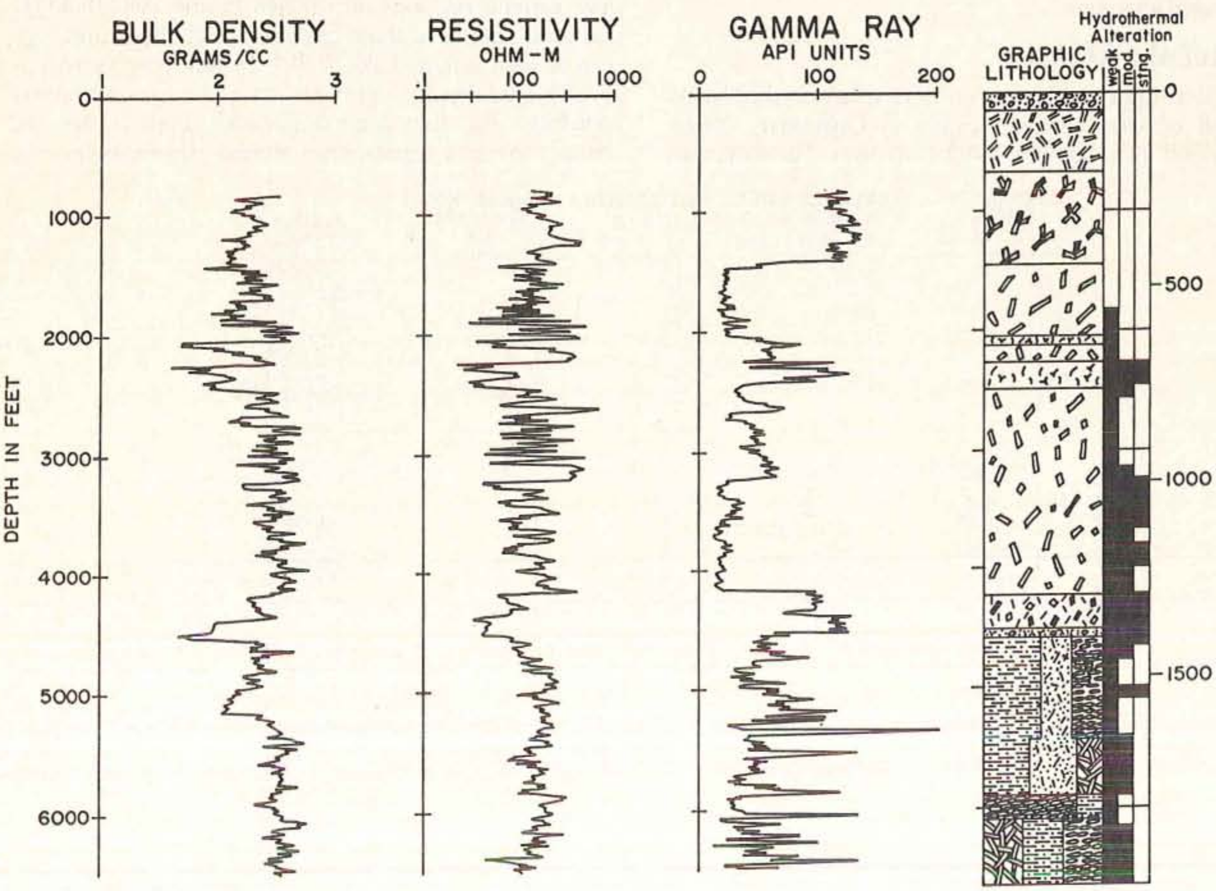

Fig. 11—Selected well logs from Ginn Well 1-13, Beowawe, NV. (Lithology legend is in Fig. 5.)

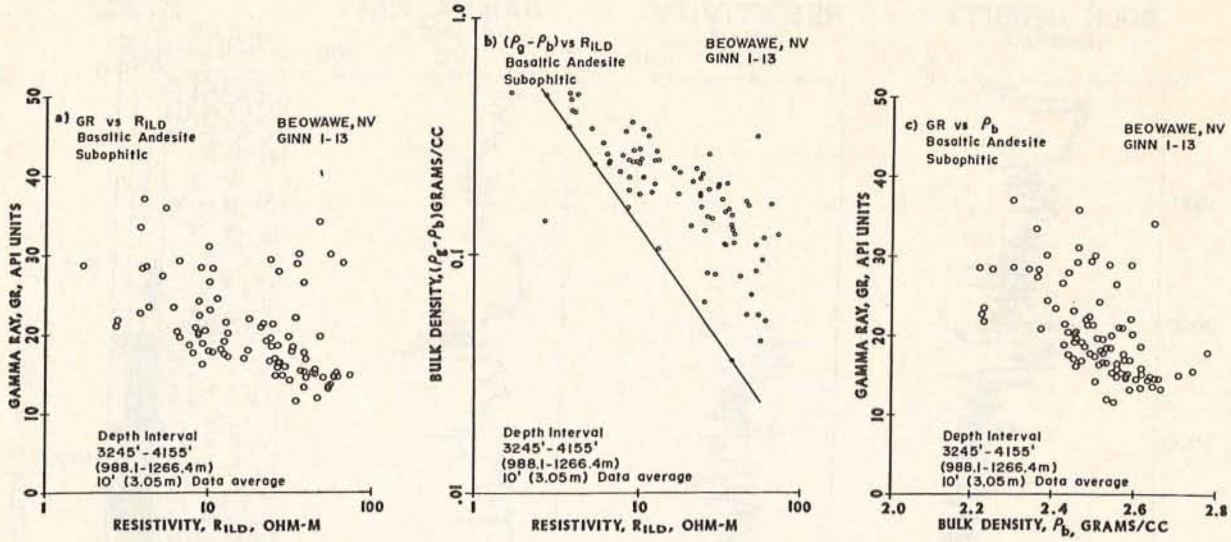

Fig. 12—Crossplots for 3,245- to 4,155-ft (989- to 1266-m) depth interval, Beowawe, NV.

reflect hydrothermal alteration of the andesite. The degree of alteration is graphed along with the lithologies in Fig. 11 and supports this interpretation. The decreasing density and resistivity probably also reflect intervals of increased porosity. Fig. 12b is plotted as described by Pickett.[32,33] Values of ρ_g equal to 2.65, 2.67, 2.70, and 2.72 g/cm^3 were tried, and 2.70 g/cm^3 appeared to produce the best linear trend in the data, as is indicated by the straight line in the figure. The scatter of points to the right of this line can indicate a change in R_w (formation fluid resistivity), rock type or, as we believe in this case, increased alteration.

Soda Lake KGRA

The Soda Lake geothermal resource area is in the Carson Desert of west central Nevada in Quaternary clastic sediments up to 4,600 ft (1402.1 m) deep. The sediments are interbedded deltaic, lacustrine, and alluvium deposits. Quaternary igneous extrusion has produced basalt flows and cinder cones in the area. Sibbett[34] has reported detailed geology of the area and interpreted basalt dike intercepts in drill holes. Fault or fracture control of this resource is less evident than for the three previously discussed areas.

Fig. 13 contains selected logs from the upper portion of Chevron Resources Co. Well 1-29. Neutron porosity, bulk density, density porosity computed using a 2.65-g/cm^3 grain density, and deep induction resistivity and gamma ray logs are plotted beside the lithology. Features similar to those observed in the Beowawe logs can be seen in Soda Lake Well 1-29. The basalt units exhibit higher density and resistivity and very low neutron porosity. The low neutron porosity suggests that the basalts are not significantly altered. Interestingly, the

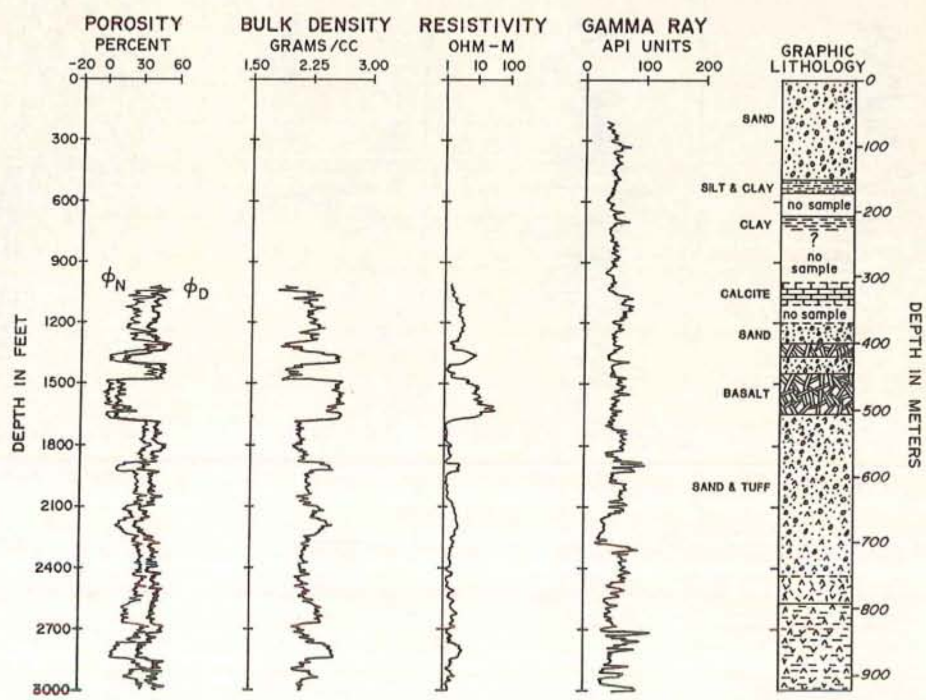

Fig. 13—Selected well logs from Soda Lake Well 1-29.

gamma ray log exhibits far less distinct lithologic correlation in Well 1-29 than observed in previous drill holes. All logs suggest more variability in the tuffaceous sands than noted in the lithologic log. This variability could reflect compositional changes from acidic to mafic tuffs and the degree of cementation. Lithologic logs typically suffer from mixing of the cuttings on the way to the surface.

Conclusions

Despite the high-temperature, often corrosive environment of geothermal wells, nearly complete suites of openhole well logs have been obtained in most industry coupled geothermal wells. Although lithologies intersected in most wells create less familiar log responses, the logs can distinguish particular lithologies. The gamma ray, neutron, bulk density, resistivity, and, to a lesser extent, the acoustic logs provide the best data for determining lithology.

While traditional log interpretation techniques, such as lithology/porosity crossplots, will work in the complex lithologies encountered in geothermal resource areas, the techniques must be used in less traditional ways to reflect the rock properties most important to the logs' response. The density and volumes of hydrous minerals, particularly in the igneous and metamorphic rocks, are often of greater importance than porosity changes. The acoustic log and density log variations will reflect the density changes, and the neutron log will reflect hydrous mineral abundances.

Logs obtained in near-surface formations, including alluvium, are important to the interpretation of surface geophysical surveys and hydrologic studies.

The most frequent log quality problems seem to be those experienced in other well logging applications. Incorrect recording scales, off-scale or saturated logs, poor calibration, and degraded signal quality caused by hole conditions are the most evident problems. The high-temperature environment is commonly handled by using high-temperature tools, circulating the borehole before or during logging, and by not using particular tools.

Acknowledgments

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SI Metric Conversion Factors

in.	× 2.54*	E+00	=	cm
ft	× 3.048*	E−01	=	m
mile	× 1.609 344*	E+00	=	km

*Conversion factor is exact.

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