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CROSSHOLE LITHOTECTONIC CORRELATION IN HIGH-GRADE METAMORPHIC ROCKS, CENTRAL SOUTHERN CONNECTICUT

David Goldberg
Lamont-Doherty Borehole Research Group

Abstract. Well logs, acquired in two scientific drill holes in central southern Connecticut near Moodus township and Gillette Castle State Park, measured the electrical, sonic, and natural radioactive properties of the rocks within and adjacent to the Honey Hill fault zone. A crosshole correlation was made with logs of these physical properties which shows distinct similarities between the metamorphic rocks encountered in each hole, even though they are separated by 8 mi (13 km). This log-based correlation indicates that an anomalous interval associated with the Honey Hill fault contact maintains a 7 ft (2 m) thickness and an apparent dip of 2-3° between the two holes. The overlying interval, consisting mainly of the Tatnic Hill and Hebron formations, thins by about 150 ft (50 m) between Moodus and Gillette Castle, and the log responses which remain similar in character indicate that tectonic compaction of this interval has taken place. Log anomalies below the fault in the Avalon Complex rocks are attributed to regional fracturing and brecciation and also correlate between the holes. Differences between the holes in fine-scale variation and absolute value of the logs are generally attributed to intrinsic mineralogy and/or localized structure. These log data enable the deformed rocks of the Tatnic Hill and Hebron formations and Avalon Complex rocks, including the Honey Hill fault zone, to be correlated crosshole, detailing the lithotectonic stratigraphy as a function of depth.

Introduction

The geologic structure of the Appalachian mountains in New England has been interpreted by researchers for decades, yet aspects of its structure and chronology are still uncertain. The tectonic history of the Appalachians is complex: they were formed in part by repeated orogeny since the late Proterozoic, which created structural ambiguities, and in part by erosion of overlapping rock masses associated with the Taconic, Acadian, and Alleghenian orogenies [Zartman, 1988]. Inadequate fossil control and metamorphism, which render age-dating difficult, have further complicated the effort to understand the geochronology of these high-grade metamorphic rocks.

In the southeastern region of Connecticut, Wintsch and Alienikoff [1987] used lead isotopes to date the Proterozoic Avalonterrane near the Honey Hill/Lake Char fault. Along the nearly 40 mi (70 km) surface exposure of this fault, geologic evidence suggests that the adjacent rocks have undergone both brittle and ductile deformation associated with the late Paleozoic Alleghenian orogeny [Ambers and Wintsch, 1990]. In particular, the overlying Tatnic Hill and Hebron formations were probably both compacted over tectonic arches and displaced along fault surfaces [Lundgren and Ebblin, 1972; Ambers and Wintsch, 1990]. Recently, the drill bit has been used to investigate the structural cross section of this region for evidence of past (and present) movement on the Honey Hill fault and its associated seismicity [Naumoff, 1988; Woodward-Clyde, 1988].

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This study uses well log measurements of electrical, sonic, and natural radioactive properties of the rocks adjacent to the Honey Hill fault to compare the physical properties recorded in two wells drilled in close proximity. Figure 1 shows the location of the drill sites and the surface exposure of faults in central southern Connecticut. The Moodus well site is located near Moodus village, east of the Connecticut River and north of the exposure of the Honey Hill fault. It was drilled in 1987 to 4,765 ft (1.45 km) using standard 6.5 in (16.5 cm) air-rotary drilling technology [Naumoff, 1988]. The Gillette Castle well site is located on the edge of the Connecticut River about 8 mi (13 km) south of Moodus near Hadlyme, Connecticut. This 3.1 in (8 cm) hole was drilled in 1984 to a depth of about 1440 ft (0.44 km). Both holes penetrated the Tatnic Hill and Hebron formations, the Honey Hill fault, and the iron-rich metamorphics of the Avalon Complex [Wintsch and Ambers, 1989; Ambers, 1989].

Well logs, acquired immediately after drilling at both sites, have given new insight into the lithostratigraphy, physical properties, and hydrology of the region [Anderson et al., 1988]. Some of this well log data — the sonic logs in particular — have been published in the literature during the past few years [Zoback and Moos, 1988; Plumb and Hornby, 1988]. Subsequently, during 1990 and 1991, short-normal and point (electrical) resistivity and natural gamma-ray activity logs were acquired in both the Moodus and Gillette Castle drill holes. These measurements are in excellent agreement with the previously recorded data and have the added advantage of providing a consistent data set, acquired with the same tools in both holes. This consistency inspired the crosshole correlation undertaken in this study.

Well-Logging Methods

The natural gamma-ray, resistivity, and sonic velocity logs were successfully recorded from 210 - 4400 ft (64 - 1340 m) at Moodus (from the water table to a borehole obstruction) and from 40 - 1440 ft (12 - 440 m) at Gillette Castle. In Figure 2 the well logs are displayed over 1400 ft (430 m) intervals in both the Moodus and Gillette Castle holes, about 700 ft (215 m) above and below the Honey Hill fault. Natural gamma-ray activity is registered in relative API units; point and short-normal resistivity are recorded in ohm-m; and sonic velocity is displayed in km/s. All of the logs were digitized, edited, and corrected for errors, such as monotonic cable stretch (usually about 0.2% of the cable length), depth registration, and scale offsets. After correction, measurement repeatability is excellent between separate passes of all of the tools.

The natural gamma-ray tool utilizes a scintillation detector, a sodium-iodide crystal, to measure the radiation emitted by the rock immediately surrounding the borehole. This radiation arises from naturally occurring radioisotopes of the potassium, thorium, and uranium decay series. The gamma-ray tool used here does not differentiate between these decay series and instead responds to a simple function of the weight concentration of the radioisotopes and the formation density. The detector measures total gamma radiation about 30 cm into the borehole wall.

The electrical resistivity tools provide measurements of the resistivity of the rock surrounding the borehole. As the solid constituents are orders of magnitude more resistive than pore fluids in most rocks, resistivity is controlled mainly by

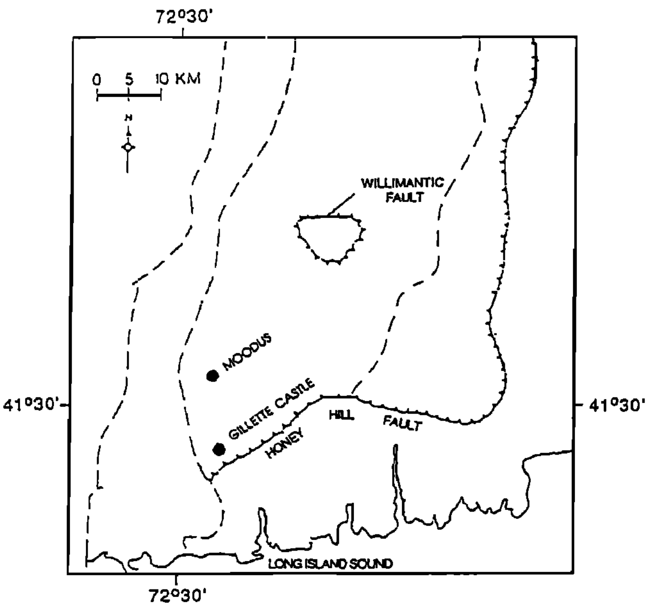

Fig. 1. Site locations of Moodus and Gillette Castle drill holes in central southern Connecticut [after Wintsch, 1987]. Dashed and stippled lines represent the surface exposures of major fault boundaries in the region.

the amount and connectivity of the pore space and the conductivity of the pore fluids. Although not relevant to these data, the conductivity of the rock matrix itself becomes important when measuring resistivity in metalliferous rocks. The simple resistivity tools used here introduce a constant current into the rock through a transmitting electrode and measure the voltage on receiving electrodes a known distance away on the logging tool. The depth of investigation into the borehole wall increases as a function of electrode separation, from a few inches for the point measurement to about 2 ft (60 cm) for the short-normal electrodes. The vertical resolution of the short-normal log is also about 2 ft (60 cm), the minimum unit thickness observable after broadening of the log response across unit boundaries.

Sonic tools are designed primarily to measure the compressional-wave velocity of the rock surrounding the borehole. In essence, the sonic tool's functioning can be thought of as a high-frequency seismic refraction experiment carried out vertically within the cylindrical borehole. An acoustic pressure pulse, generated in the borehole fluid, radiates energy into the rock, which arrives later at a receiver a known distance away on the logging tool. This arrival time yields the compressional wave velocity, and the source-receiver separation determines the vertical resolution and penetration of acoustic energy into the borehole wall. The sonic logs were acquired at Moodus in 1987 by Schlumberger and at Gillette Castle in 1984 by the US Geological Survey, the exception in this study of data that was acquired using different tools.

In igneous and metamorphic rocks, gamma-ray activity is typically low, under 10 API units; however, uranium-rich breccias or pegmatites, clay-rich alteration byproducts, and some granites have high gamma-ray values [Paillet, 1991]. Resistivity in igneous and metamorphic rocks is typically high, often orders of magnitude greater than the 10's of ohm-m found in sediments, with the important exception of high electrical conduction by fractures, clay, or radioisotopes in brecciated or altered rocks [Paillet, 1991]. Typical velocities found in metamorphic rocks are also high, often greater than 6 km/s, and similar results were anticipated in the rocks encountered at Moodus and Gillette Castle. In the following two sections of this paper, the logging results are examined first in each hole separately and then are correlated crosshole.

Results

The general character of the log responses in each hole can be correlated as a function of depth with the particular geologic units encountered: the Canterbury Gneiss, Tatnic Hill and Hebron formations above the Honey-Hill fault contact, and the gneisses of the Avalon Complex below [Ambers, 1989; Ambers and Wintsch, 1989]. As expected for metamorphics, all of these rocks have high values of electrical resistivity and sonic velocity; however, gamma-ray activity is uncharacteristically high as well.

In Figure 2, the log responses recorded over 1400 ft (430 m) depth intervals adjacent to the fault in both holes show several low-resistivity and low-velocity anomalies. As in similar studies in crystalline rocks, such anomalies can be attributed to water-filled or mineralized fractures which increase the electrical conductivity and reduce the sonic velocity [Moos, 1990; Paillet, 1991]. High gamma-ray values are observed here and are attributed to localized differences in intrinsic mineralogy. These log features may correspond with thin, uranium-rich allenite-cemented breccias or with potassium-rich pegmatites observed in outcrop [R. Wintch, pers. comm, 1992], which may cause low-resistivity and low-velocity anomalies, but do not appear to influence the velocity and resistivity logs as do breccias and open fractures. In fact, neither hole shows a good correlation between the natural gamma-ray activity and resistivity or sonic velocity, except at the Honey Hill fault contact. High gamma-ray peaks and low velocity and resistivity anomalies coincide at these depths, perhaps indicating the presence of a radioisotope-rich mylonite.

In absolute terms, point resistivities average nearly 10^4 ohm-m in the Moodus hole, almost two times the average short-normal value. A similar relationship is observed between point and short-normal resistivities at Gillette Castle. In most porous rocks, the point resistivity is lower than the short-normal measurement. This observation can be explained by the presence of a greater number and greater connectivity of electrically conductive pathways over the longer electrode spacing of the short-normal tool, thereby reducing the apparent bulk resistivity of the rock. According to previous investigations at the Moodus site, intense natural fracturing was identified by eye in the core, by acoustic televiewer, and by electrical imaging of the borehole wall [Zoback and Moos, 1988; Plumb and Hornby, 1988]. Although this systematic difference between the point and short-normal resistivity logs is observed, the character of each log consistently resembles the other, which indicates that fractures probably remain open at least 0.5 m from the borehole wall.

The sonic log's character, which generally resembles that of the resistivity logs, shows good correlation between high velocities and high resistivities in the Avalon Complex and between variable velocities and variable resistivities in the Tatnic Hill and Hebron formations. The statistical correlation coefficient between the velocity and resistivity logs is only about 0.4, indicating that the fine-scale variations are not replicated in both measurements. Different electrical and acoustic log responses to mylonites, breccias, and fractures probably account for the poor fine-scale correlation. Overall, the electrical and acoustic log responses, however, are similar for the rocks encountered in each hole. A comparison between the log responses at Moodus and Gillette Castle is discussed below.

Comparison Between Moodus and Gillette Castle Sites

The resemblance and continuity of the log responses from Moodus and Gillette Castle enables a crosshole correlation and a quantitative estimation of changes in the thickness of units adjoining the Honey Hill fault. The Moodus and

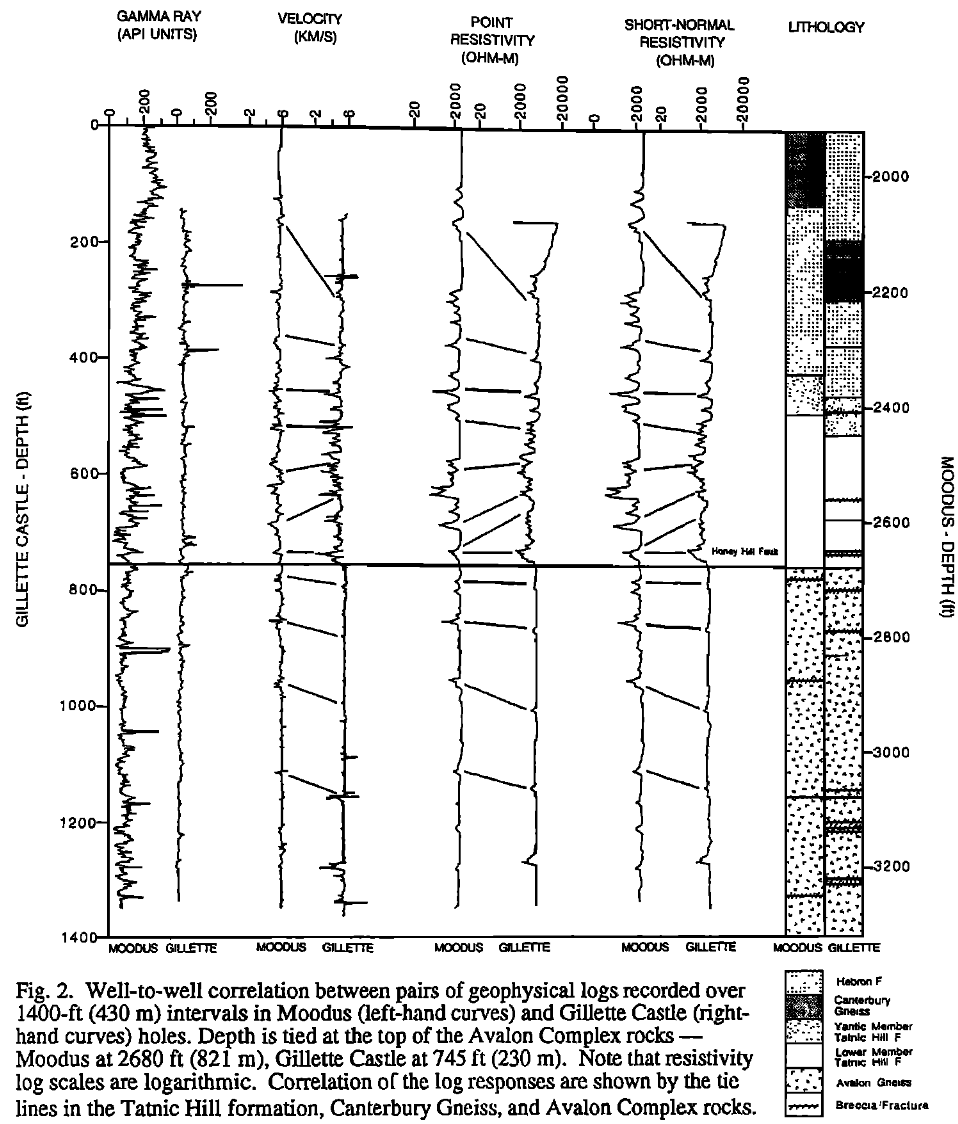

Fig. 2. Well-to-well correlation between pairs of geophysical logs recorded over 1400-ft (430 m) intervals in Moodus (left-hand curves) and Gillette Castle (right-hand curves) holes. Depth is tied at the top of the Avalon Complex rocks — Moodus at 2680 ft (821 m), Gillette Castle at 745 ft (230 m). Note that resistivity log scales are logarithmic. Correlation of the log responses are shown by the tie lines in the Tatnic Hill formation, Canterbury Gneiss, and Avalon Complex rocks.

Gillette Castle sites are 8 mi (13 km) apart. In Figure 2, pairs of resistivity, gamma-ray, and sonic velocity logs from each hole, aligned at the top of the Avalon Complex, indicate a relative deepening of the gneissic Canterbury sill, a thinning of the Tatnic Hill and Hebron formations, a continuous and dipping Honey Hill fault contact, and the correlation of breccias and fractures within the Avalon Complex. Differences in absolute value of the logs, as well as in fine-scale variations, however, indicate that the structure and stratigraphy on a fine scale is variable. Crosshole correlation of lithotectonic units may, therefore, be limited to a general identification of log character by unit, depending on the resolution of the logging tool used; it may not always be possible to distinguish fine features.

In the interval above the Honey Hill fault contact, similarities in the log responses between holes enables excellent lithotectonic correlation and estimation of the thickness of units in the Tatnic Hill and Hebron formations. In Figure 2, the log character in the unit near the Yantic member of the Tatnic Hill formation is observed to be particularly consistent between the holes. Because the log character remains similar in the Tatnic Hill and lower Hebron formations between Moodus and Gillette Castle, the thinning of the interval by about 150 ft (50 m), or 20%, is probably due to thinning of the rock during deformation. This evidence supports field observations that the rocks in the 8 mile area between the holes, at least down to the depth of the Honey Hill fault, were deformed by extension over structural arches [Lundgren and Ebblin, 1972].

The apparent dip of the Honey Hill fault and nearby rocks has been extrapolated regionally from drill core and cuttings data by Ambers and Wintsch [1990]. The continuity of the well log data enables the depth of the Honey Hill fault to be pinpointed at 2655 ft (809 m) and at 725 ft (221 m) in Moodus and Gillette Castle holes, respectively. Both the apparent dip of the contact (2-3° N-NE) and the width of the anomaly (7 ft or 2 m) can be clearly determined. From correlation of the resistivity and velocity logs, the rock sequence just above the Honey Hill fault contact apparently thickens by about 40 ft (12 m). Below the fault, log anomalies within the Avalon Complex correlate to breccias observed in the Gillette Castle core and appear similar to anomalies in the Moodus hole. Although present at slightly higher stratigraphic depths relative to the fault, the similar character of these anomalies suggests that structural features persist over the 8 mile separation between holes. At Moodus, some of these features correspond to fractures observed in an acoustic televiewer log [Plumb and Hornby, 1989].

Localized differences exist between the holes in the gamma-ray, resistivity, and sonic log responses. For example, the gamma-ray log values are on average two times higher at Moodus than at Gillette Castle, probably because the concentration of radioisotopes intrinsic to the Moodus rocks is higher. Thin, high, gamma-ray breccias or pegmatites appear to be localized and not correlated with depth between holes. The average resistivity of the rocks is also consistently higher at Moodus, although the same rock is encountered at shallower depth at Gillette Castle. This may indicate a greater abundance of open or mineralized fractures, increasing the rock conductivity, which is consistent with the incidence of a shallow depth of closure for thin microcracks [Seeberger and Zoback, 1982]. Similarly, the average sonic velocity is higher at Moodus, particularly in the Tatnic Hill formation, also indicative of more open microcracks at Gillette Castle. This observation, however, may result from deeper, sealed fractures at Moodus or from differing responses of the sonic tools utilized by Schlumberger and by the U.S. Geological Survey.

Overall, the similarity in the character of the logs between Moodus and Gillette Castle enables a crosshole correlation in deformed metamorphic rocks over an 8 mi (13 km) area. A more regional interpretation, using additional well logs, could constrain an isopach map of the metamorphic units and faults, and the lateral extent of ductile and brittle deformation in the region could be determined.

Conclusions

A crosshole correlation of electrical, sonic, and natural gamma-ray logs between Moodus and Gillette Castle, Connecticut, was performed and reveals an overall similarity of log responses in the metamorphic rocks encountered. The character of log anomalies associated with the Honey Hill fault contact and the adjacent Tatnic Hill formation is consistent in both the electrical resistivity and sonic log responses. The fault contact is about 7 ft (2 m) thick and, in rough estimation, dips 2-3° N-NE in this region. The overlying Tatnic Hill and Hebron formations thin by about 150 ft (50 m) between the two holes, which is consistent with a geologic interpretation that ductileextension over structural arches, as well as regional brittle faulting deformed these rocks.

Similarities between the logs in the overlying Canterbury Gneiss and the underlying Avalon Complex gneisses are also correlative, indicating that structural features continue in these metamorphic rocks over the 8 mi (13 km) separation between holes. Differences in the fine-scale variation and the absolute value of the logs between the two holes are generally attributed to intrinsic mineralogy and/or localized fracturing and structure.

The successful crosshole correlation in this metamorphic terrane suggests that well logging techniques can be used to determine constraints on the regional extent of deformation. Well logs provide critical information when quantifying crosshole lithotectonic correlations, even those using simple instruments, since hole cuttings and core alone are rarely representative of the continuous stratigraphy. If deep holes capable of being logged were drilled over an extended region of central southern Connecticut, they could be used to quantify a detailed, three-dimensional isopach map of metamorphic basement rocks. With this additional cross-sectional information, the lateral extent of ductile and brittle deformation could be determined, adding valuable insight into the orogenic history of this complex region.

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D. Goldberg, Lamont-Doherty Geological Observatory, Borehole Research Group, Rte. 9W, Palisades, N.Y. 10964

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