The Geological Application of Wireline Logs: A Keynote Perspective

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ABSTRACT

Wireline logs have served generations of geologists as the principal medium for lithostratigraphic correlation in the subsurface. However, the expanding range of logging measurements, novel techniques of analysis and display, and integrated geological studies have dramatically broadened the scope of geological applications of wireline logs. Subsurface investigations can gain major new insights into geology from these measurements that supplement traditional geological methods. Modern astronomy has benefited enormously from the expansion of observation beyond the narrow bounds of the visible spectrum to the range from gamma-ray to radio wavelengths. To some extent, our studies of geology in the subsurface may progress in an analogous manner, but they will require innovative methods of database creation and data display that map raw digits into imagery at all scales, with immediate geologic impact.

INTRODUCTION

The phrase the geological application of wireline log is something of a tautology; what other applications are there? Because wireline tools make measurements of properties of rocks in the subsurface, their logging records are intrinsically geological. To be sure, a semantic shift could be attempted to confine wireline logs to geophysics. However, even this proves increasingly difficult because, for example, the properties recorded by some nuclear tools measure elemental concentrations by techniques similar to those used in geochemical laboratories. As another example, the resolution of borehole electrical imagery has long passed the point at which small-scale sedimentary features and trace fossils are observed and studied routinely. Fundamentally, a host of rock properties is measured by logging tools, and these are part of the larger enterprise called geology.

But can logging data and their analysis by petrophysical methods be considered an integral part of geology? Petrophysical logs are a vital source of geologic information from the subsurface (where the vast bulk of rocks resides), which otherwise would be a geophysical world pierced by occasional geological glimpses provided by core and fragmentary drill cuttings. However, if assessments of subsurface geology from wireline logs are included within the fold of geology, it would probably be useful to make some distinction from the classical geology of outcrop studies.
THE ROLE OF LOGS IN SUBSURFACE GEOLOGY

Science, by its very nature, is an agent for change. New models or ways of looking at the world can gain ground only through rethinking in an expanded synthesis. As in geology, developments in astronomy have changed both our understanding of the universe and the methods used to study it. But is an astronomer still identified by his use of an optical telescope? How does a specialist in stellar X rays relate to core astronomy? What is the appropriate name for astronomical studies outside the visible spectrum? In truth, there has been a radical change in astronomy in this century. Ground-based telescopes have been limited to a rather “weathered” view of the universe because of atmospheric fluctuations and light pollution from natural and man-made sources that perturb the night sky. The operation of the orbital Hubble telescope has moved optical observation above the disruptive atmosphere, for fresh pictures that are rich in new detail. Perhaps the excitement felt by an astronomer looking at Hubble images is akin to that of the field geologist who works for the first time with pristine core from a formation in the subsurface that was seen previously only in its weathered outcrop expression.

More important, in this analogy with wireline-logging tool sensors, the range of astronomical observation has expanded dramatically from the narrow keyhole of the visible spectrum (Figure 1). Studies in the broader spectrum can help astronomy only in its fundamental purpose of a descriptive mapping of the universe. So, for example, the orbiting Compton Gamma Ray Observatory has done much to revolutionize our understanding of the universe from its observations across an extraordinary six decades of the electromagnetic spectrum. Gamma-ray images show celestial features that are invisible to conventional astronomy in a way analogous to that of the gamma-ray spectrum, which reveals patterns of striking geological significance in visually monotonous shales.

Interestingly enough, there appears to be no widely accepted collective name that distinguishes these newer astronomical methods from classical telescopy, other than the “new astronomy” (Henbest and Marten, 1996). Clearly, this term will seem increasingly absurd as “new” ages to “old.” However, there are already signs that what is now novel and strange will be absorbed as an organic part of mainstream astronomy. Any distinction of a “new astronomy” will simply fade away as its usefulness comes to an end. Perhaps some term such as “virtual geology” might serve a similar role, as a term that promotes the use of logs in subsurface geology beyond providing formation tops for a lithostratigraphic correlation framework. Ultimately, methods that would now be termed petrophysical should become such an integral part of subsurface geological study that it would be hard to imagine the practice of subsurface geology without them. At that point, the geological application of wireline logs would be a core discipline of subsurface geology and would automatically be associated with that name. Until that time, “virtual geology” or other unsatisfactory terms probably will be used to describe newer methods that are receiving limited treatment in subsurface geology manuals and textbooks.

Finally, how should the spread of petrophysical methods of subsurface geological investigation be incorporated within traditional geology? In considering an answer, it is important to consider the evolution of geological investigations in this century. Until about forty years ago, comparatively little was known of the geology in the subsurface of southern England, although an impressive amount had been inferred from classical field studies. On the face of it, this is a remarkable situa-

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Figure 1. The electromagnetic spectrum.
tion for one of the most densely populated regions on the planet, but it reflected the needs and concerns of society. Earlier in the century, field geological methods were instrumental in the location and exploitation of coal resources and metallic ores that fueled the Industrial Revolution. With the shift to liquid and gaseous fossil fuels, the higher demands on groundwater, and the increasing concern about subsurface contaminants, borehole penetration of British rocks both offshore and onshore has increased substantially. Clearly, the additional information from the subsurface has advanced the cause of traditional geology. However, at the same time, many critical rock properties of pore networks and fluid contents, which are target parameters of subsurface investigation, are not accessible to the eye or hammer. Even if they were, their systematic analysis would require numerical estimates rather than visual descriptions.

Therefore, in satisfying the needs of contemporary society, tried and true field methods should be maintained vigorously, while new techniques and goals are incorporated. Of course, much of this is already happening, with field studies of reservoir- and aquifer-analog exposures at a hierarchy of scales that cannot be matched in subsurface studies. Even the richest petrophysical data set is currently limited to description of a very narrow borehole, while the coarse scale of seismic resolution is still largely insensitive to important features that can be seen on the outcrop. Reliance on core studies for subsurface geology has always been limited by the expense of recovery but, sad to say, the perceived expense of housing existing core is now leading to the loss of large collections through cost-cutting measures, much precipitated by mergers of oil companies. By contrast, the costs of digital data storage continue to fall, so that the preservation of petrophysical measurements is not under immediate threat, other than from simple neglect—a failure of geologists to appreciate the rich information content of logs concerning subsurface geology.

**SUBSURFACE VIRTUAL GEOLOGICAL MAPPING**

Lang (1986) noted that the overwhelming use of geophysical logs was as an aid for lithostratigraphic correlation. Almost certainly, this observation holds true today, but correlation is done increasingly on geologic workstations using raster logs rather than by grappling with logs on paper copy (Montgomery, 1997). Raster logs are merely electronic images of the paper copy, so correlation remains entirely a pattern-recognition task for the geologist. Vector logs are currently more expensive than raster logs but contain the digital information that can be processed for compositional analysis. In addition, the digits of the vector log allow correlation by automated methods. Regardless of whether done visually or by computer methods, the end result of correlation between well logs is a set of formation tops that, when linked between borehole control, describe surfaces. The geometrical information in maps and cross sections is rich in its geological implications regarding not only tectonic history but also regional sedimentary architecture (Figure 2). Automated correlation methods have an additional advantage of being able to consider several wells simultaneously in a 3-D synthesis that precludes geometrical impossibilities in their search for the most reasonable solution (Olea et al., 1997). A by-product of this approach can be the generation of a giant “dipmeter log” among boreholes (Figure 3); its patterns of dip vectors show unconformities and records of compaction and tectonic movements.

The older electrical logs responded primarily to pore volumes and fluids; this inhibited more imaginative geological applications, beyond the correlative tracing of unit boundaries. However, in sedimentology, the study of vertical grain-size differences as an indication of depositional facies encouraged the recognition of signatures in log-shape profiles, and more detailed interpretation was made possible by electrical borehole imagery. This depositional-environment analysis has been termed the “second age of log analysis” by Selley (1992), who also considered a third age to be the use of logs in the analysis of diagenetic changes of leaching and cementation.

Everyone has a different reading of history, but it could be argued that a major shift in geological content occurred with the introduction of nuclear logs. Up to that time, lithological typing tended to be restricted to a binary distinction between rocks with low resistivity (typically shales) and rocks with relatively high resistivity (“nonshales”). To be sure, the introduction of the first nuclear log, the gamma-ray log, maintained the focus on differentiation of shales from other rock types, but subsequent refinement of the gamma-ray log to spectral estimates of potassium, uranium, and thorium sources has markedly extended its range of geological application. In particular, the widespread proliferation of neutron-density- and photoelectric-logging measurements has made possible the indirect estimation of mineral composition in lengthy sections and in multiple locations within many sedimentary basins. Computer processing of these compositional profiles (e.g., Figure 4) is relatively straightforward, using inversion methods that follow the pioneering work of Savre (1963). Although geochemical logs are much rarer in occurrence, extensions of this inversion procedure applied to measured elemental concentrations led to mineralogical profiles of igneous, metamorphic, and sedimentary sequences that can be considered to be normative rock compositions (Doveton, 1986).

Compositional mapping of formations across a region in the subsurface poses special problems, the resolution of
Figure 2. Regional lithostratigraphic section from automated correlation of gamma-ray logs of the Muncie Creek (Pennsylvanian) genetic unit in Kansas. The section crosses the carbonate-dominated Upper Pennsylvanian shelf. The shelf has a pronounced carbonate-bank margin that downlaps into shales in the northern end of a flysch foredeep in the Ouachita Basin of Oklahoma. Adapted from Olea et al. (1998). Lithostratigraphy is indicated by gamma-ray log; graphic patterns represent percentage of shale content ranges, with 0 to 20 shown as black, 20 to 60 as gray stipple, and greater than 60 percent as dark gray. White marks are intervals that are not correlated.
which is needed. Individual boreholes could be thought of as “outcrops,” but wireline logs of them have very limited lateral ranges. Logs used in compositional estimation must be corrected for environmental conditions and normalized for measurement error. Broad trends in simple (one-component) compositional changes can be mapped in the three dimensions of depth and geographic axes, by interpolating statistical moments of logs (Figure 5). Alternatively, kriged estimates can be mapped areally, based on semivariogram (autocorrelation) analysis of spatial variability of the logged property, between wells. Mapping of multiple components can be done by a 2-D extension of the inversion procedure that is used in individual wells. In this procedure, inverse matrix coefficients are applied to map grids of log properties rather than to log responses of zones in depth. When applied to the compositional estimation of relatively thick formations, these interpretive maps (e.g., Figure 6) have been validated by “ground truth” provided by the more limited core control (Bornemann and Doveton, 1983).

Advances in technology are interesting in their own right, but in a cost-conscious age, practical applications and benefits are of primary concern. The Kansas Geological Survey continues to map surface geology, but it is asked more often to address problems of the subsurface, concerning fossil

Figure 3. Regional-dip plot from automated correlation of gamma-ray logs among three wells on the downthrown block of the Humboldt fault, northern Kansas. The increased throw with depth shows the Humboldt fault to be a growth fault, active over long geologic time; breaks in the dip pattern show an excellent match with known regional unconformities. Adapted from Olea et al (1997).
fuels, water, and plumes of pollutants. The principal source of subsurface data is the survey’s collection of hundreds of thousands of paper wireline logs. Increasingly, this passive archive of analog traces is being converted to digital data that are stored in a dynamic medium. The Digital Petroleum Atlas and the Dakota Aquifer Program are two examples of projects in which both logging data and petrophysical images are immediately accessible on the World Wide Web (www.kgs.ukans.edu). In a more ambitious initiative, the survey is compiling a statewide petrophysical database of modern digital logs as the Kansas Virtual Geology Program. Although the core of the completed database will consist of raw digits from individual wells, the data will be coupled with software for analysis and display of regional geology. Kansas Virtual Geology will be available on the Web and will serve as a virtual observatory of Kansas subsurface geology.

Special problems—such as interpolation and normalization—are to be surmounted, but Kansas Virtual Geology will be used to reach beyond formation surface topology to mapping of a wide variety of petrophysical properties and their transforms. Have these activities distracted the survey from its historic mission of mapping and surveying the rocks of Kansas? It hardly seems so, when its core library is expanding to be one of the largest in the U.S. Midcontinent. With the increasing availability of digital cameras, digital core images and logging data probably will be integrated closely in a subsurface geological synthesis. Clearly, the road forward calls for close integration of traditional and newer methods and information in the mapping of subsurface geology. The experience of the Kansas Geological Survey is being replicated by other geological agencies, with variations dictated by local needs and availability of subsurface information, principally wireline logs.

**CONCLUSIONS**

As demands of society increase for more sources of water, more energy resources, environmental cleanup, and controls of pollution sources, studies of subsurface geology will increase and prosper. The geological application of wireline logs will be a key component of this work. Some geologists might regret this development as being somewhat alien to the subject they learned as students. However, it is to be hoped that informed reflection will show this to be an exciting opportunity to learn new skills—skills that open facets of geology that were unimaginable a generation ago.
Figure 5. Quartic shale-proportion trend profile of the Simpson Group (Middle Ordovician) in southern Kansas. Contours are spaced at decile intervals. Shale proportions greater than 0.3 are shaded; proportions greater than 0.7 are heavily shaded. The onlap pattern captures the major Middle Ordovician transgression over carbonate rocks of the Arbuckle Group at the Kansas-Oklahoma border, in its passage northward across the North American craton (Doveton et al., 1984).

Figure 6. Simplified petrophysical lithofacies map of the Viola Limestone in southern Kansas, generated by inversion of neutron, density, and sonic logs and implemented as grid-to-grid operations in an automated-contouring software package. Adapted from Bornemann and Doveton (1983).
REFERENCES CITED


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