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DEVELOPMENT OF GEOTHERMAL LOGGING SYSTEMS IN THE UNITED STATES

(Peter Lysne, Distinguished Member of the Technical Staff, Geoscience Research Drilling Office: MS 1033, Sandia National Laboratories, Albuquerque, NM 87185, USA; Tel: (505)844-8885, Fax: (505)844-3952; E-mail: pclysne@sandia.gov)

Abstract

Logging technologies developed for hydrocarbon resource evaluation have not migrated into geothermal applications even though data so obtained would strengthen reservoir characterization efforts. Two causative issues have impeded progress: (i) there is a general lack of vetted, high-temperature instrumentation, and (ii) the interpretation of log data generated in a geothermal formation is in its infancy. Memory-logging tools provide a path around the first obstacle by providing quality data at a low cost. These tools feature on-board computers that process and store data, and newer systems may be programmed to make "decisions". Since memory tools are completely self-contained, they are readily deployed using the slick line found on most drilling locations. They have proven to be rugged, and a minimum training program is required for operator personnel. Present tools measure properties such as temperature and pressure, and the development of noise, deviation, and fluid conductivity logs based on existing hardware is relatively easy. A more complex geochemical tool aimed at a quantitative analysis of potassium, uranium and thorium is in the calibration phase, and it is expandable into all nuclear measurements common in the hydrocarbon industry. A fluid sampling tool is in the design phase. All tools are designed for operation at conditions exceeding 400°C, and for deployment in the slim holes produced by mining-coring operations. Partnerships are being formed between the geothermal industry and scientific drilling programs to define and develop inversion algorithms relating raw tool data to more pertinent information. These cooperative efforts depend upon quality guidelines such as those under development within the international Ocean Drilling Program.

Introduction

Downhole logging and surface geophysical measurements have become a backbone for hydrocarbon reservoir analysis. Since the first recorded borehole measurements by the Schlumberger brothers in 1927, advances in hardware and interpretative methods have produced an impressive series of successes. In his 1990 keynote address to the Society of Professional Well Log Analysts, Paul Worthington noted these successes and envisioned that within five years there will be an industry-wide consensus regarding a multidisciplinary approach to reservoir definition (Worthington, 1991). This approach will range from the petrophysics of individual pores at a scale of 10^{-4} meters to surface geophysical investigations with investigative lengths of 10^{2} meters. Cooperation in this effort is necessary due to the magnitude of the task and its importance in an era of declining hydrocarbon resources and increasing costs.

An effort of this magnitude is not a feature of the geothermal thrust in the United States. While some surface geophysical studies are used, these studies are limited (e.g.,

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Goldstein and Stein, 1988, and ref. therein). Furthermore, there is a general lack of downhole measurements even though they are required to interpret surface studies, to extrapolate core data away from a hole, and to correct production difficulties.

An often-cited obstacle to downhole measurements is the fact that tools used in low-temperature formations are not compatible with the geothermal environment, and the cost of developing and maintaining a suitable tool suite exceeds the anticipated revenues from logging services. But a market can only be supported if measurements produce a meaningful output. Since interpretative techniques developed for hydrocarbon reservoirs are not proven or may not be pertinent in geothermal formations, a second obstacle is the general inability to relate log data to meaningful information. In some respects, the development of a viable geothermal logging industry is impeded by the chicken-egg syndrome.

In 1992 program was instituted at Sandia National Laboratories to address the obstacles noted above. It involves a cooperative effort between industry, scientific drilling programs, and national laboratories.

Memory-Logging-Tool Concept

Hostile environment tools found in the logging service industry are capable of operation to 260°C, and thus are applicable to some, but not all, geothermal applications. Furthermore, size constraints are imposed by the diamond coring techniques used in some geothermal operations. Taken together, the temperature and the tool diameter provide initial criteria for the design of logging equipment. Given present needs and realistic technologies, a modern tool will be operable to at least 400°C and will be about 50 mm in diameter (Lysne, Worthington and Pyle, 1990).

Conceptually, two classes of tools are able to meet these criteria. The first class utilizes an electrical wireline to transmit power and data between the tool and the surface, and it is exemplified by tools common to the logging industry. The second class is completely self-contained in that power is obtained from batteries, and data are stored in a memory system. Even though memory tools have been around for decades, they have not found common usage due to past limitations. This situation is changing rapidly due to improvements in digital technology.

Both classes of tools were used to make high-resolution temperature measurements in the VC-2B scientific corehole to 295°C (Lysne, 1992). While data were of equivalent quality, the tool using an electric wireline failed about one-half of the time due to wireline or cable-head difficulties. Significantly, the memory tool has never experienced a data loss. This record includes the faithful recording of fishing exercises made when the tool was twice dropped through 2.5 km (8,200 feet) of internal upset drill pipe.

Cost considerations weigh heavily in the establishment of logging services, and memory tools are effective due to a number of issues. These tools are programmed at the surface by linking the tool to a personal computer running a simple, menu-driven program. This fact, coupled with the point that the tools are rugged and mechanically simple, minimizes operator training. It has been found that personnel will become operators after a day or so of hands-on experience. Secondly, the slick line deployment system is almost always available on site so exercises may be undertaken on the spur of the moment and without the mobilization and maintenance of a special truck. Finally, while the development cost of prototype tools is understandably high, it is envisioned that simple tools will become inexpensive almost to the point of being expendable (est. 0.1% of hole cost). Memory tools then will be suitable for high-risk duty.

While memory tools are inexpensive, logging engineers raise the point that the memory concept is flawed by the lack of communication between the tool and the operator. The greatest concern is that a tool will fail, yet the logging run continue due to lack of information. Perhaps future tools will possess some means of communicating a failed condition to the surface. In any event, memory tools must possess reliability to be creditable.

In the same vein, logging strategies are often evolved on the basis of real-time data. Memory tools preclude this approach. This point is not as valid now as it was in the past since newer computer systems support languages that are "intelligent". Thus, a logging strategy that contains contingencies may be programmed into the tool. Finally, the power available in a battery operated tool is limited. This means that power-intensive measurements are constrained to short durations.

Sandia Tool Suite

Three memory tools will form the backbone of the initial Sandia tool suite. These tools meet the temperature and size criteria noted above. The background and status of these tools is discussed in this section.

In 1988, Sandia contracted with the Geophysical Research Corporation (GRC), Tulsa, for the development of a temperature-measuring tool (Duda, 1988). The cost of this prototype tool was $58,000. The tool was funded jointly by DOE/Office of Basic Energy Sciences and DOE/Geothermal Development.

The GRC/Sandia temperature tool has seen about thirty deployments in VC-2B and other holes including hot holes drilled by the Ocean Drilling Program on the Juan de Fuca Ridge, cf. Figure 1. The status of this tool is best described by the statement of independent ocean scientists given to panels of peers: "The tool of choice." (Becker, 1990), and: "..a superb temperature tool that worked flawlessly even with rough handling." (Langseth, 1990). A precision (0.005%) pressure measurement will be incorporated into this tool in the near future. A new version of this tool is scheduled for field tests early in 1994. The intent of this tool is to achieve significant cost reduction through the use of commercially available electronic systems. Furthermore, the tool will be less than 2 meters long so that it may be transported as ordinary luggage on an aircraft. This means that if a wireline facility is available on site, all of the additional equipment necessary for a logging operation can be anywhere in the world on very short notice.

A second tool under development features a sodium iodide sensor for the spectral recording of natural gamma rays emitted by potassium, and the daughter products of uranium and thorium. These "KUT" measurements will provide an elementary mineralogical analysis, and they will be an indicator of the deposition of scale in geothermal wells. Future applications may involve the addition of radioactive gamma and neutron sources, although such sources significantly change the regulatory conditions that govern the transportation and deployment of the tool. Such sources would permit a neutron activation analysis of aluminum for clay assays, the determination of densities through the

Compton scattering of gamma rays, and the determination of water content through the slowing of high-energy neutrons. Pulsed neutron generators could be incorporated into the tool for more sophisticated activation analyses, but severe limitations exist due to their power requirements.

During the course of the VC-2B Program, it was found that present fluid sampling tools leak and do not deliver pristine specimens to the surface (Lysne, 1991). Consequently, a fluid sampling tool is in the design stage. The tool will be smart in that a pre-programming of the memory system will allow sampling based on, say, the nearest approach of the hole to the critical point of water or the precipitation state of a critical mineral.

An essential feature of the sampler proposal is that total system development is to be co-sponsored by the US Department of Energy/Basic Energy Sciences and the Ocean Drilling Program, with the latter agency supporting the development of an uphole analysis system. This division results in approximately equal development costs, and it provides each agency with an identifiable program element. A panel of geochemists, the Borehole Sampler Support Group (Edmond, 1991), has been convened by the Ocean Drilling Program to help in the coordination and implementation of this effort. A significant portion of the Group's efforts will be directed toward the interpretation of fluid-sampler and other data. But interpretation issues deal with a much broader range of subjects than are exemplified by the fluid-sampler tool.

Interpretation Issues

From the viewpoint of a logging specialist, physical properties fall into two categories: (1) primary properties that can be readily determined downhole, and (2) secondary properties that are of importance, but are difficult to measure directly using downhole instruments. The primary properties include quantities such as borehole shape, temperature, resistivity, sonic velocity, hydrogen content, and density. These properties often delineate quantities or features of interest, and they are used in hole-to-hole correlation. Furthermore, the resistivity, the sonic velocity, and the density are necessary to calibrate surface geophysical studies. Secondary properties include porosity, permeability, lithology, oxidation state, and water saturation. These quantities may be determined from core, but core may not be available if drilling conditions are bad, if industry holes of opportunity are exploited for scientific purposes, or if budgetary constraints are over-riding.

Foundations for the measurement of primary properties are based on the defining equations of classical physics, on a knowledge of proper boundary conditions for the solution of the ensuing partial differential equations, and on a model for the material properties of the media surrounding the sonde. The material model contains one or more adjustable parameters that represent quantities of the first category. The adjustable parameters are obtained through routines that fit measured quantities (voltages, time differences, count rates, etc.) to the model. To illustrate these concepts, appropriate relations for four tools commonly used to determine porosity are listed in Table 1. Due to the importance of porosity to the hydrocarbon industry, resistivity, sonic, neutron, and gamma tools have received considerable attention in recent years. A cogent discussion of these and other tools has been published (Hearst and Nelson, 1985); a review of techniques used in scientific programs is also available (ODP, 1990).

The relevance of the material model plays an important role in evaluating a tool's response. For example, the response of resistivity tools usually is based on Ohm's Law, a linear relation between the electric field and the current density. This material model is proper as long as the formation is isotropic and homogeneous on a scale that is small compared to characteristic volumes introduced in the solution of the differential equations that govern a tool's response. Similarly, the neutron tool used to measure hydrogen content is accurate as long as the porosity, the water saturation, and the amount of material with large thermal neutron absorption properties is constant within each characteristic volume. Such information is best obtained from core, although complete core is not needed. This situation illustrates that core and logs are complementary systems, and they should be used together to provide information at a minimum cost.

In the past, the solution of differential equations governing tool responses was tedious, and often inexact due to the large characteristic volumes and symmetry constraints introduced to make the problem tractable. Thus, tools were calibrated using test pits designed to simulate the range of subsurface conditions that tools were expected to encounter. This approach leads to the "dolomite", "limestone", or "sandstone" calibrations that are applicable to clean sediments, but of uncertain applicability to other materials.

Recently, fast computers using modern finite-element and Monte Carlo algorithms have mitigated the problem of modeling a tool's response since both very small characteristic volumes and three-dimensional geometries are tractable. Now the cost of evaluating a tool's performance is far less than that encountered when test pits were a necessity. This means that the effect of variations in the material models can be thoroughly explored if knowledge of the interior workings of a tool are available. Unfortunately, some logging companies treat this information as proprietary. If cooperative companies cannot be found, re-development of an existing tool concept may be justified to insure a better understanding of tool responses.

Consider now the relations between primary and secondary properties. In principle, these relations are governed by the basic physics, and appropriate relations could be found by following paths similar to those discussed above. However, geometrical issues are very complex and occur on a size scale commensurate with pore dimensions. Even the best computational techniques cannot solve such detailed problems. Perhaps statistical techniques will provide solutions. For the present, a major difficulty arises because correlations between primary and secondary properties are uncertain and ambiguous.

Table 1 lists relations that have been used to tie primary properties to porosity. The ambiguity in these relations is emphasized by the over fifty variations of Archie's Law (a skeptic might note that Archie's Law is a linear fit on a log-log plot that implies no theoretical justification). Clearly, there is a need for a better fundamental understanding of relations between primary and secondary properties, and advances in the understanding of these relations will have a profound effect on both scientific and applied endeavors. But guidelines are needed to insure that interactions between programs with fundamentally different goals and aspirations proceed smoothly. One set of such guidelines is underdevelopment in the international Ocean Drilling Program (ODP).

ODP Guidelines for System Development

The ODP is an international research consortium dedicated to exploring the structure and history of the Earth beneath the oceans. The program receives primary support from the US National Science Foundation and seven international partners: Canada-Australia consortium, France, Germany, Japan, European Science Foundation, Russia (inactive), and the United Kingdom.

The ODP has maintained a modest effort in tool development for nearly a decade. While a few tools have been successful and have moved on into the industrial sector, many have languished due to an underestimation of the development difficulty and cost. Furthermore, engineering deficiencies in these "Third-Party" tools have resulted in inordinate expenditures of ship's time for a limited data return. Thus, the ODP has adopted a set of guidelines for tool development (ODP, 1992).

A feature of the ODP plan is that a *Principal Investigator* must be identified, and that this individual is the primary proponent for the development and use of the tool. Among other issues, this investigator must submit a plan that identifies development milestones, that makes provisions for land testing, that specifies the usefulness of the proposed measurements, and that contains a statement that the tool would be available for post-development deployment in the ODP. It is most important to note that Principal Investigator is tasked with leading the development of a measurement system, not just a tool.

An ODP tool development program follows a prescribed course consisting of three stages. A *Development Tool* is either a tool that is under development externally for use in the ODP or a tool that has been developed outside the ODP for other purposes, and is being considered for ODP deployment. Unlike tools in more advanced stages of development, the scientific success of a cruise cannot depend on a Development Tool.

After the development stage, the tool attains the status of a *Certified Tool,* and it is available for scientific deployment. The request for certification includes cost estimates for routine operation including data processing, details concerning spare parts, operating and maintenance manuals, and a demonstration of the usefulness of the data.

Finally, a *Mature Tool* is an established tool that has become part of the ODP tool suite. Such a tool is effectively owned by the ODP.

The ODP guidelines for tool development are new and evolving. The tasks that are placed on the Principal Investigator are difficult, and require strong support from numerous scientific and engineering disciplines. This support will be costly. But the programmatic consequences of failed efforts are much more costly since failures stifle innovation. It is not clear how the ODP will muster the necessary resources to support evolutionary efforts; it is clear that strong scientific rationale is necessary to justify their existence. The ODP, working through the entire JOIDES Panel structure, is forming a consensus regarding the evolution of downhole measurement systems. The resulting model will form the basis for a more general technology-development thrust that will influence all areas of the geological sciences.

Concluding Remarks

There is a clear need for new downhole measurement tools and interpretation techniques within the various scientific drilling programs. Furthermore, this need extends into institutions that are recovering resources from the crust, or using the crust as a repository for wastes. The depressed condition of the hydrocarbon industry precludes the strong advances that this sector offered to the science of downhole measurements in the past. However, the prevailing economic condition means that doors will be open for cooperation between scientific, government, and industrial institutions.

Acknowledgments

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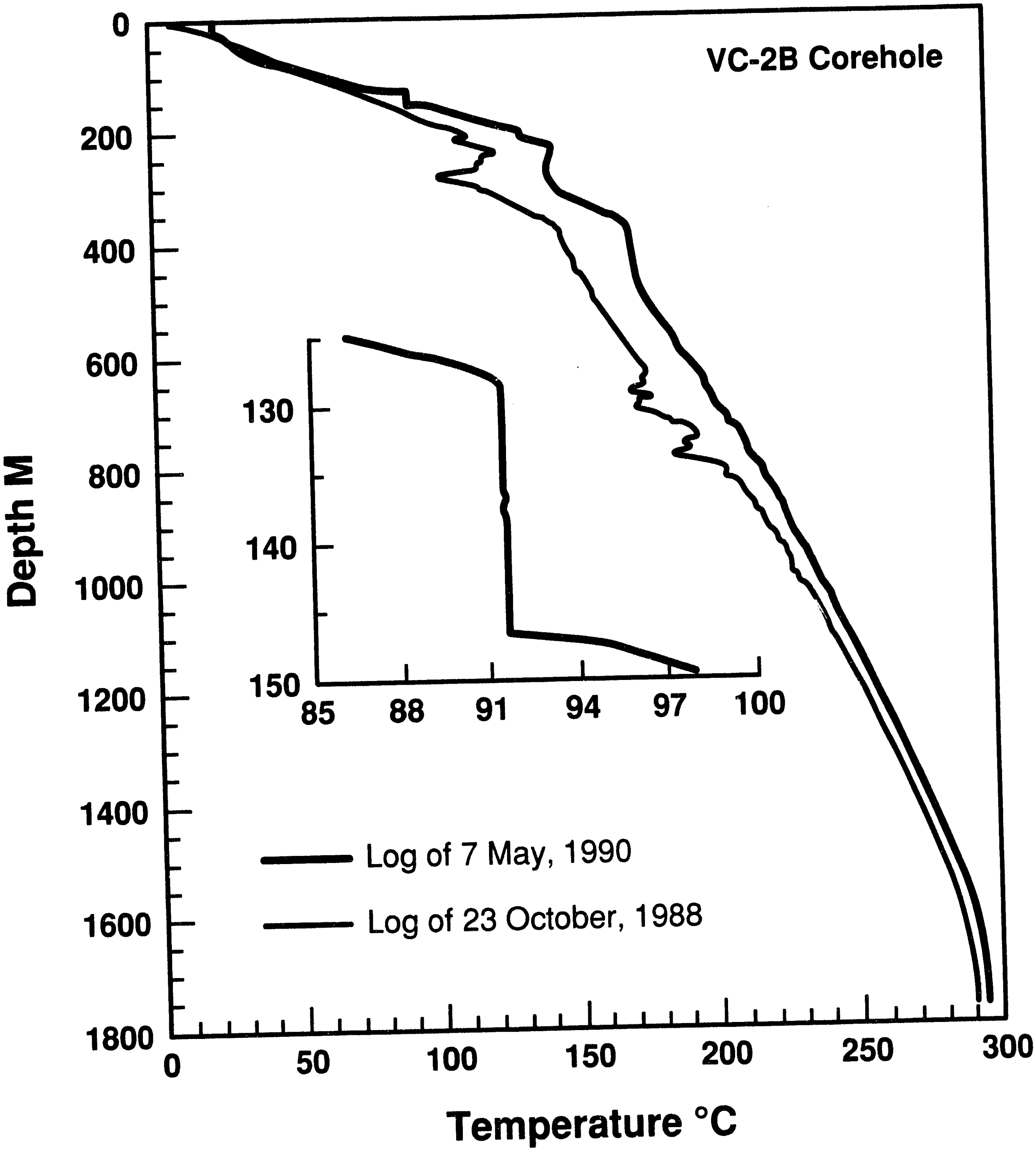
TABLE 1. Resistivity, Sonic, Neutron, and Gamma Tools Commonly Used to Measure Porosity.

Underlying Physics	Bulk Material Model	Primary Property	Interpretive Model	Secondary Property
Maxwell's Eqs.	Ohm's Law	resistivity	Archie's Law	porosity
Newton's Eqs.	Hook's Law, density	sonic velocity	Wyllie's Law	porosity
Boltzmann's Eq.	elemental composition of matrix, Z>1	hydrogen content	ratio, pore water to bound water	porosity
Boltzmann's Eq.	elemental composition of matrix	density	grain density	porosity

Figure Caption

Figure 1. Temperature logs made in the VC-2B corehole, Valles Caldera, NM, USA. The log of May, 1990 was made shortly after circulation of drilling fluids was stopped, and the fine-structure on the log shows permeable zones of lost circulation that were candidates for fluid-sampling experiments. The insert illustrates the liquid-vapor interface after the fluid level in the hole had dropped to an equilibrium level.


VC-2B Corehole
Depth M
0
200
400
600
800
1000
1200
1400
1600
1800
0
50
100
150
200
250
300
Temperature °C
130
140
150
85
88
91
94
97
100
Log of 7 May, 1990
Log of 23 October, 1988

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