



Borehole Geophysics

Spontaneous potential, induction and EM logging

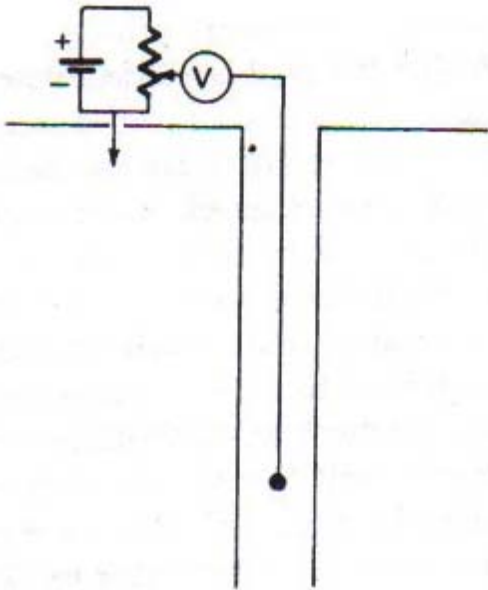
Various different techniques for electric logging exist and have numerous applications in the oil-field and mining industry. Many specific tool designs were brought forward for specific applications making this field rather complicated and complex to understand. We will cover only a few main topics:

- SP or self-potential
- Galvanic resistivity
- Laterologs
- Induction logging
- Magnetic logging

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SP, self-potential, spontaneous potential

If an electrode is placed in a well, a potential difference can be observed between it and another electrode on the surface. **No current is introduced into the formation.**



The measurement is completely passive and because no excitation is used, the type of logging has become known as spontaneous or self-potential. **The SP log can be used to distinguish between shale and other formations which are porous and permeable**, provided the salt concentration of the formation fluid differs from that of the shale.

SP measurements:

In the image on the left, a battery and variable resistor are used to counterbalance any constant voltage offsets introduced by the reference electrode. **The SP measurement is a relative one in the sense that trends and variations observed within the well are of interest rather than absolute values.**

SP electrode in a borehole, connected to voltmeter and bucking circuit.

[Source: Hearst et al., 2000]



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SP, self-potential, spontaneous potential

The downhole electrode is metallic, often lead or stainless steel and should be separated from other metallic objects to not introduce any spurious voltage effects.

An electrode should be insensitive to temperature, water flow and water chemistry (corrosion). Typically a copper-copper sulfate electrode is used, but it is difficult to maintain. Instead lead, bronze or stainless steel electrodes are used.

This single downhole electrode responds to potential gradients produced by the flow of electric current in the borehole. Within the Earth, electrical potentials arise from the transport of charged ionic species, chemical reactions, and the flow of fluids. Thus, the electrical phenomena are due to forces which are basically non-electric.

Concentration imbalances cause ionic transport and generate diffusion potentials, which are generally recognized as the dominant contributor to SP in sedimentary sequences. Chemical reactions (reduction – oxidation) and fluid flow (electro-kinetic) effects are less commonly observed in conventional practice.



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Diffusion and streaming potentials

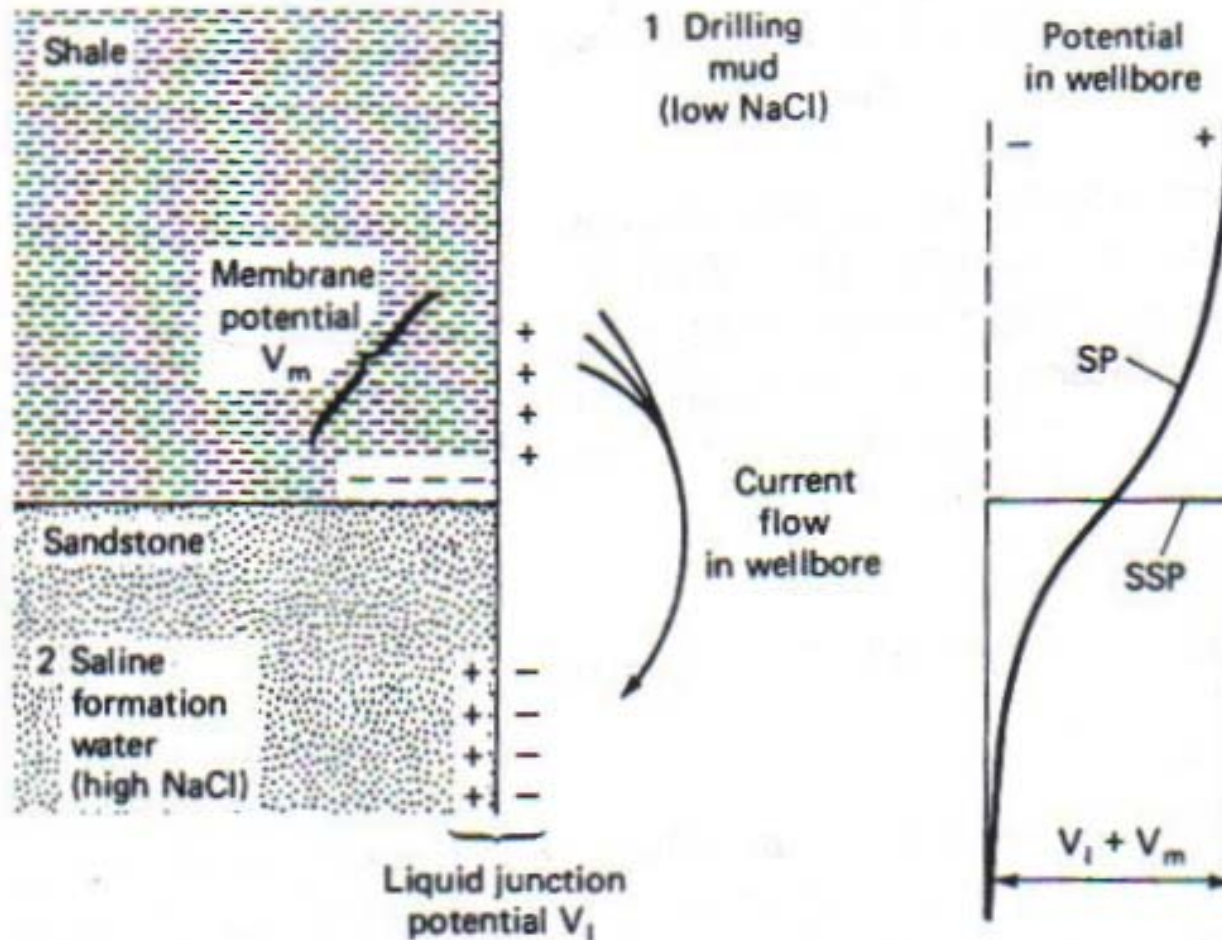
Diffusion potentials

The diffusion of ions under the influence of concentration gradients is the main source of SP. Ions tend to migrate from zones of high to low concentration. Because the transport properties of cations and anions differ, migration along the chemical gradient proceeds more rapidly for one than the other, with consequent separation of charge and the establishment of a voltage to counter it.

Streaming potentials

When a differential pressure is applied across a rock sample, fluid flows in accordance to Darcy's law. As fluid moves through the pore space transporting mobile charges, the charges separate causing a voltage. This voltage is called streaming potential. The voltage induced by the pressure increases linearly with the pressure applied. In the borehole, streaming potentials are probably always present to some extent because the borehole pressure is greater than formation pressure, but are usually not detectable on the SP log.

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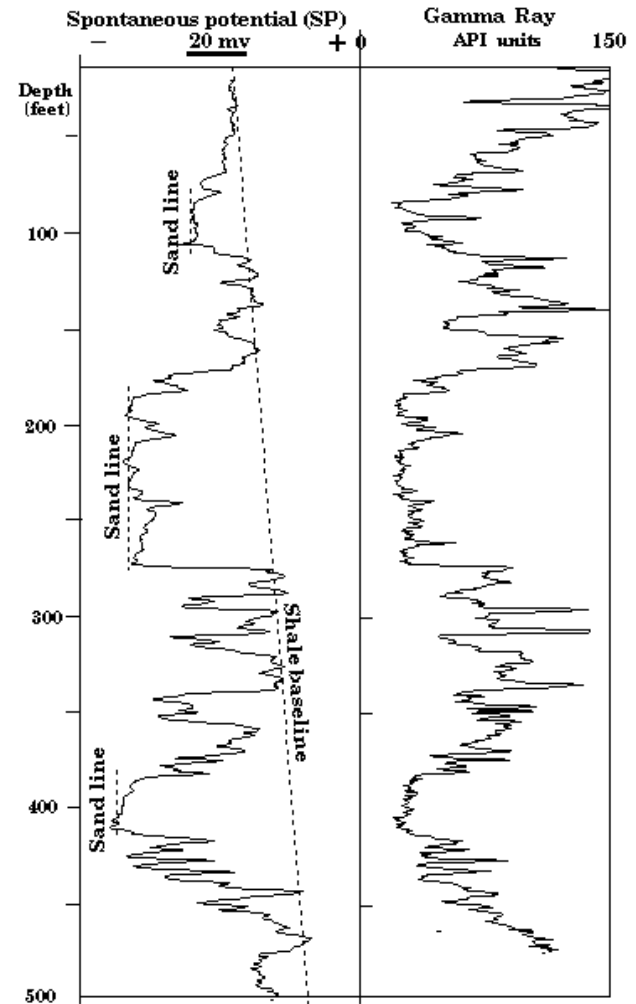
Representation of diffusion potentials in a borehole between shale and sandstone. SSP = static self-potential.

[Source: Hearst et al., 2000]

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The image to the right shows examples of the Spontaneous potential (SP) and gamma-ray log from the KGS Jones #1 well in Dakota. Although both logs record different physical properties, they are comparable because of their sensitivities to shale and both can be used to differentiate between sandstones and shale. The stronger sandstone differentiation at greater depths on the SP log is caused by greater salinities in the deeper sandstones.

The displacement on the log between the shale and sand lines is the "static self-potential" (SSP).



Source: www.kgs.ku.edu/Dakota/vol1/petro/petro05.htm



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Galvanic Resistivity

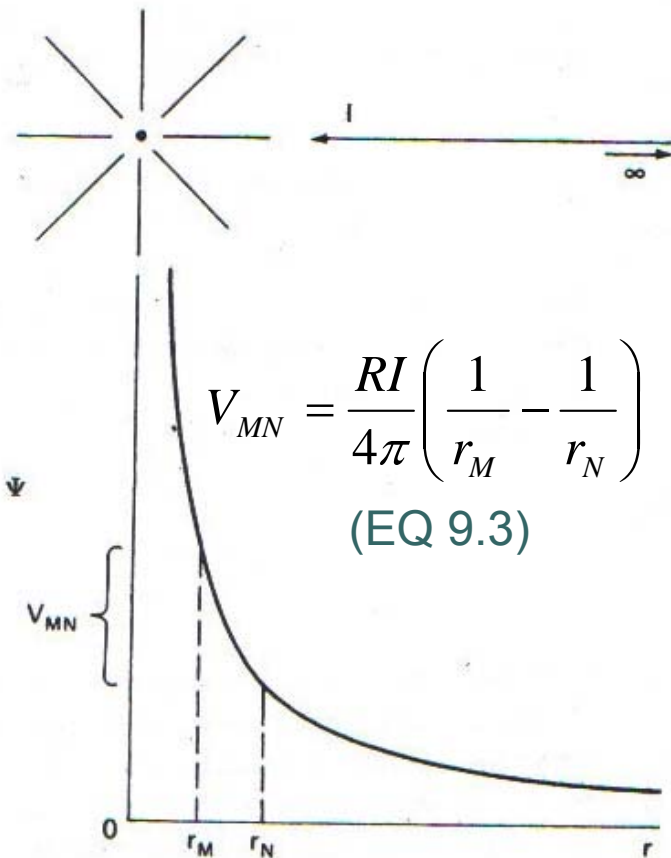
Galvanic resistivity tools consist of one or more metallic electrodes through which an electric current is transmitted into the borehole fluid and thus into the formation. One or more potential electrodes measure the resulting voltage differences established by the electric current flow.

Different electrode configuration have been developed to measure formation resistivity. The simplest devices measure the voltage at one or two points in response to a constant electric current input.

To understand the response of the individual electrode configurations we start with the potential (Ψ) of a single input electrode. The input current is represented by the electric field \mathbf{E} .

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Galvanic Resistivity



Source: Hearst et al., 2000

For a single input current at $r = 0$ the potential can be found by integrating \mathbf{E} :

$$\Psi(r) = -\int_{\infty}^r \vec{E} d\vec{r} = -\int_{\infty}^r R\vec{J} d\vec{r} \quad (\text{EQ 9.1})$$

The current density \mathbf{J} at any radius r is the original source strength divided by the area of the sphere ($1/4\pi r^2$). The other necessary condition to find a solution is given by definition of $\Psi = 0$ at $r = \infty$.

The results is then:

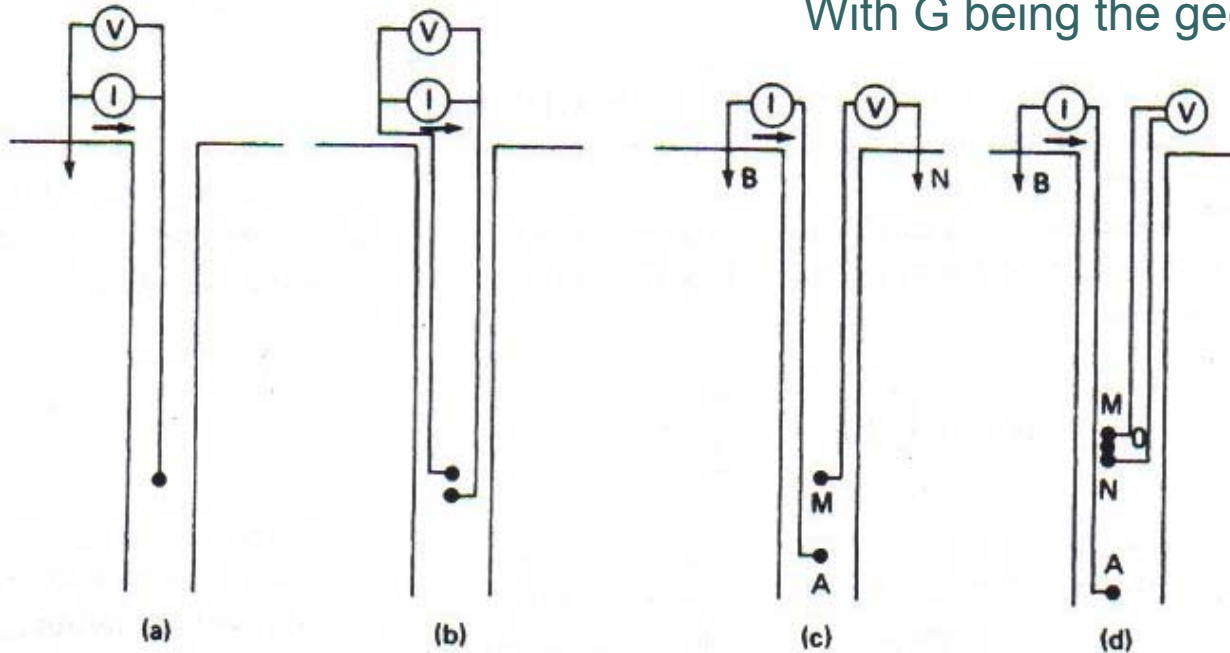
$$\Psi(r) = -\int_{\infty}^r \frac{RI}{4\pi \cdot r^2} dr = \frac{RI}{4\pi \cdot r} \quad (\text{EQ 9.2})$$

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Galvanic Resistivity

$$R = G V / I \quad (\text{EQ 9.4})$$

With G being the geometry factor



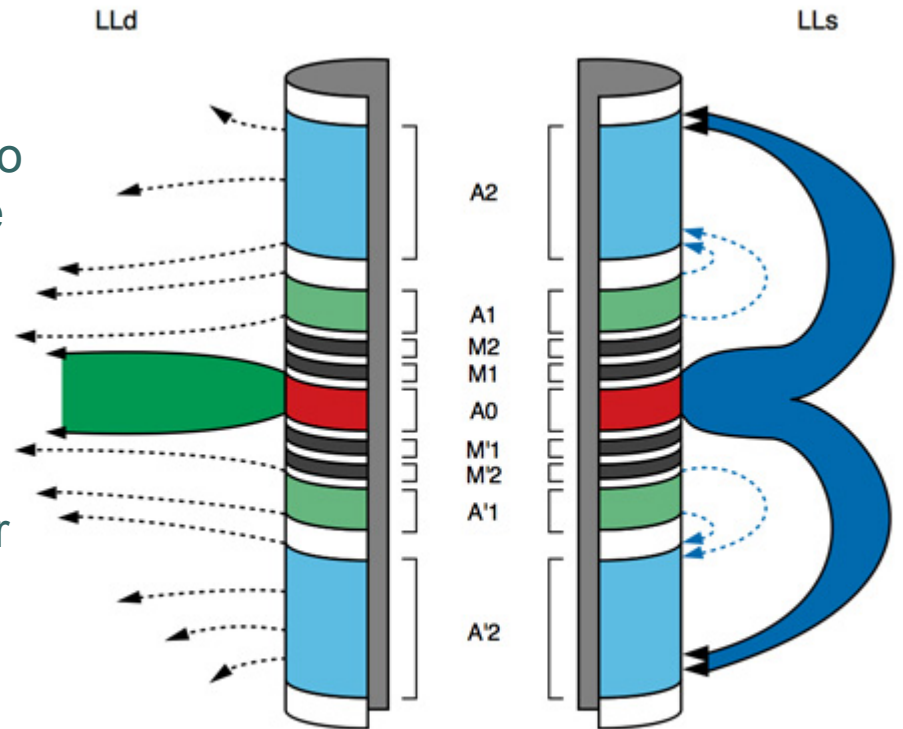
Various electrode arrangement for galvanic resistivity measurements: (a) single-point resistance, (b) differential resistance, (c) 'normal' array, and (d) lateral array. In all cases a current source I is used to inject a current. The resulting potential differences are then measured at the volt-meter V .

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'Laterolog' or focused log

Guarded and focused logging tools are designed to define the boundaries of thin beds, particularly resistive one, and measure their true in situ resistivity. To do so, auxiliary electrodes are placed above and below the central current electrode (see image on right).

The effective current that is used in the measurement is focused around the central electrode and flows perpendicular away from the logging tool into the formation. Typically two different sets of electrode arrays are built onto the same tool to allow for shallow and deep formation penetration, which helps determine fine-scale formation properties.

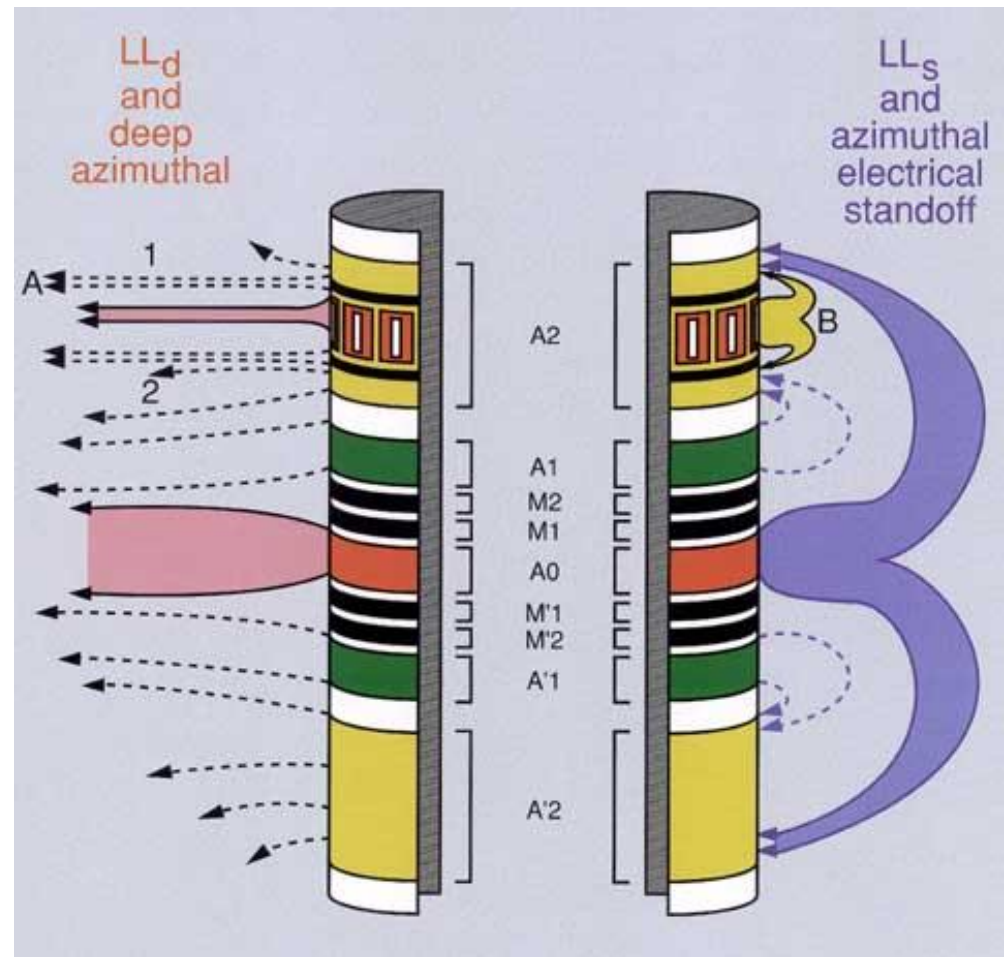


Dual Laterolog sonde electrode distribution and current path shape.

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'Laterolog' or focused log

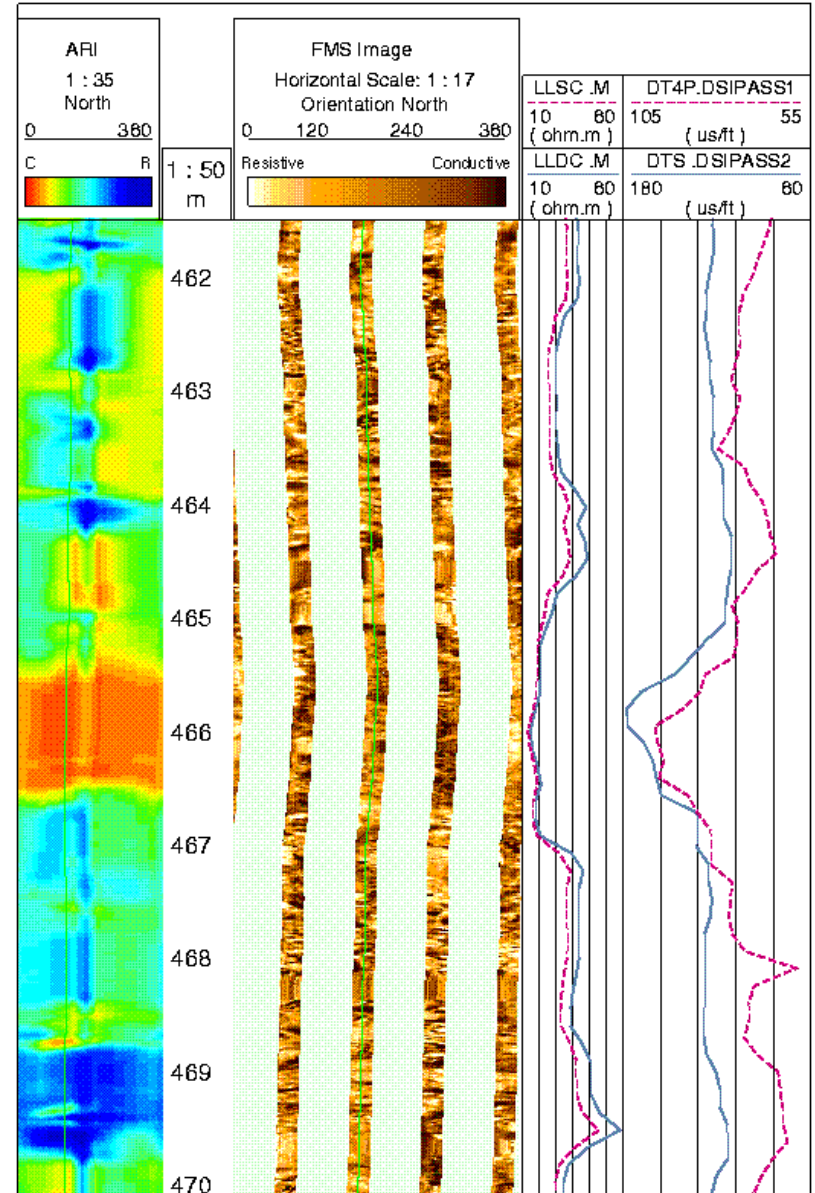
Azimuthal resistivity imager (ARI) works like the laterolog, but also provides a 360 degree image of the borehole resistivity (somewhat like the RAB or FMS). The image to the right shows an example of the ARI tool (from LDEO).



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'Laterolog' or focused log

Example of the ARI tool response (left panel) in comparison to the FMS image (middle panel). The color of the ARI image is set so that conductive rocks appear as red zones and resistive rocks are blue. The right panel shows the single laterolog values (shallow and deep) compared to sonic traveltime data [from LDEO].





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Induction logging tools

Up to this point we have discussed methods of resistivity measurements which pass electric currents into the formation by means of a galvanic contact. The inductive method on the other hand utilizes a transmitter coil to set up an alternating magnetic field which induces current flow in the formation (consult the Maxwell equations for the mathematical treatment of the Induction Law by Faraday).

The induced current generate a secondary magnetic field which is sensed by a receiver coil. Because no galvanic contact is required induction tools can be operated in wells in which the borehole fluid is either not present (air-filled) or highly resistive. The development of the induction method was partially motivated by the introduction of non-conductive, oil-based drilling mud.

Inductive methods have been developed and widely applied in mineral exploration, where highly conductive targets are sought.



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Magnetic logging

Rock magnetism \mathbf{M} is the sum of its remanent and induced components M_{rem} and M_{ind} . The magnitude of the induced component is expressed in terms of susceptibility. Within a rock the direction of M_{ind} is colinear with the inducing field \mathbf{H} . The direction of the remanent magnetization reflects the direction of the ambient field at the time the remanence was acquired and is therefore often not aligned with the present-day field.

Remanence and susceptibility are controlled by a limited number of iron-rich minerals which are classified as ferrimagnetic. Prominent among them are pyrrhotite (iron sulfide) and members of the iron-titanium oxide system. Magnetite is the most magnetic mineral in this group. Ultimately, remanence and susceptibility are controlled by the grain size of magnetic minerals.

Susceptibility logs can be acquired by measuring the change in inductance of a multi-turn coil. The tool consists of a coil wrapped around a core of known high-susceptibility material in such a way that the susceptibility of the surrounding rock changes the pre-set self-inductance of the coil-core sonde.