Well Logs from Shads No. 4 (Amoco), Catoosa, Oklahoma

by

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Introduction

A series of test holes drilled by Amoco at a location northeast of Tulsa, Oklahoma penetrate some 2700 feet (823 m) of Paleozoic section. Arrangements have been made for the U.S. Geological Survey (USGS) to make use of the holes for experimental tests of cross-hole geophysical methods. Some of the holes are cored and their close proximity to one another makes them good candidates for cross-hole experimentation. In preparation for the cross-hole work, logs were obtained in two of the holes, Shads 4 and 5, during March 29 through April 8, 1988.

Here we report on the data from Shads 4, in order to make it available for inclusion with future work on the site. The logs from Shads 5 are not reported because the holes are only 10 feet (3 m) apart so the logs are very similar. Also, a 472-foot (144 m) section of Shads 5 is cased, making it inaccessible to our open-hole logs.

The USGS operates a set of "slim-hole" (less than 3-inch diameter) probes designed for mineral evaluation and geotechnical applications. All of these probes could be run in the 4.5-inch diameter Shads 4 and Shads 5 holes. Specifications for the probes are given in the Appendix. Some of the probes, such as magnetic susceptibility and induced polarization, are required for mineral exploration but are not commonly run in oil and gas applications. Hence the set of logs from Shads 4 is rather unique in this regard.

The probes are run singly as there is no provision for stacking them. Consequently log acquisition is slow by oil industry standards, requiring several 10-hour days to complete the seven successful runs made in Shads 4 (normal resistivity, density-caliper, gamma-ray – neutron, sonic, temperature, induced polarization, and magnetic susceptibility). In addition, unsuccessful runs were made with a borehole drift survey probe, a magnetometer probe, and a slim-hole dipmeter which is under development.
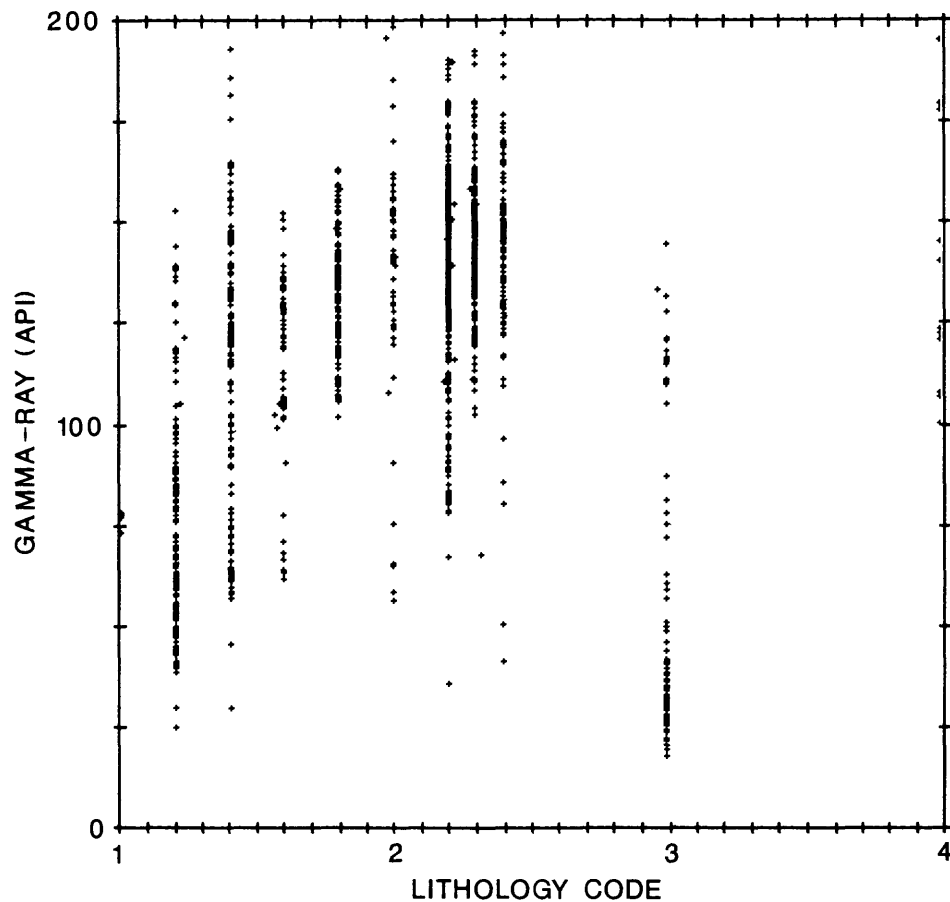
Log Processing

The field logs were recorded digitally on cassette tapes with a HP9845 computer. Editing, scale conversions, and borehole corrections were done in the office on a second HP9845 computer using software developed by Jim Scott. Because the HP9845 system does not lend itself to plotting logs in the traditional well log format, the data were transferred to a commercial log processing system on a VAX 780 computer where depth shifts, well log plots, and cross-plots were done. In addition, some geological observations made available by Amoco were added to the data set.

Discussion

Lithology and gamma-ray logs

Lithology was determined by Amoco (Hinch, undated) from cored well Shads 1, located within 150 feet (46 m) of Shads 4. A numerical code was assigned to the core description (see table in Figure 1) so that a lithology curve could be plotted alongside the logs (Plates 1 and 3). Some depth shifting of the lithology curve to the Shads 4 logs was required, and an apparent sandstone interval interval not present in Shads 1 was added at 1208 feet

Figure 1. Gamma-ray response as a function of observed lithology over the depth interval 277 to 1244 feet (84-379 m). Table shows numerical codes assigned to different lithologies.

The figure includes the following table of lithology codes:

Code	Lithology
1.0	congolomerate
1.2	sandstone, clean
1.4	sandstone, argillaceous
1.6	sandstone & shale, interbedded w ss > 50%
1.8	shale & sandstone, interbedded w sh > 50%
2.0	shale, tan
2.1	shale, green
2.2	shale, gray
2.3	shale, dark gray
2.4	shale, black
3.0	limestone
3.2	dolomite
3.4	chert
4.0	coal

(368 m). Otherwise the match between observed lithologies and log character
is quite good, as illustrated by the progressive increase of gamma-ray with
shaliness (Figure 1). Note that the cleanest sandstones in the sequence have
considerable gamma-ray response, indicative of significant amounts of clay or
mica.

Porosity-related logs

No porosity analysis has been performed at this point. However some
comments are in order on the three logs which are often used to determine
porosity -- density, neutron, and sonic velocity. These three logs are
plotted together in Plates 1 and 2.

The density log was reduced according to the compensation algorithm
described by Scott et al (1988). In the relatively smooth bore of Shads 4,
compensation effects were not large.

The neutron - thermal neutron probe is uncompensated, that is, there is
only one thermal neutron detector. Conversion from count rate to porosity is
based on calibration at the American Petroleum Institute pits in Houston and
includes a correction for borehole diameter.

The sonic log was run with a two-foot receiver spacing. Compressional
wave transit time is presented in units of microseconds per foot.

A common technique in log analysis is to cross-plot two log responses in
order to reveal the effects of lithology (Figures 2 and 3). it is also common
practice to assume that simple linear relationships hold between observed
(bulk) and mineralogical properties:

$$\rho_b = (1-\phi)\rho_m + \phi\rho_f$$

$$\Delta t = (1-\phi)\Delta t_m + \phi\Delta t_f$$

where ρ is density, ϕ is porosity, Δt is sonic transit time, and the
subscripts b, m, f refer to bulk, matrix and fluid properties, respectively.
The corresponding linear equation for neutron response is usually taken care
of by calibrating in pits of known lithology and porosity, rather than by
dealing with mineral and fluid "neutron porosity" equivalencies. The
"sandstone porosity" line in Figure 2 is obtained by setting ρ_m=2.65 gm/cc
and Δt_m=57 usec/ft, typical values for clean sandstone. Well log data from a
clean sandstone of variable porosity should scatter along this line, heavy
minerals which increase the bulk density cause data points to migrate
downward; clays which increase the transit time cause data points to migrate
to the right. The distribution of data in the density-sonic plot are
reasonable and give assurance that both probes functioned properly and are
properly calibrated.

The density-neutron plot (Figure 3) indicates that there may be a problem
with the neutron readings because none of the sandstone data closely approach
the calibration line. The problem is probably not severe because we have
already observed that the sandstones are not free of clay (Figure 1).
Nevertheless, the neutron calibration requires confirmation and the neutron
porosity log is quantitatively the least trustworthy of the three porosity
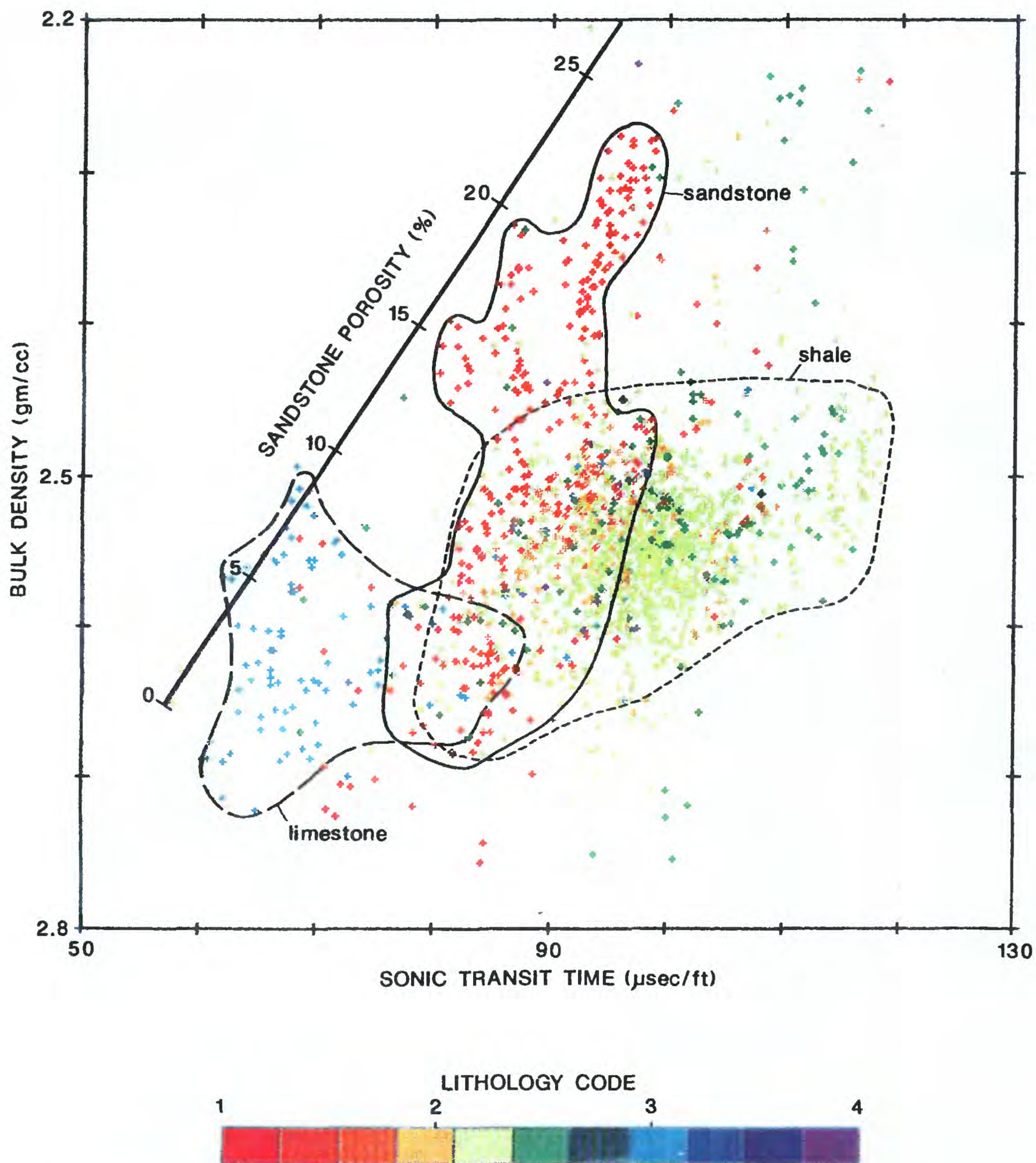logs.

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Figure 2. Density-sonic crossplot over depth interval 277 to 1249 feet (84–379 m). Sandstone points include facies codes 1.0–1.6, shale 1.8–2.4, and limestone 3.0–3.4.
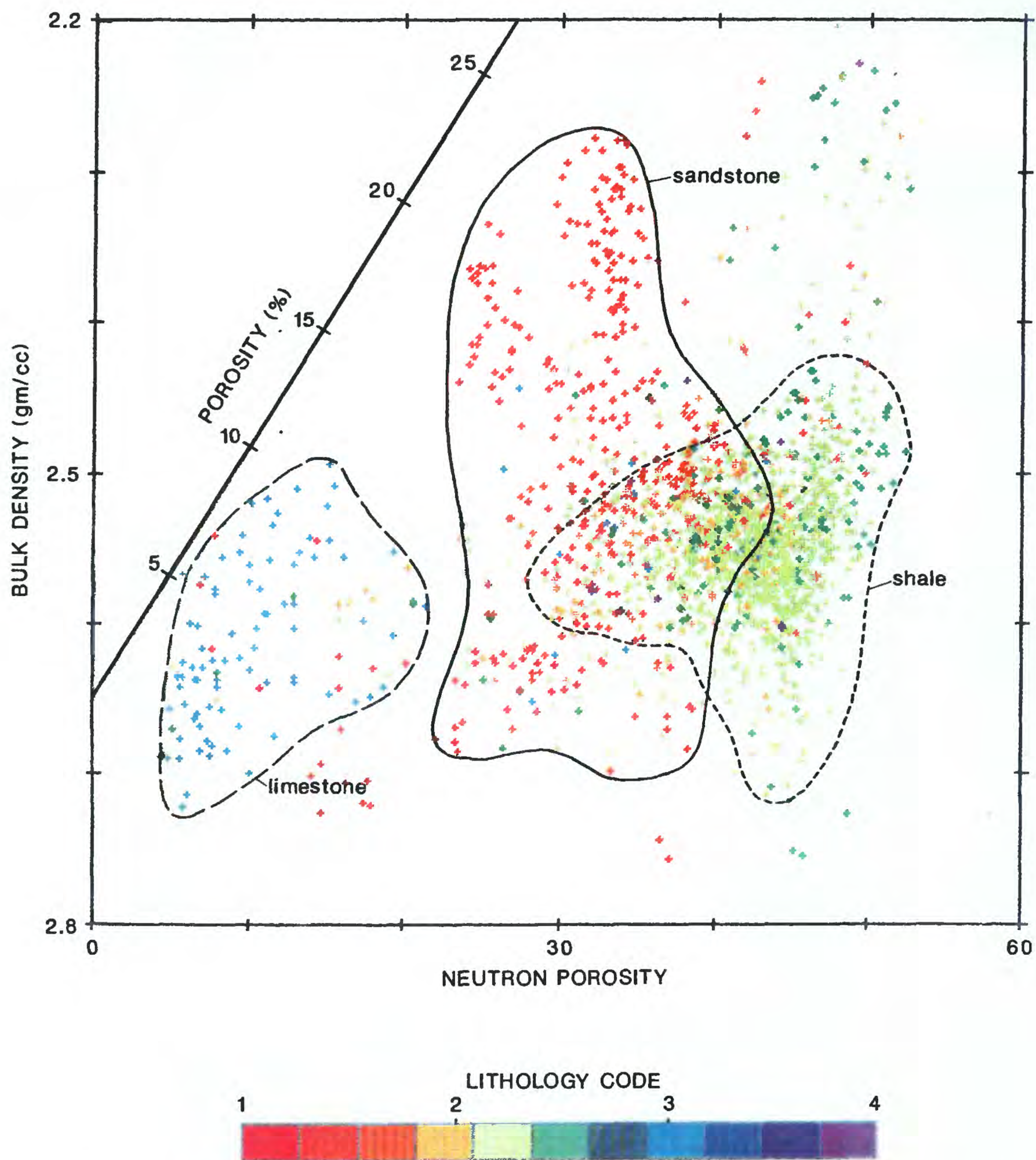
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Figure 3. Density-neutron crossplot over depth interval 277 to 1249 feet (84-379 m).

Temperature Log

The continuous temperature log was obtained by logging downward; other logs had been run prior to the temperature run so that some stirring of the borehole fluid may have occurred. The temperature log is best viewed on the 1:1200 plot of Plate 1. Temperature increases from 18°C at the top of the hole to about 39°C at 2650 feet (808 m). A temperature gradient log was computed from the temperature log by taking differences over 5-foot separations. The gradient changes markedly at different depths in the hole, reflecting lithology changes. The table below lists the depth intervals picked by eye for averaging (and shortened to avoid transition effects), the dominant lithologies, and the arithmetic mean of the temperature gradient.

Depth (ft)	Lithology	Gradient (°C/km)
400-800 (122-244 m)	Skinner and Red Fork Sandstones	40.4
900-1170 (274-357 m)	Booch Sandstone	49.6
1260-1570 (384-479 m)	Mississippi Lime and Woodford Shale	24.6
1600-2600 (488-792 m)	Arbuckle Formation	14.5

We expect uniform vertical heat flow in this environment, in which case the thermal gradient is proportional to the reciprocal of thermal conductivity of the formation. Because water conducts heat less well than most minerals, the water content, whether free or bound to clays, is a dominant control on formation thermal conductivity. That is, high water content decreases the thermal conductivity and raises the thermal gradient. This explains the overall correlation between thermal gradient and the three porosity-sensitive logs, density, neutron, and sonic in Plate 1.

Electrical and magnetic logs

Resistivity measurements are made with a set of four "normal" (pole-pole) electrodes on a 1.75-inch mandrel with transmitter and receiver spaced at 8, 16, 32, and 64 inches. Theoretical curves for the normal array published years ago (Schlumberger 1949, 1955) show the adverse effect of large hole diameter and low mud resistivity on the resistivity response. In the 4.5-inch Shads 4 hole with conductive mud, the four apparent resistivity traces are separated markedly (Figure 4) as the 8-inch probe responds to the mud and the 64-inch probe response is dominated by the formation.

Incorporation of the Schlumberger response curves into a computer algorithm (Scott, 1978) enables us to compute a correction to each of the four resisitivity traces. To do so, we need an estimate of R_m, the mud resisitivity, which was not obtained at the site. However, an estimate can be obtained by plotting the four resistivity readings on log-log paper and sliding them over the Schlumberger curves until a match is obtained. This fitting exercise should be done for points taken from fairly uniform sections of the log to approximate an infinitely thick bed. Also the tool diameter correction given by Scott should be used in computing the correct ratio of electrode spacing to hole diameter, AM/d.
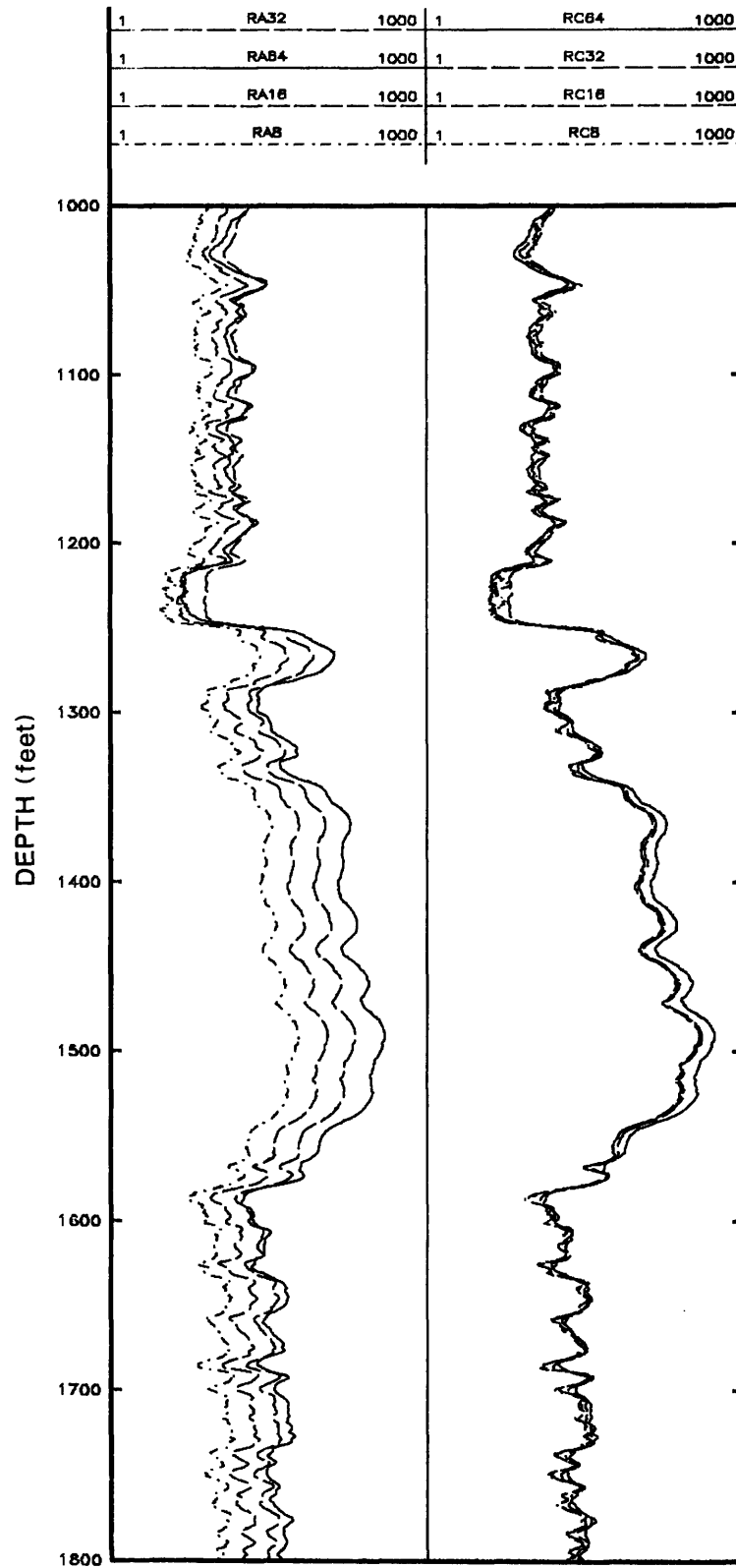
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Figure 4. Electrical resistivity logs, normal electrode configuration, with uncorrected apparent readings on the left and borehole corrected readings (Rm = 0.11 ohm-m) on the right.

This procedure indicated a value of R_m between 0.10 and 0.12 ohm-meters, a value which was confirmed by successively applying the borehole correction for several R_m values ranging from 0.08 to 0.14. The four curves converge best for values between 0.10 and 0.12, as judged from inspection of plots. A final result computed for 0.11 ohm-m is shown in Figure 4.

The induced polarization probe responds to sulfide and clay minerals. It can be seen from Plates 1 and 3 that the response is greatest in the upper 1240 feet (378 m) of the hole. Observations of pyrite in core by Hinch are point-plotted alongside the IP curve in Plate 3, and the correspondence is reasonable. The IP curve could now be used as a guide for studying the pyrite occurrences in the shaly sections.

The magnetic susceptibiltiy curve is quite active in the sandstone and shale sequence from 130 to 1250 feet (40 to 381 m), unresponsive in the limestones from 1250 to 1544 feet (381 to 471 m), and shows sporadic occurrences of magnetic minerals in the Arbuckle below 1600 feet (488 m). Within the upper 1000 feet (305 m) of sandstone and shale, the magnetic susceptibility correlates well with the density curve (Figure 5). This apparent correlation is enhanced by the very similar spatial frequency content of the two curves. Portions of the two logs are cross-plotted in Figure 6; the correlation appears valid for the "sandstones" as susceptibility increases with bulk density. It has been suggested that this trend could result from the preservation of magnetic minerals by calcite cementation (R. Reynolds, p.c.).

Summary

Log data from the Shads 4 well have been presented to provide reference logs for anticipated cross-hole work. In this respect, the density log appears to be quite adequate for computation of rock porosity when grain density data become available from core analysis.

The logs can also serve to stimulate studies on rock properties. In particular the induced polarization log can be used to look at the sulfide and clay sources of polarization, and the magnetic susceptibiltiy log serves as a backdrop for studies on the occurence of magnetic minerals in sediments.

References

Hinch, H. H., undated, Report on SHADS No. 1: Amoco Production Company internal report, 89 p.

Scott, J. H., 1978, A Fortran algorithm for correcting normal resistivity logs for borehole diameter and mud resistivity: U. S. Geological Survey Open-File Report 78-669, 12 p.

Scott, J. H., Muller, D. C., and Jiajin, L., 1988, A Compensated Density Tool for Mineral Logging: The Log Analyst, v. 29, no. 2, p. 123-131.
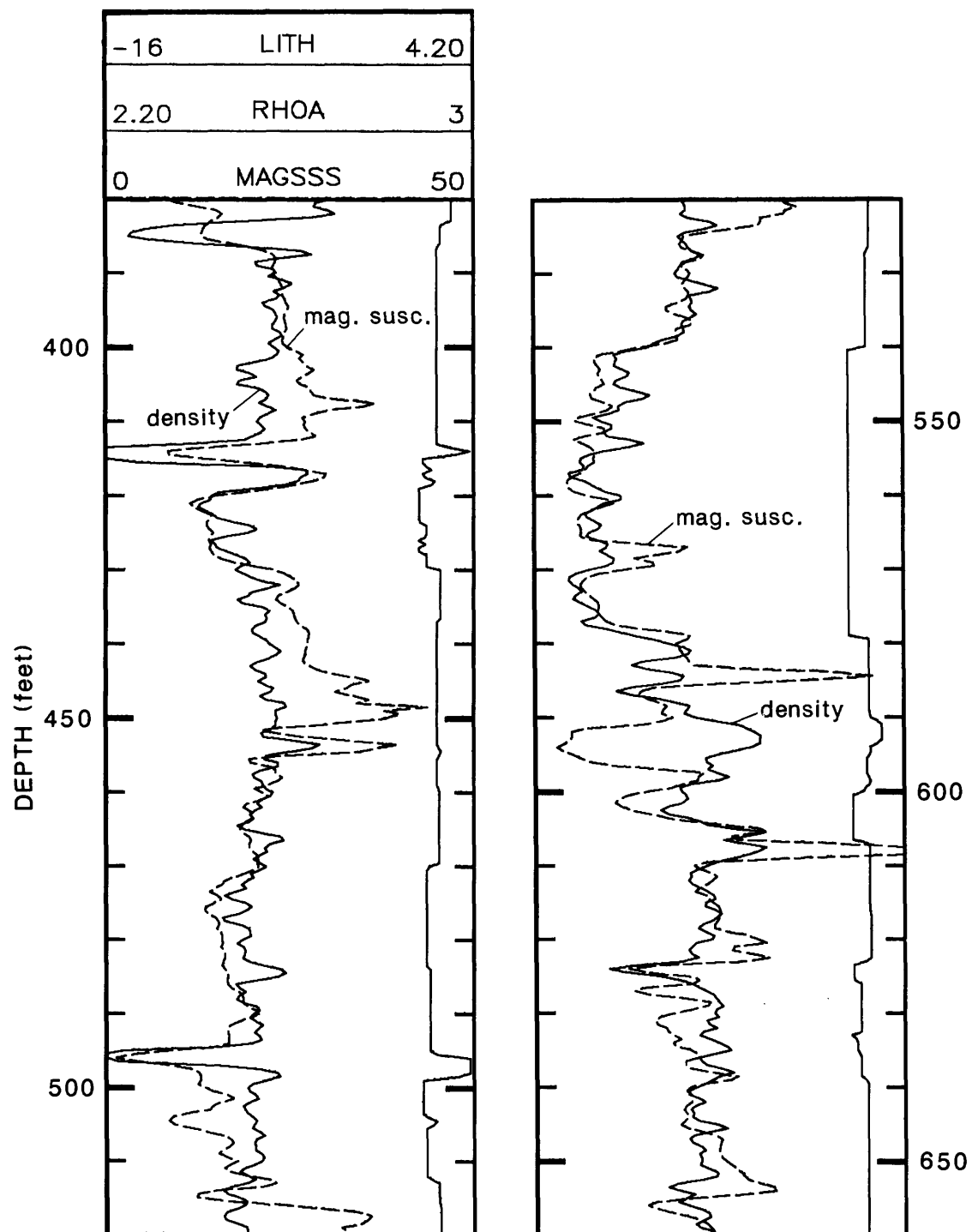
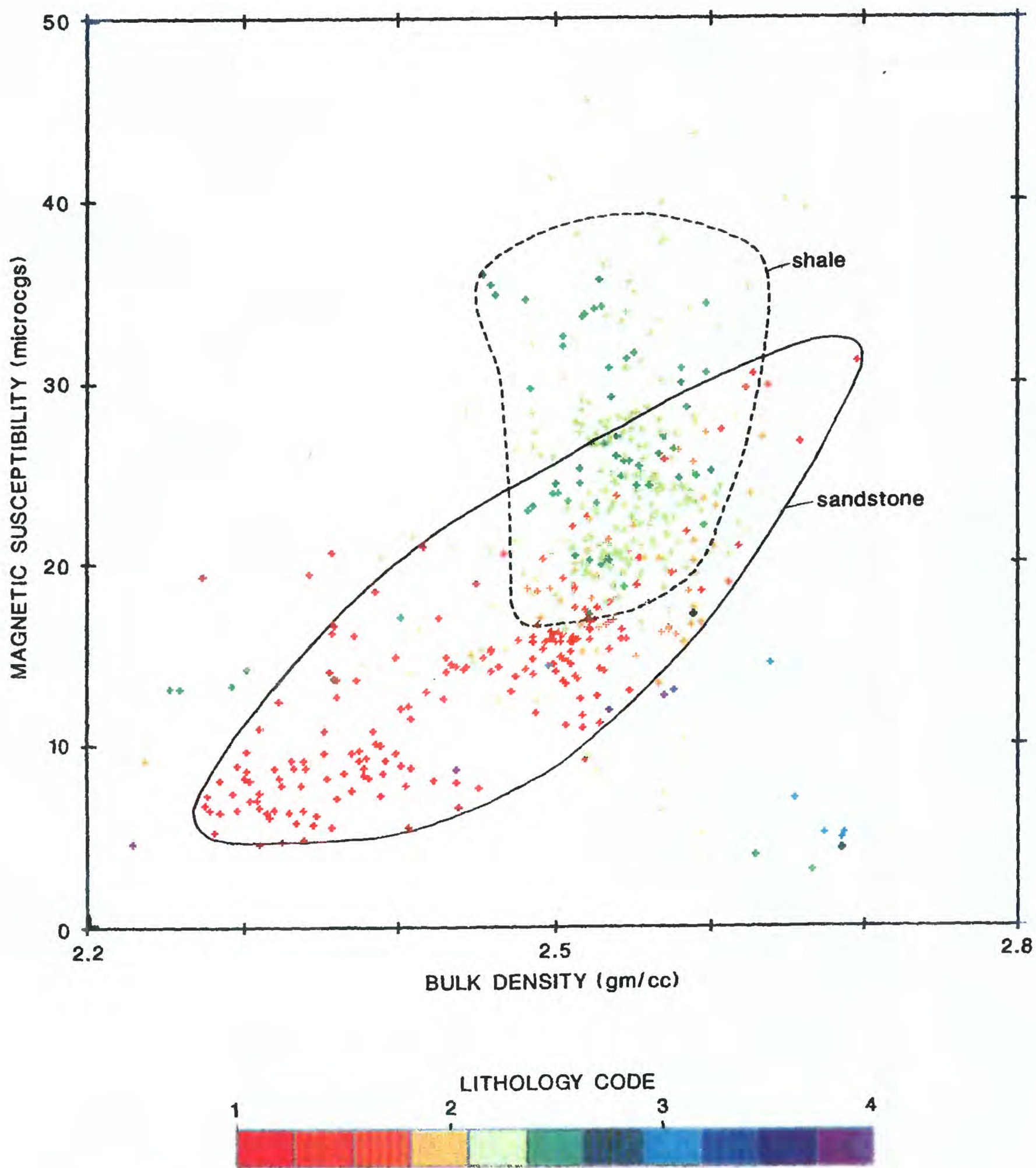Figure 5. Magnetic susceptibility and bulk density logs for depth interval 380 to 660 feet (116-201 m).

Figure 6. Magnetic susceptibiltiy vs. bulk density from the depth interval 383-660 feet (117-201 m).

Appendix

Specifications of logging probes
U.S. Geological Survey, Branch of Geophysics
Compiled by J. H. Scott

1. Natural gamma ray and neutron-neutron combination probe.
     - Manufacturer: Comprobe, Inc.
     - Diameter: 1 5/8 in (4.13 cm).
     - Length: 9.2 ft (2.8 m).
     - Pressure rating: 20 k psi (138 M pascal).
     - Temperature rating: 225°F (107°C).

   Total-count gamma ray measurement:
     - NaI-photomultiplier detector.
     - Calibrated for uranium assaying in DOE Grand Junction test pits, and
       for API gamma ray units in API pits, University of Houston.
     - Output in cps, $eU_3O_8\%$, or API gamma ray units.
     - Used for in situ uranium assaying, lithologic identification, and
       stratigraphic correlation.

   Neutron-neutron measurement:
     - He-3 detector spaced 16 in (40.6 cm) from source.
     - Am-Be source (3.0 Ci Am-241).
     - Calibrated in API pits, University of Houston, and porosity test
       pits, Birdwell SSC, Tulsa.
     - Output in cps, API neutron units or neutron porosity index.
     - Used for estimating porosity in fluid-filled holes, and for
       stratigraphic correlation.

2. Density and caliper combination probe.
     - Manufacturer: Mt. Sopris Instrument Co.
     - Diameter: 2 in (5.08 cm).
     - Length: 5.8 ft (1.77 m).
     - Pressure rating: 5.8 k psi (40 M pascal).
     - Temperature rating: 122°F (50°C).

   Density measurement:
     - Dual CsI-photomultiplier detectors, collimated and spaced 8.15 in
       (20.7 cm) and 13.86 in (35.2 cm) from source.
     - Cs-137 source (100 mCi), collimated.
     - Calibrated for borehole diameter and standoff (rugosity)
       compensation corrections in air-filled and water-filled holes in
       USGS test pits, Denver Federal Center.
     - Output in cps, apparent density, and compensated density.
     - Used for determining bulk density and for estimating porosity.

   Caliper measurement:
     - Single arm caliper presses density detectors and source against hole
       wall.
     - Hole diameter range: 2-24 in (5-61 cm).
     - Used for measuring hole diameter and applying corrections to other
       logs.

3. Magnetic susceptibility and resistivity combination probes.
    - Manufacturer: USGS.

	Slimhole probe	High pressure probe
- Diameter:	2 1/4 in (5.72 cm)	2 3/4 in (7.00 cm).
- Length:	8 ft (2.4 m)	8 1/2 ft (2.6 m).
- Pressure rating:	3 k psi (20 M pascal)	15 k psi (103 M pascal).
- Temperature rating:	194°F (90°C)	194°F (90°C).

    Both probes:
    - Single induction coil in Maxwell bridge.
    - Susceptibility measured by quadrature channel, 10^{-5} to 1^{-1} cgs (10^{-4} to 10^{0} SI).
    - Relative resistivity measured by in-phase channel below 0.1 ohm-m.
    - Induction coil maintained at constant temperature by oven.
    - Calibrated in USGS test pits, Denver Federal Center.
    - Output in cgs or SI units.
    - Used for detecting high susceptibility anomalies caused by concentrations of ferromagnetic minerals, low susceptibility anomalies caused by alteration of ferromagnetic minerals, and low resistivity anomalies associated with massive sulfides and graphite.

4. 3-D magnetometer and borehole deviation combination probe.
    - Manufacturer: OWL Technical Associates.
    - Diameter: 2 in (5.08 cm).
    - Length: 7.5 ft (2.29 m).
    - Pressure rating: 5 k psi (34 M pascal).
    - Temperature rating: 150°F (65°C).

    Magnetometer measurements:
    - 3-component fluxgate (mutually perpendicular coils).
    - Range -80,000 to +80,000 nT, readout resolution 10 nT.
    - Output in nT for magnitude of magnetic field, angular degrees for azimuth and inclination of magnetic vector.
    - Used for measuring magnitude and direction of polarization of strongly magnetized volcanic rocks and for detecting anomalies caused by concentrations of strongly magnetized ferromagnetic minerals.

    Borehole deviation measurement:
    - Gyroscope (±1° resolution) and 2-component inclinometer (±0.1° resolution).
    - Directional measurements are not affected by presence of magnetic minerals or steel casing.
    - Used to obtain probe orientation information for data reduction of magnetometer measurements, and to make hole deviation surveys.

5. Sonic velocity and waveform probe.
    - Manufacturer: Mt. Sopris Instrument Co.
    - Diameter: 2 3/8 in (6 cm).
    - Length: 10.2 ft (3.1 m).
    - Pressure rating: 158°F (70°C).
    - Receivers: 3 broadband piezoceramic units spaced 12 in (30.5 cm) apart, selectable in pairs for measurements between 1-2, 2-3 (12 in spacing) or 1-3 (24 inch spacing).

- Transmitter: piezoceramic unit with center frequency of
  approximately 24 kHz, positionable at either 3 ft (91.4 cm) or 4 ft
  (121.9 cm) from near receiver by means of interchangeable spacers.
- Outputs: interval transit time (microseconds/ft) of P-wave (first
  arrival) between selected pair of receivers, relative amplitude of
  first-arrival energy, and digitized waveform (amplitude vs. time).
- Interval transit time is used to determine P-wave velocity of
  formation and to estimate porosity; amplitude is used to detect
  fracturing and other sources of attenuation, and waveforms are used
  to determine S-wave velocity in 'fast' formations.

6. Resistivity - multiple electrode probe.
    - Manufacturer: Mt. Sopris Instrument Co.
    - Diameter: 1 13/16 in (4.6 cm).
    - Length: 9 ft (2.74 m).
    - Pressure rating: 5.8 k psi (40 M pascal).
    - Temperature rating: 248°F (120°C).
    - Electrodes: lead rings at 7 positions on the probe, arranged so
      that they can be configured for 4 simultaneous measurements in the
      normal configuration at AM spacings of 8, 16, 32, and 64 in (20.3,
      40.6, 81.3, and 162.6 cm), or for single -channel measurements in
      the Wenner or dipole configurations at interelectrode spacings of 8
      or 16 in (20.3 or 40.6 cm).
    - Output (A. J. Farstad 4-channel resistivity moduel): apparent
      resistivity which can be corrected for hole diameter and mud
      resistivity effects by use of caliper log and fluid resistivity
      measurements.
    - Used for determining formation resistivity, estimating porosity,
      detecting fractures, and as an aid in identifying lithology.

7. Induced polarization (IP) spontaneous potential (SP), and resistivity.
    - Manufacturer: Mt. Sopris Instrument Co.
    - Diameter: 1 7/8 in (4.76 cm).
    - Length: 12.7 ft (3.87 m).
    - Pressure rating: 5.8 k psi (40 M pascal).
    - Temperature rating: 248°F (120°C).
    - Electrodes: lead rings configured so that normal spacings of 4 in
      (10.2 cm) or 16 in (40.6 cm) can be selected.
    - Output: IP in mV/V, SP in mV, and resistivity in ohm-m.
    - Used for detecting IP anomalies associated with sulfides, clays and
      graphite; for detecting SP anomalies associated with lithologic
      variations, for determining formation resistivity and as aid in
      identifying lithology.

8. Temperature probe (high accuracy).
    - Manufacturer: Joe Sena.
    - Diameter: 1 5/8 in (4.13 cm).
    - Length: 4.9 ft (1.5 m).
    - Pressure rating: 5 k psi (34 M pascal).
    - Temperature rating: 200°F (94°C).
    - Sensing element: Platinum wire, readout by 4-point resistance
      measurment 0.01°C resolution.

9. Caliper - temperature - fluid resistivity combination probe.
    - Manufacturer: Mt. Sopris Instrument Co.
    - Diameter: 2 in (5.08 cm).

- Length: 10.6 ft (3.22 m).
- Pressure rating: 5.8 k psi (40 M pascal).
- Temperature rating: 266°F (130°C).

Caliper measurement:
   - 3 spring-loaded retractable arms.
   - Measurement range: 2-20 in (5.1 - 51 cm) hole diameter.
   - Output: hole diameter, inches or cm.
   - Used for detecting fractures and washouts, and for obtaining hole
     diameter information for applying corrections to other logs.

Temperature measurement:
   - Two-terminal linear current sensor, 0.014°F (.025°C) resolution.
   - Measurement range 32-300°F (0-150°C).
   - Output: Temperature, degrees centigrade.
   - Used for determining temperature of borehole fluid and anomalies
     associated with inflow of groundwater in permeable formations.

Fluid resistivity measurement:
   - Four-terminal pass-through fluid resistivity sensor (Wenner
     configuration with 3-cm interelectrode spacing).
   - Measurement range 0-200 ohm-m.
   - Output: fluid resistivity, ohm-m.
   - Used to measure fluid resistivity for estimating salinity and for
     applying corrections to resistivity logs.

10. Dipmeter probe (3-arm, microguard resistivity).
   - Manufacturer: OWL Technical Associates.
   - Diameter: 2 in (5.08 cm).
   - Length: 12.7 ft (3.9 m).
   - Pressure rating: 5 k psi (34 M pascal).
   - Temperature rating: 158°F (70°C).
   - Resistivity range: 0.5 - 500 ohm-m.
   - Depth resolution: 0.05 in (0.13 cm).
   - Hole diameter operating range: 2-9 in (5.1 - 22.9 cm).
   - Probe orientation measurement system: 3-component fluxgate
     magnetometer (mutually perpendicular elements) and 2-component
     inclinometer (mutually perpendicular).
   - Outputs: hole diameter, 3 microguard resistivity channels, 3
     magnetometer channels, and 2 inclinometer channels.
   - Used to calculate strike and dip of bedding planes and fractures.

11. Borehole deviation (directional survey) probe with magnetic orientation.
   - Manufacturer: OWL Technical Associates.
   - Diameter: 2 in (5.08 cm).
   - Length: 4.5 ft (1.4 m).
   - Pressure rating: 4 k psi (27.6 M pascal).
   - Temperature rating: 122°F (50°C).
   - Output: azimuth (magnetic sensor) and angle of probe tilt (biaxial
     inclinometer) with azimuthal readout to ±1° and inclination to
     ±0.1°.
   - Used to make directional surveys in boreholes inclined up to 25°
     from the vertical in open holes (no steel casing) drilled through
     rocks without significant concentrations of ferromagnetic minerals.