

Introduction to Downhole Logging

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Well Logging Principles and Applications
G9947 - Seminar in Marine Geophysics
Spring 2008

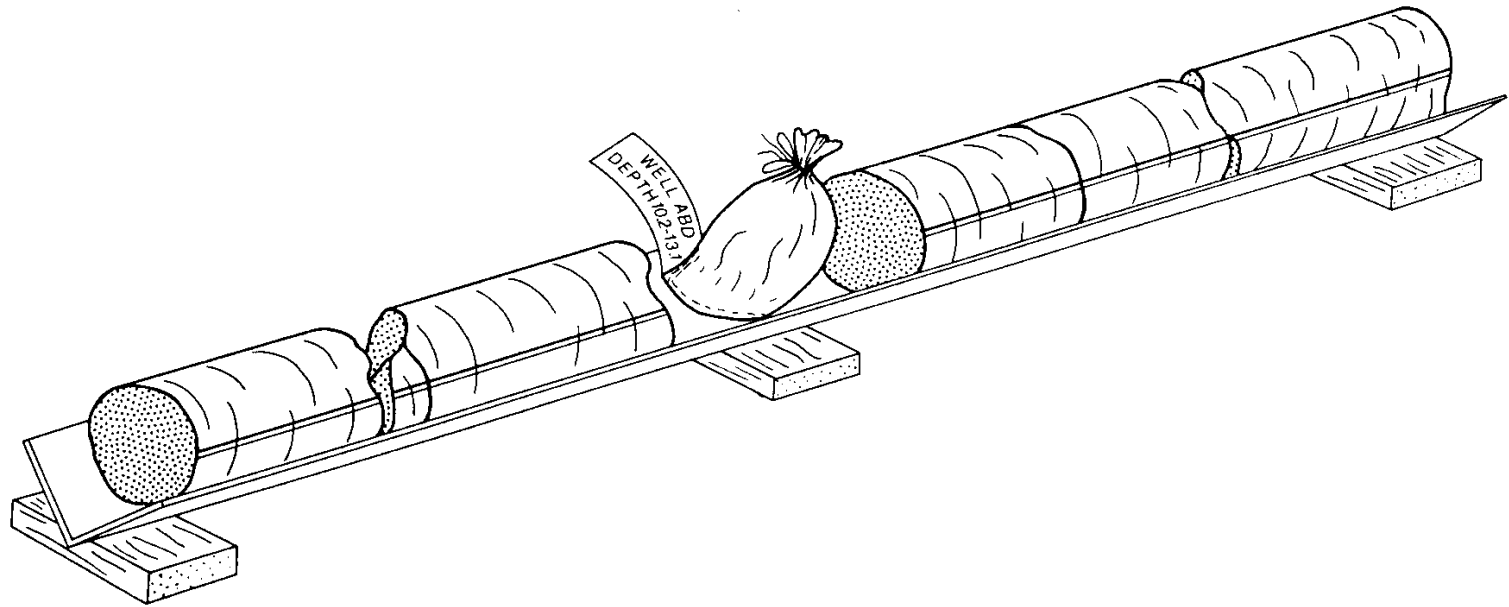


Fig. 3.2 Core pieces fitted together on a length of angle-iron. A rubbly section is contained in the bag. The parallel lines marked on the core, which would be in contrasting colours, indicate the way up.

in si·tu

in the natural or original position or place

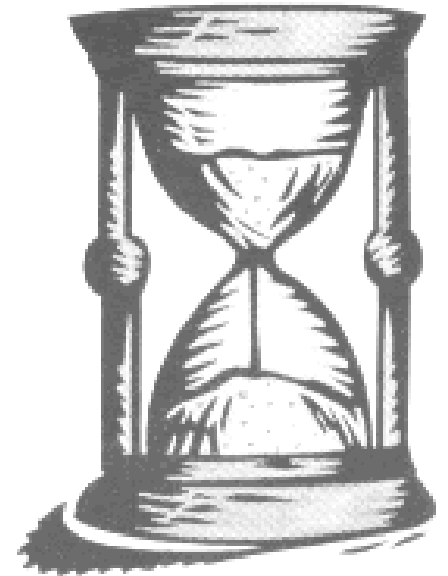
Pronunciation: (")in-'sl-(")tü, -'si-, -(")tyü *also*

-'sE-, -(")chü

Function: adverb or adjective

Etymology: Latin, in position

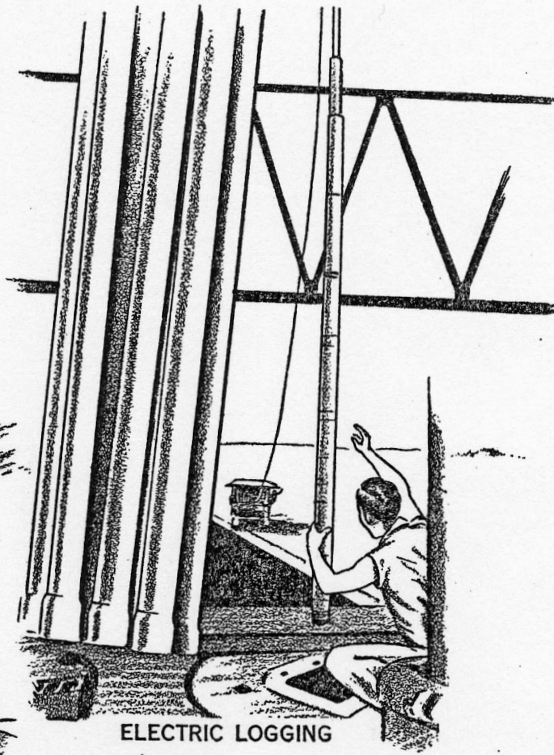
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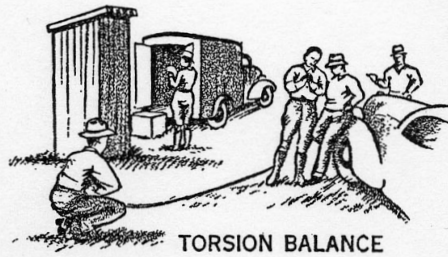
GEOPHYSICS AT WORK



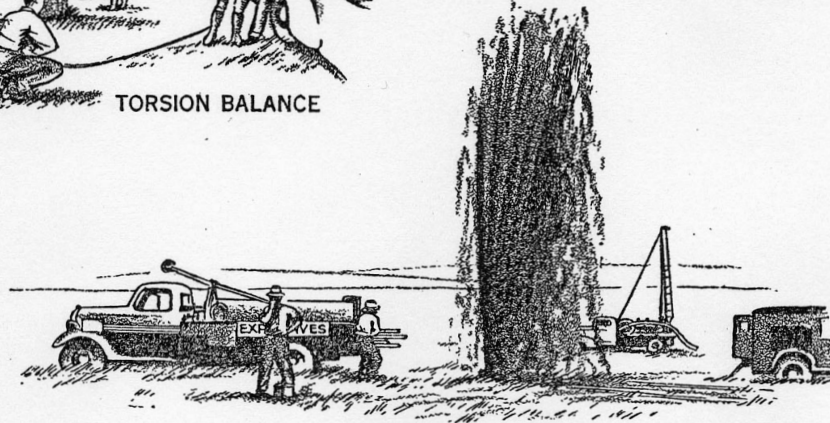
MAGNETOMETER



ELECTRIC LOGGING



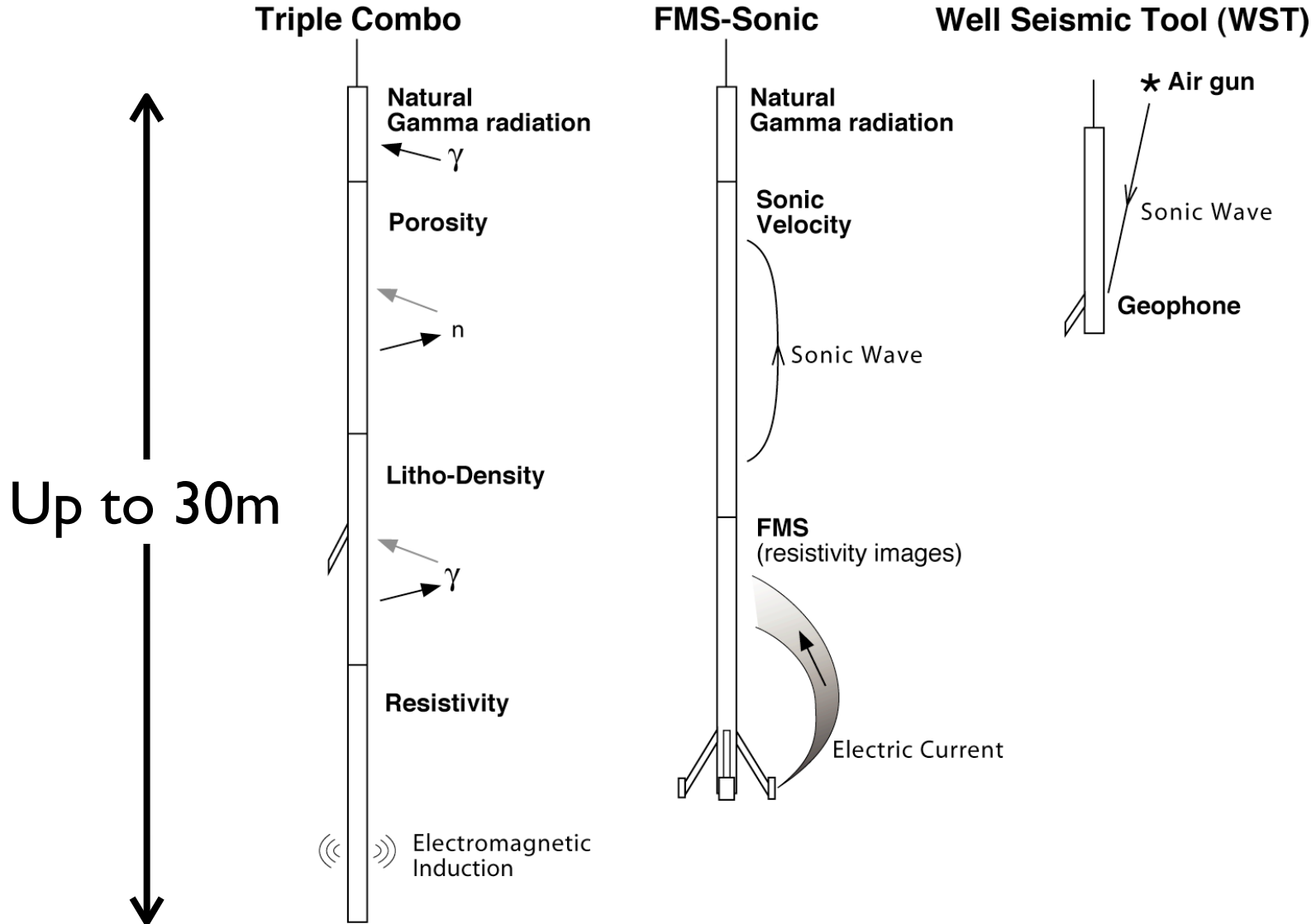
TORSION BALANCE



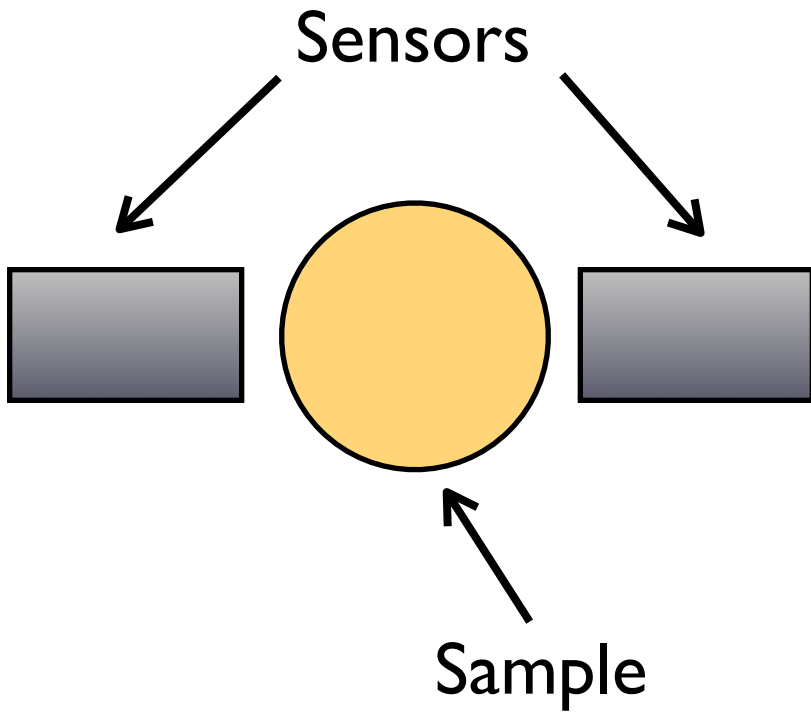
SEISMOGRAPH

Many geophysical methods are used in attempting to determine the attitude, character, and contents of rocks beneath the surface. These sketches show men busy at some of those in common use.

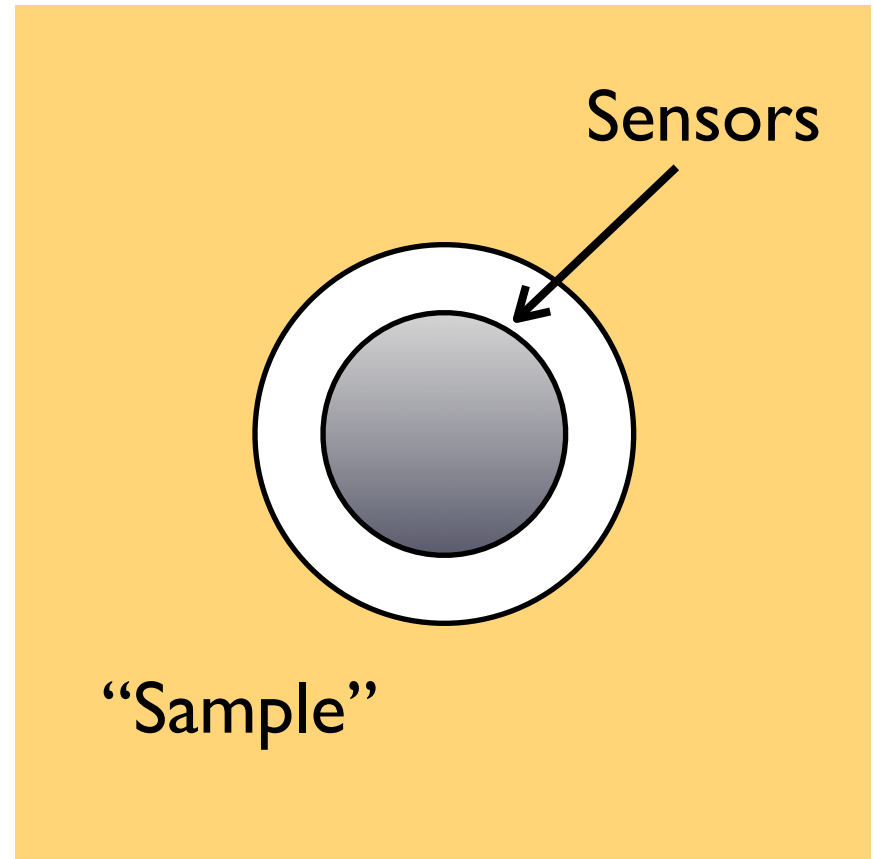
Wireline tool strings



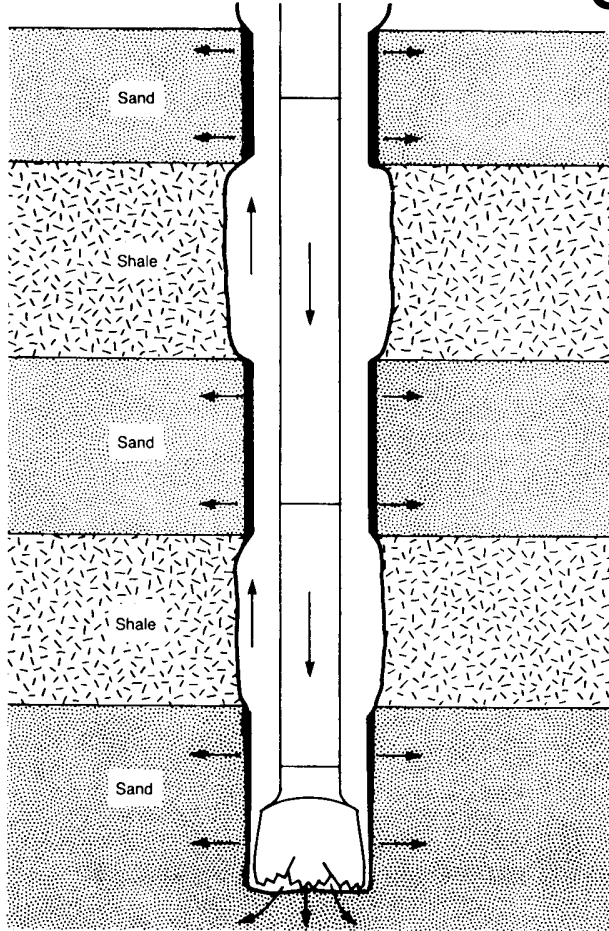
Measurements on core samples



Measurements in the borehole



6-arm caliper



Degradation of the formation during and after drilling. Overpressured mud is indicated to be invading porous and permeable sand formations with the formation of a mudcake. The mud circulation also causes borehole washout in the shale zones. From Dewan.¹

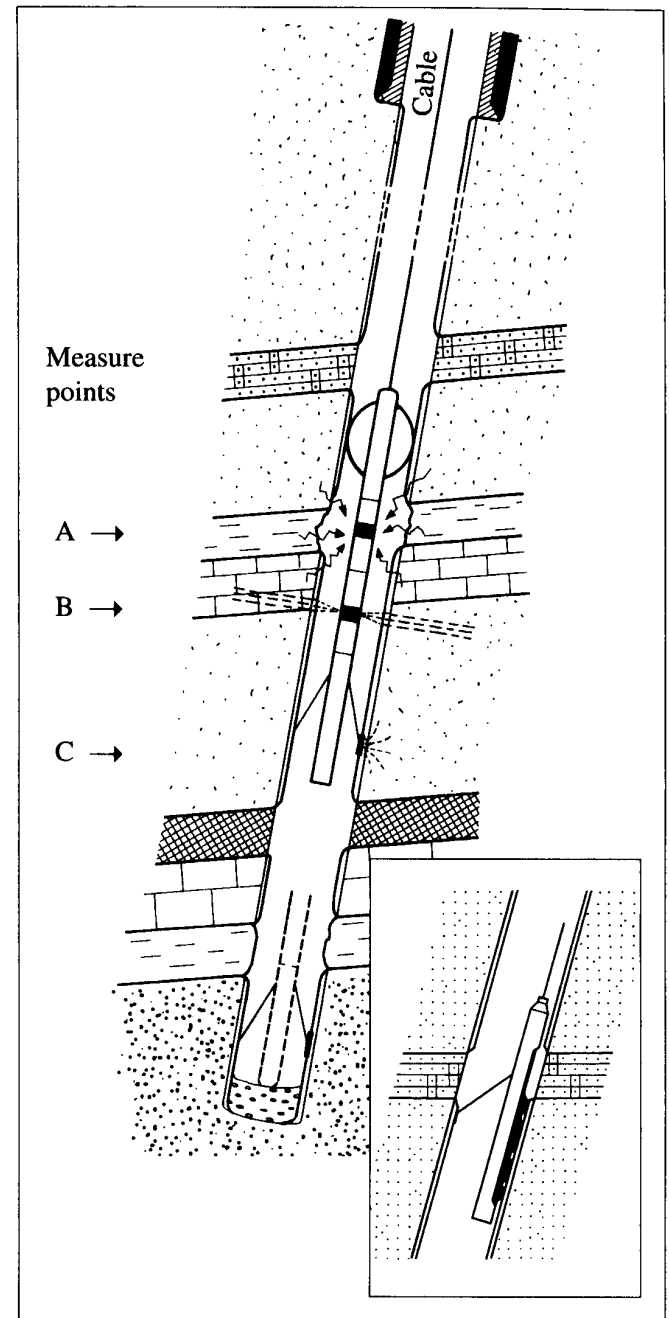
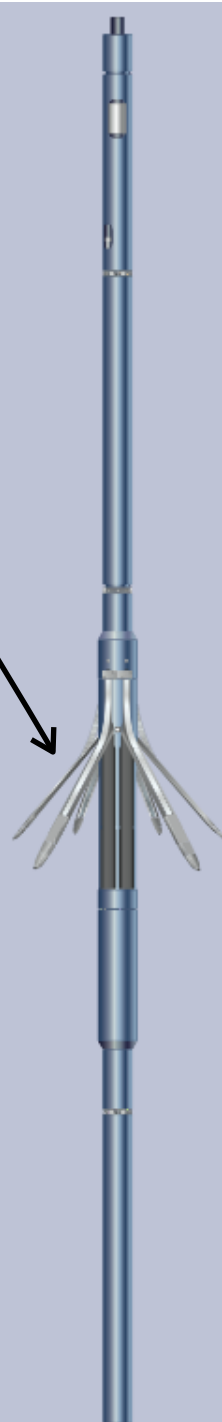


Fig. 1.1 Logging tools in the wellbore.

- Nuclear Logs
 - Natural gamma ray
 - Density
 - Neutron
 - Thermal neutron capture
- Sonic
- Electrical / magnetic
- Imaging
- Vertical seismic profile (VSP)
- Logging While Drilling
- Examples

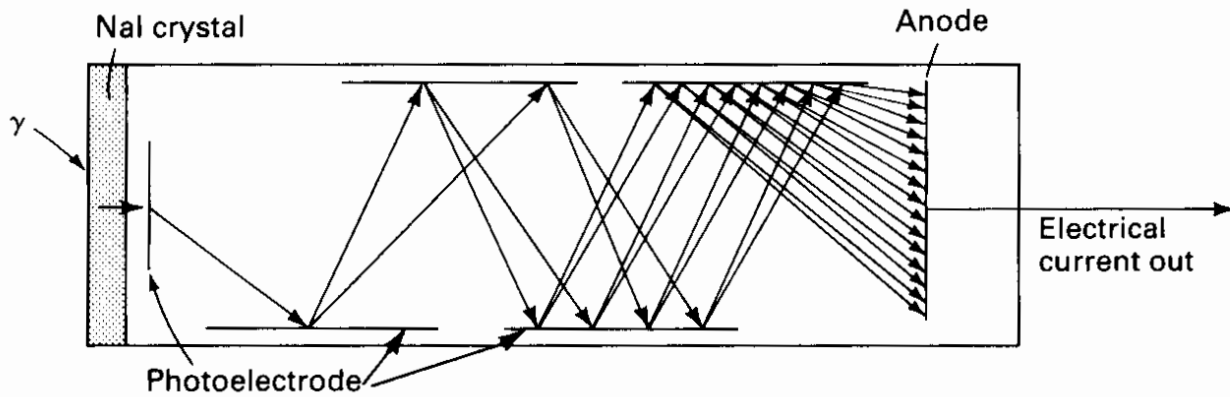


Figure 7.4 Schematic of a scintillation counter. An incident gamma ray on the scintillation crystal of NaI causes the crystal to emit a photon, which then causes the photoelectrode to emit electrons. The number of electrons is multiplied as each strikes a series of electrodes, finally being collected by an anode where the consequent current is proportional to the energy of the incident gamma ray.

- Gamma ray \approx shale indicator
- Gamma ray log

$$\text{GR(API)} = 4\text{Th(ppm)} + 8\text{U(ppm)} + 16\text{K(\%)}$$
- Compensated gamma ray

$$\text{CGR(API)} = 4\text{Th(ppm)} + 16\text{K(\%)}$$
- CGR ignores U, which is not always associated with shales

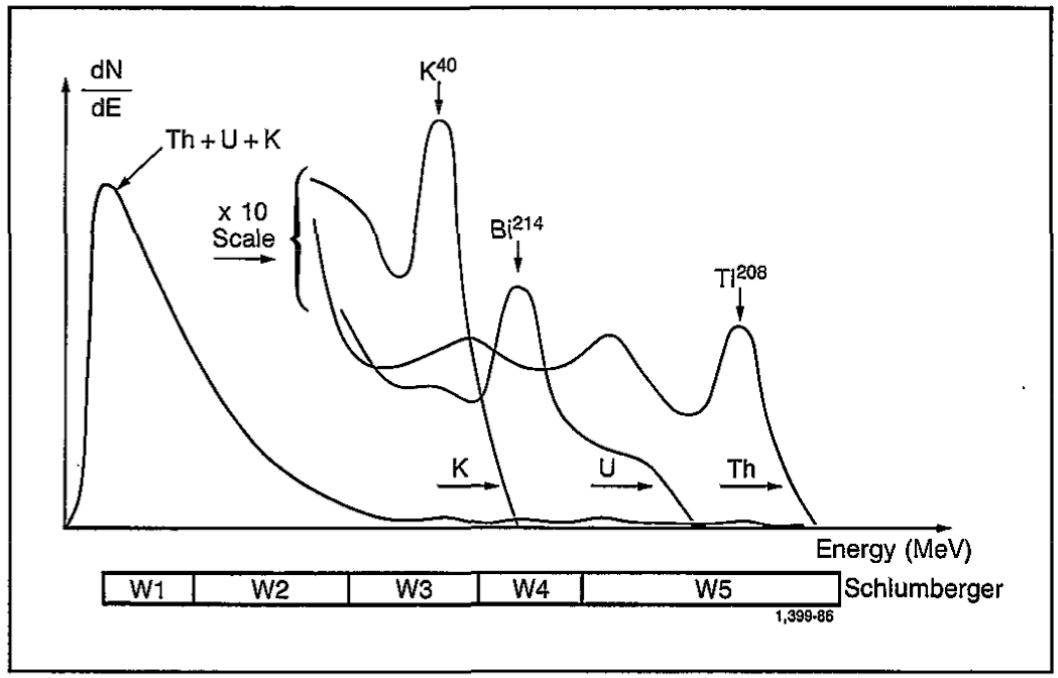
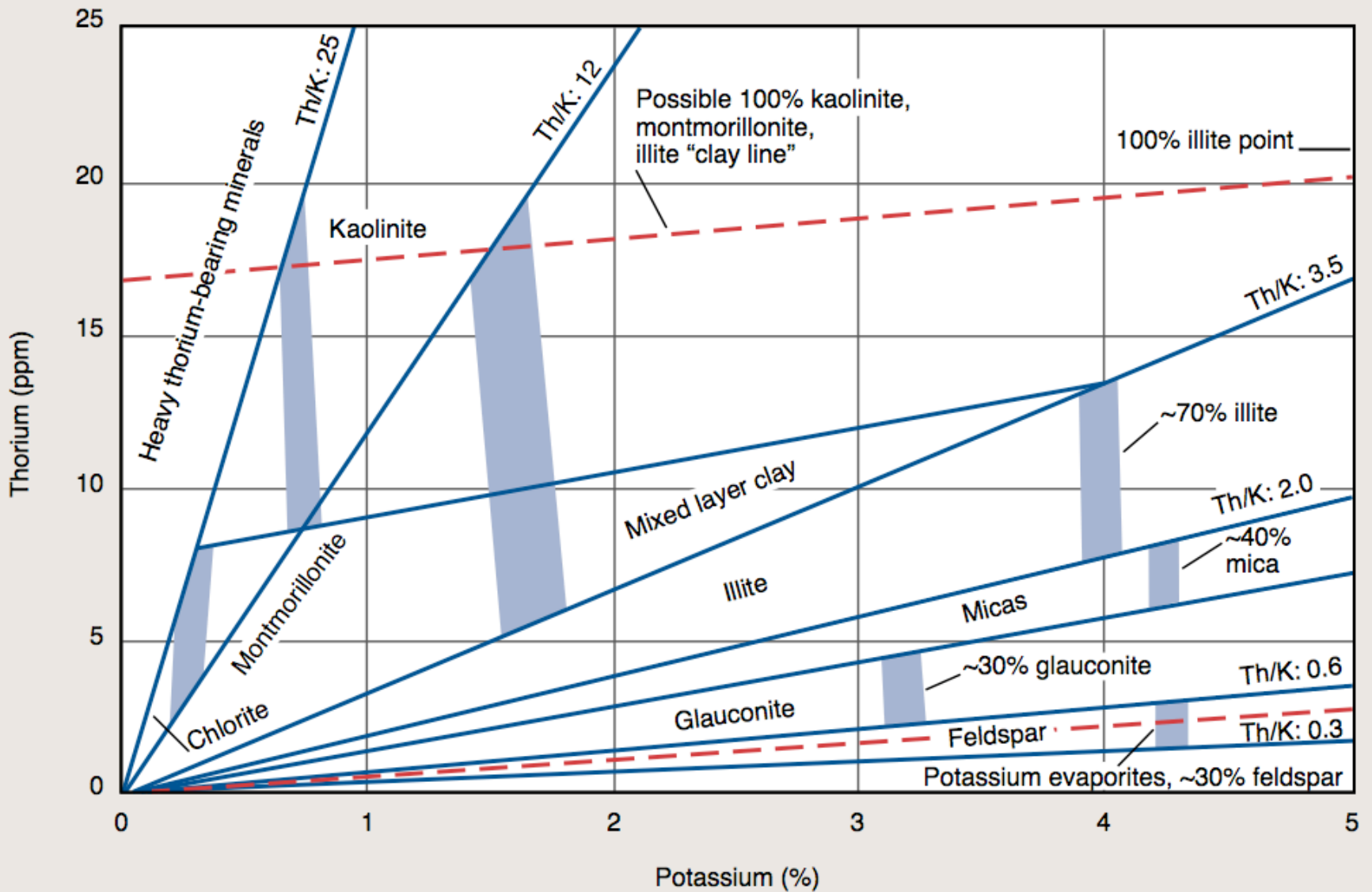
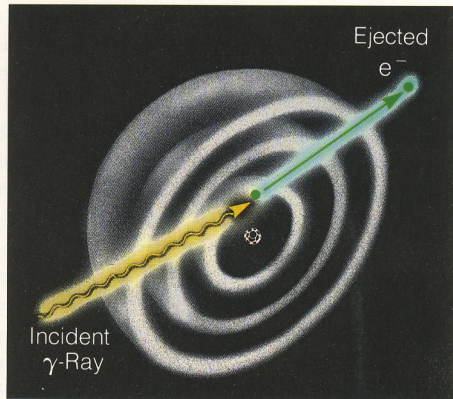


Fig. 3-9—Potassium, thorium, and uranium response curves (NaI crystal detector).

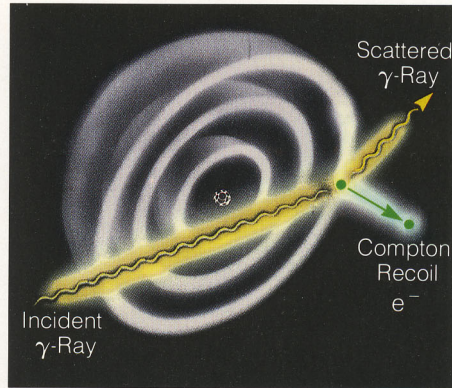


Photoelectric absorption



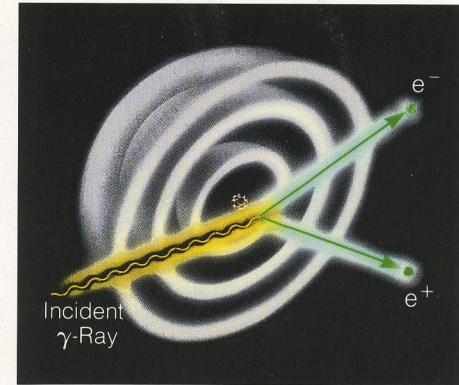
□ In photoelectric absorption, a low-energy γ -ray disappears as it collides with an atom, ejecting an electron from orbit.

Compton scattering



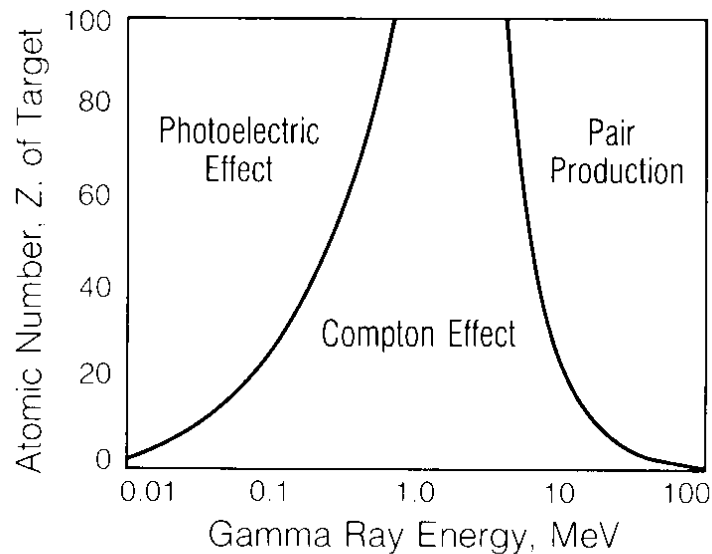
□ In Compton scattering, the γ -ray changes course when it bounces off an orbital electron.

Pair production



□ In pair production, a γ -ray collides with a nucleus, disappears, and converts into an electron and a positron. If the γ -ray has enough energy, it knocks an electron out of the innermost shell.

gamma ray energy →



^{137}Cs source of
662 keV gamma rays

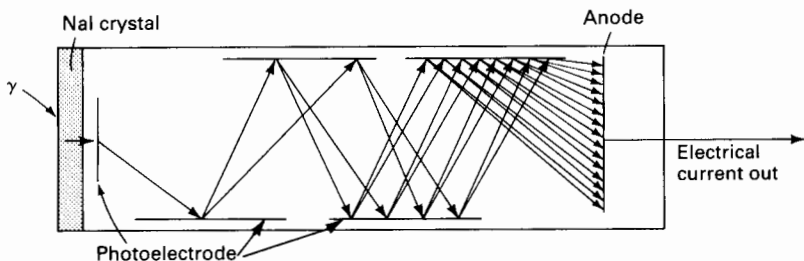
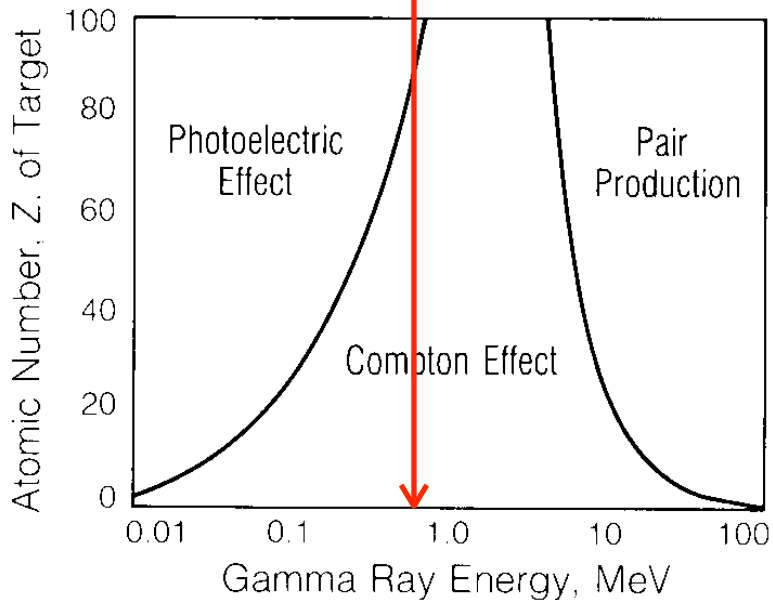
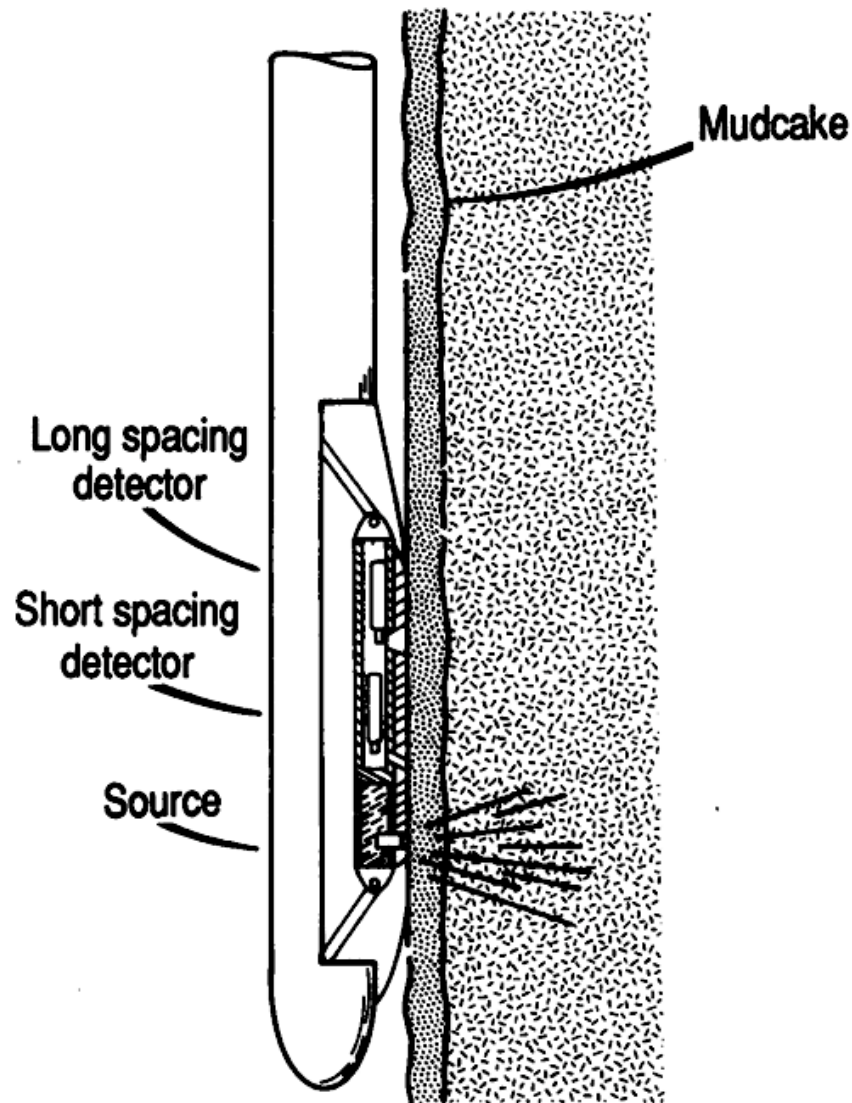


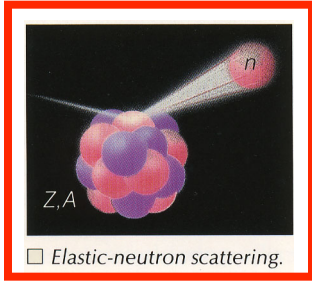
Figure 7.4 Schematic of a scintillation counter. An incident gamma ray on the scintillation crystal of NaI causes the crystal to emit a photon, which then causes the photoelectrode to emit electrons. The number of electrons is multiplied as each strikes a series of electrodes, finally being collected by an anode where the consequent current is proportional to the energy of the incident gamma ray.



Electron density index

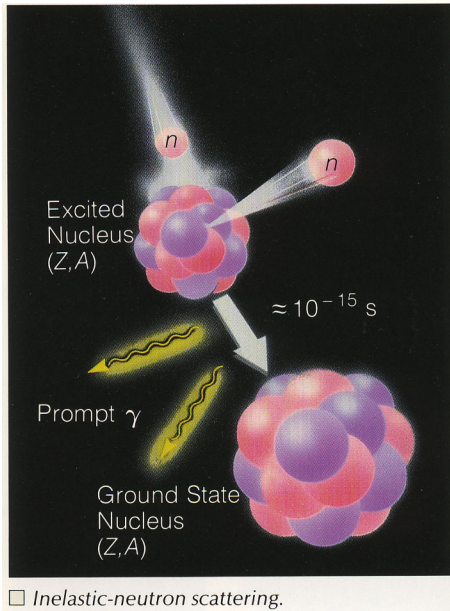
$$\rho_e \equiv 2 \frac{Z}{A} \rho_b$$

Fast/slow n

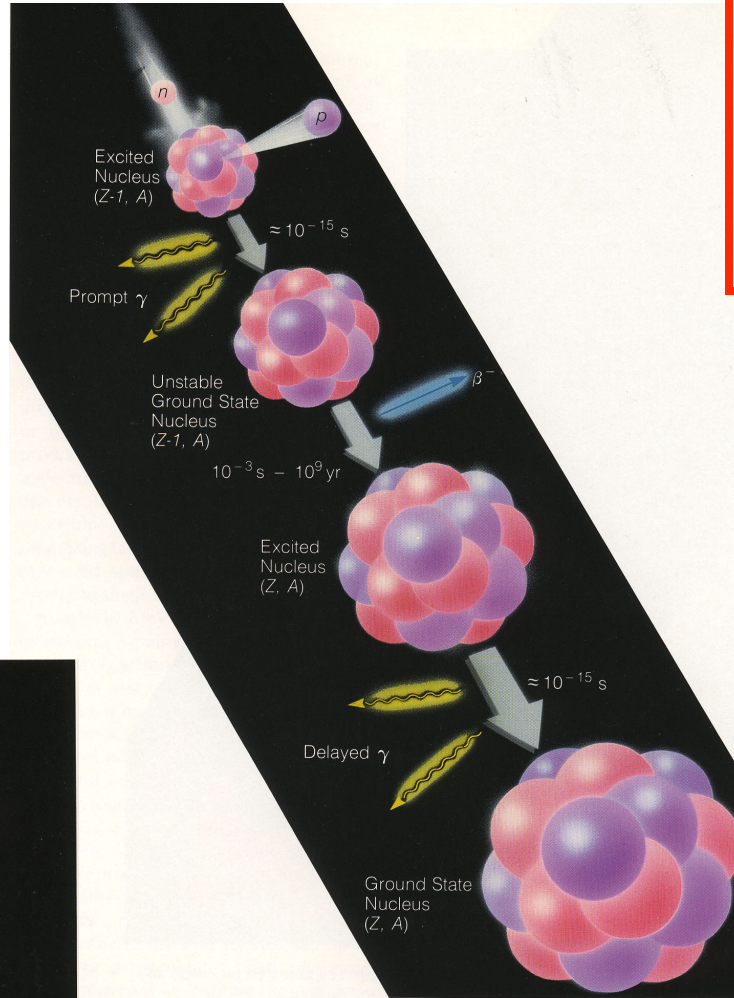


Neutron porosity

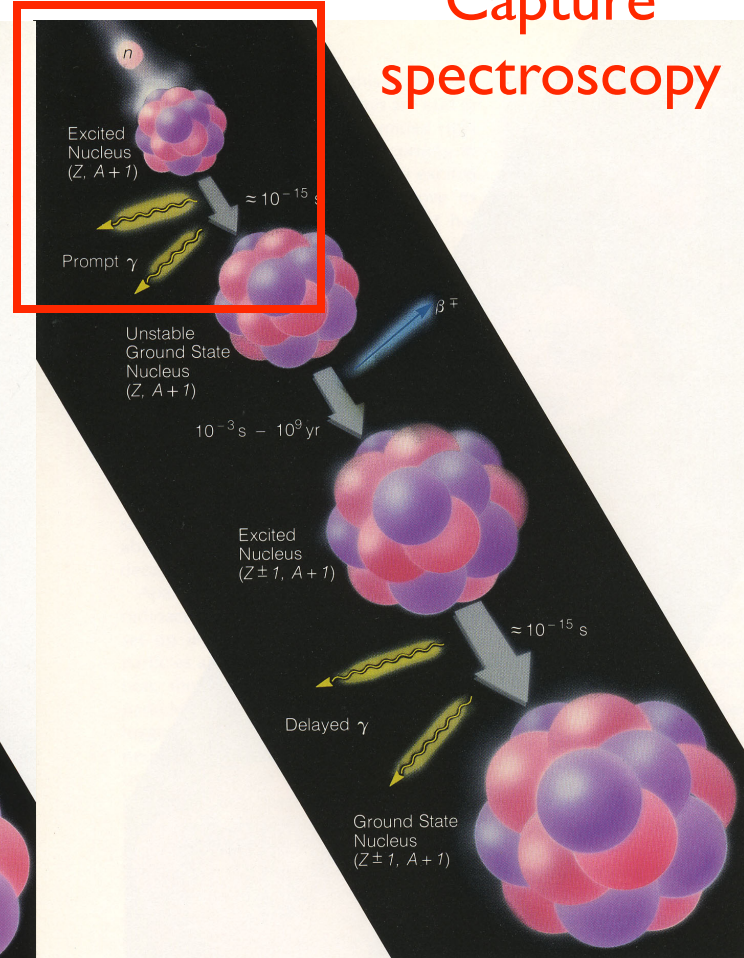
Fast n



Fast n



Slow n

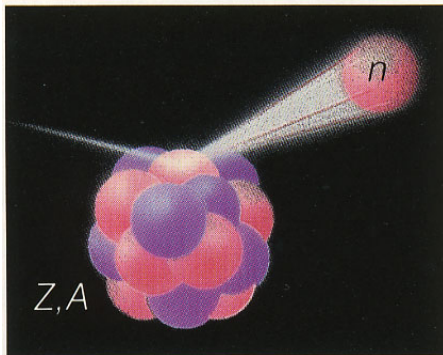


Capture spectroscopy

Fast n sources:

- $^{241}\text{Am}-^9\text{Be}$ (4.35 MeV)
- Accelerator (14MeV)

Thermal n energy = 0.025eV



□ Elastic-neutron scattering.

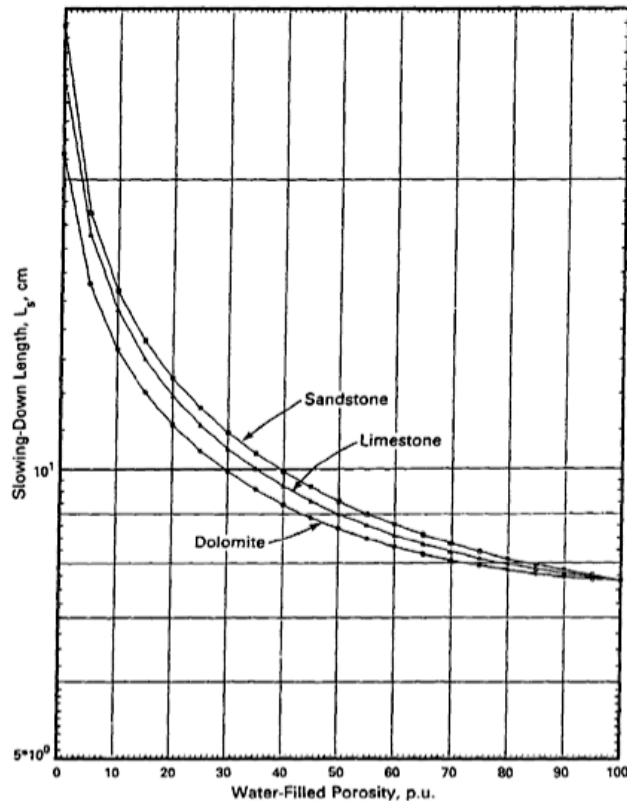
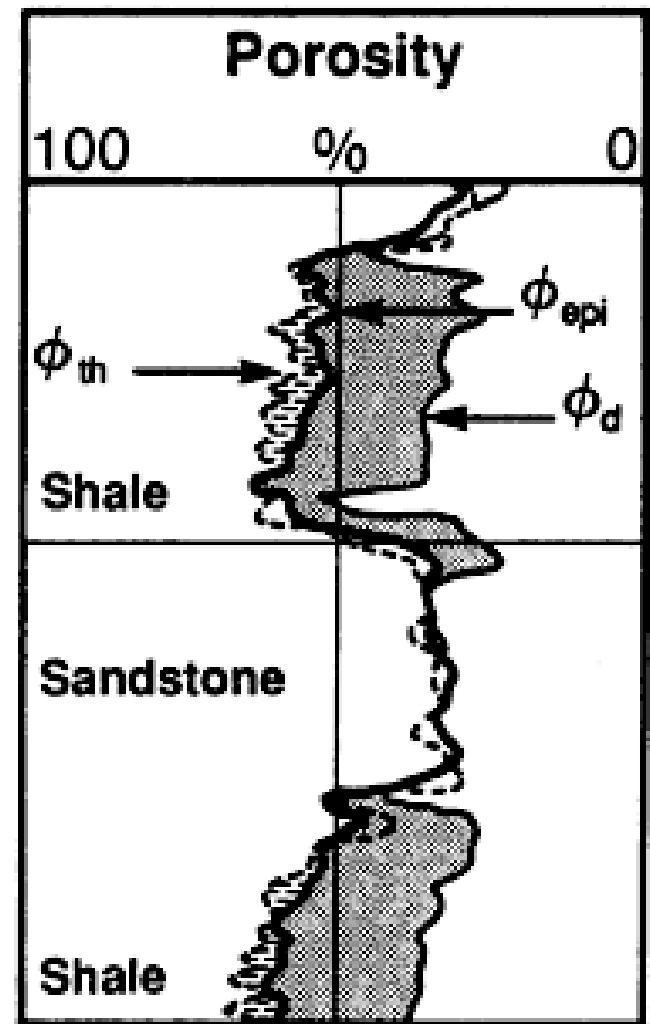


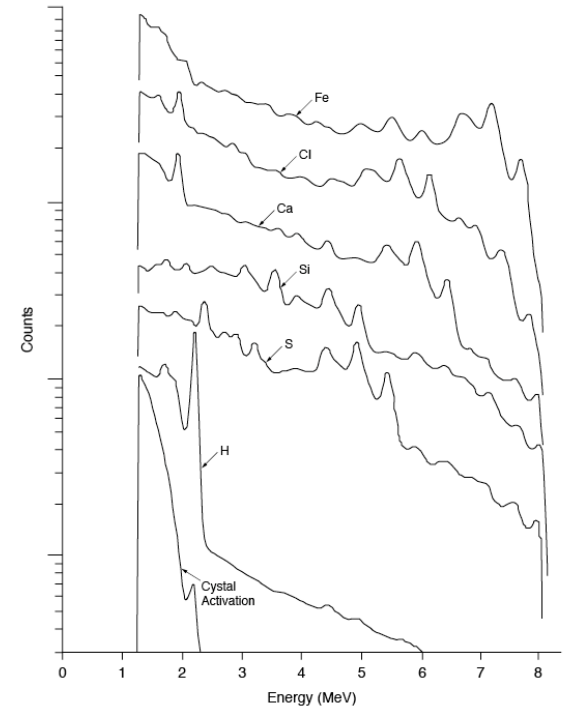
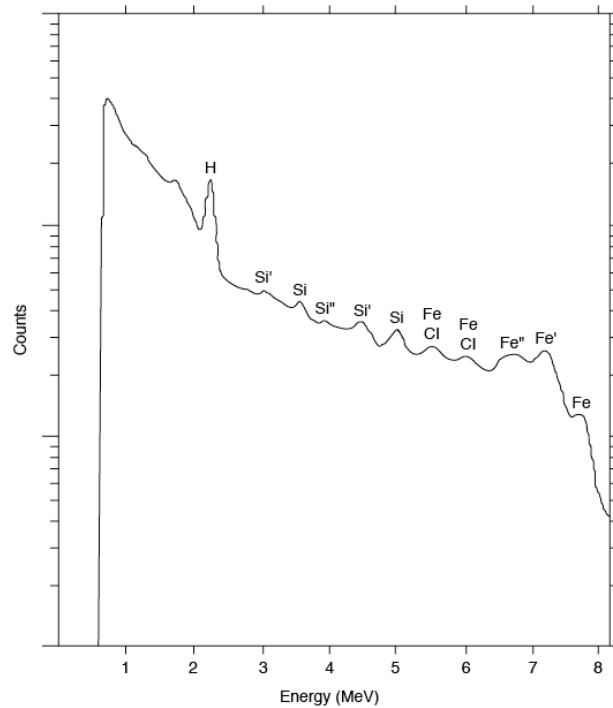
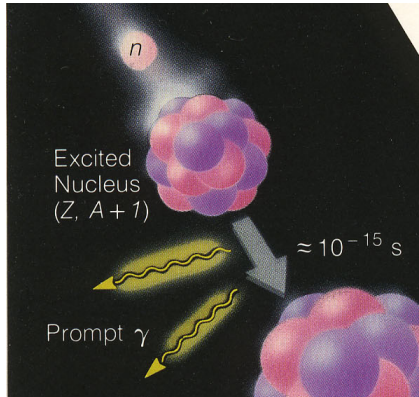
Figure 1 The slowing-down length of three common rock types as a function of porosity. From Ellis (36).

- Neutrons lose most energy bouncing off H nuclei
- Slowing-down length for high-energy neutrons to reach epithermal energy (0.1-10 eV) depends on water-filled porosity
- Measurement: flux of thermal-epithermal scattered neutrons

Fig. 5. Neutron and density log estimates of porosity (ϕ_{th} , thermal neutrons; ϕ_{epi} , epi-thermal neutrons; ϕ_d , density). Agreement between the three is seen in a sandstone layer, which contains no clay minerals. In the shale zones above and below, the neutron estimates exceed the density estimate because of the high H concentration associated with the clay minerals. [Adapted from (11)]



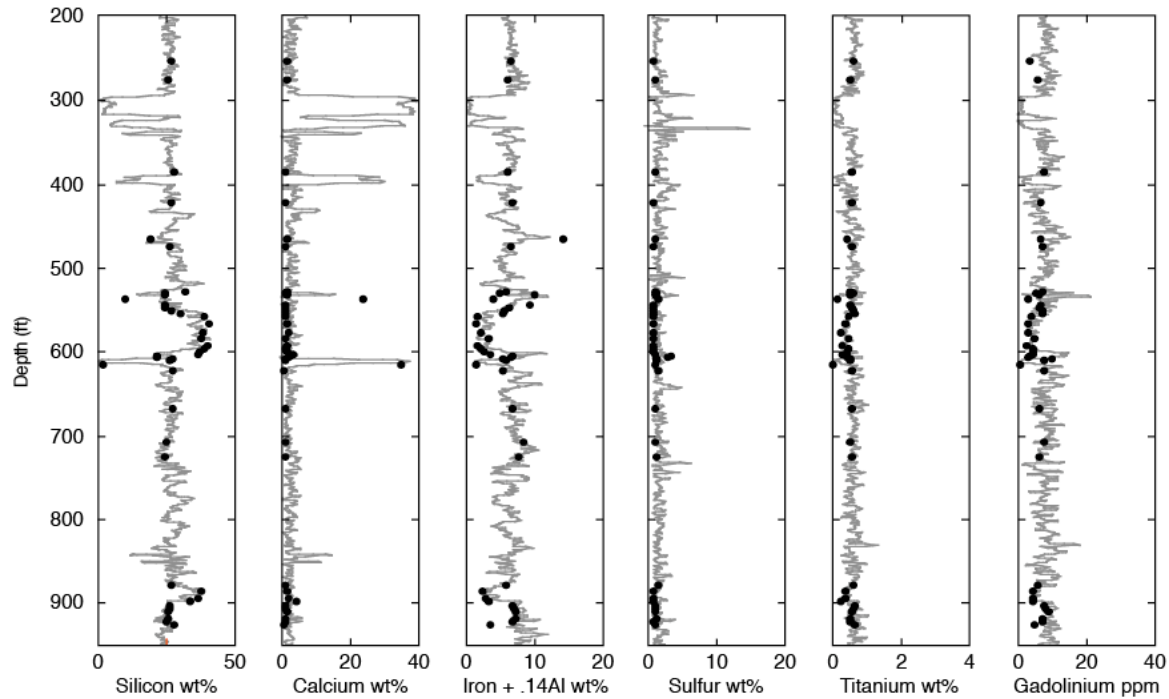
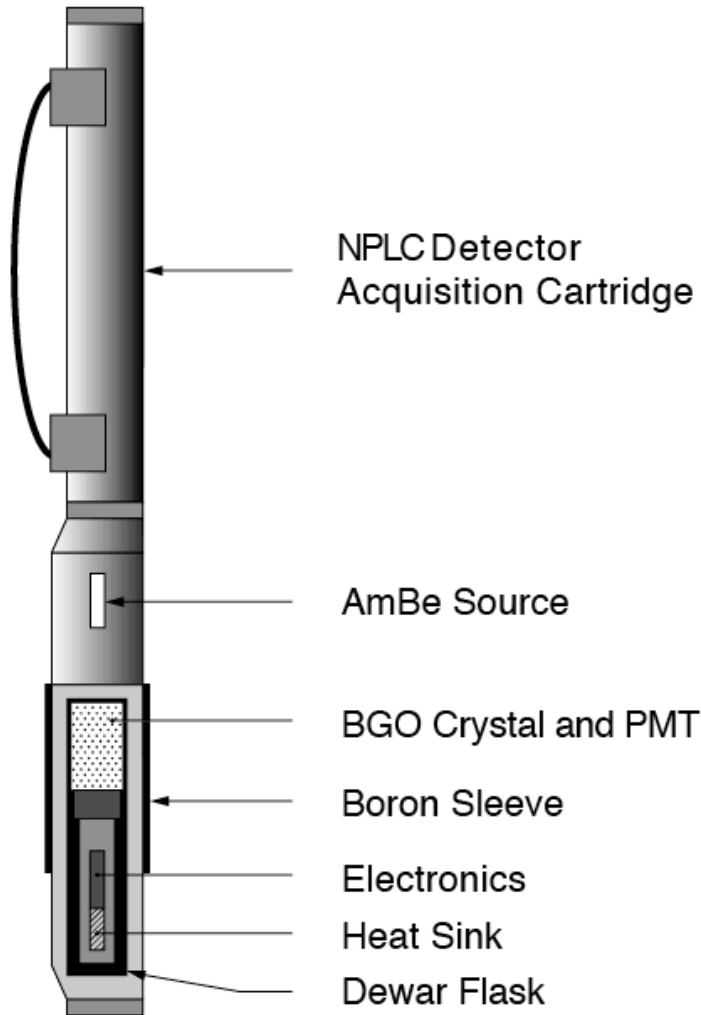
Thermal n capture spectroscopy



$$\text{Measured gamma-ray spectrum} = \sum \text{Elemental yield} \times \text{Element gamma-ray spectrum}$$

Detection depends on

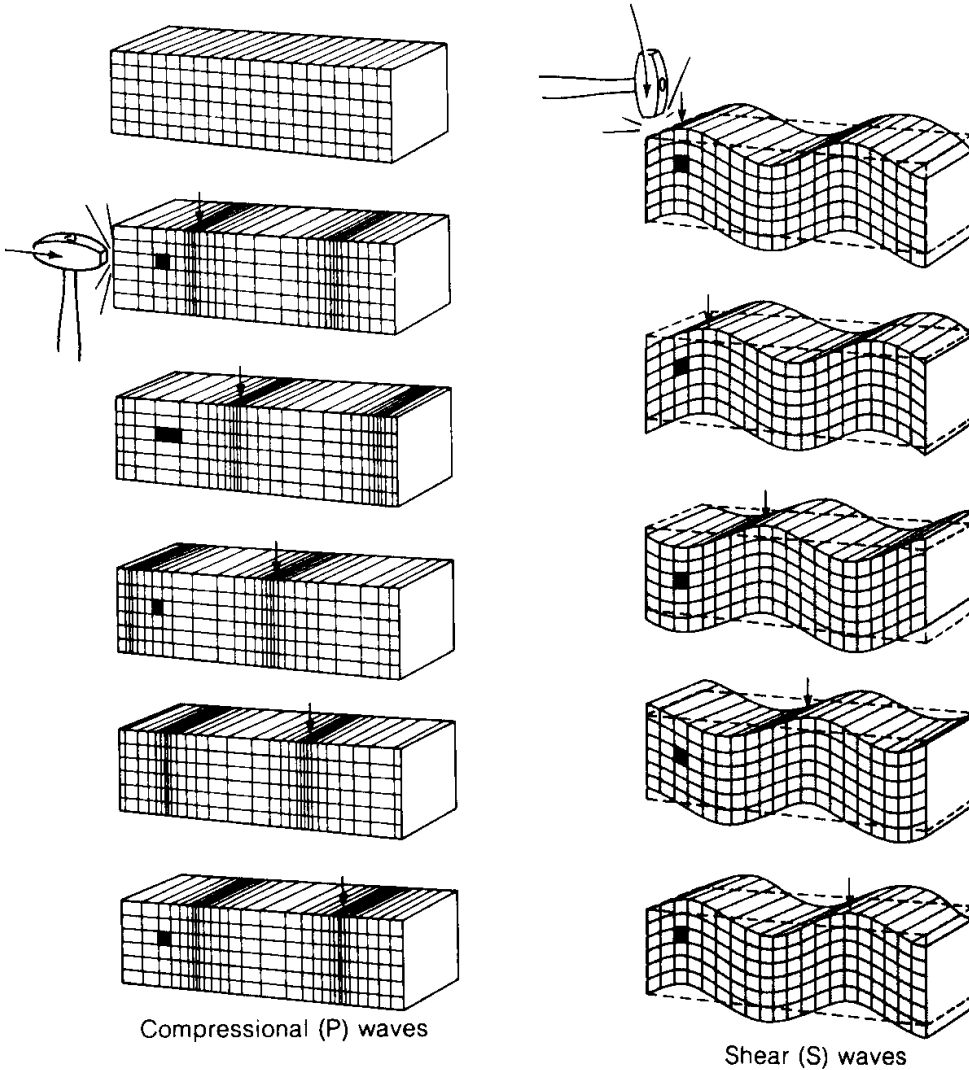
- Thermal n absorption cross-section
- Character of gamma ray spectrum
- Elemental abundance



• = Core plug analysis

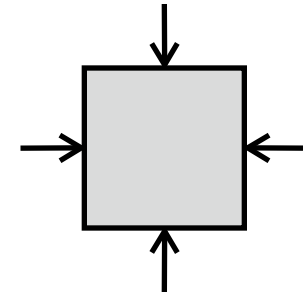
Elemental Capture Spectroscopy (ECS)
measures elemental concentrations of
Si, Ca, S, Fe, Ti, and Gd

- Nuclear Logs
- Sonic
 - Monopole
 - Dipole
- Electrical / magnetic
- Imaging
- Vertical seismic profile (VSP)
- Logging While Drilling
- Examples



$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad V_S = \sqrt{\frac{\mu}{\rho}}$$

Bulk modulus K relates compressional stress and strain



Shear modulus μ relates shear stress and strain



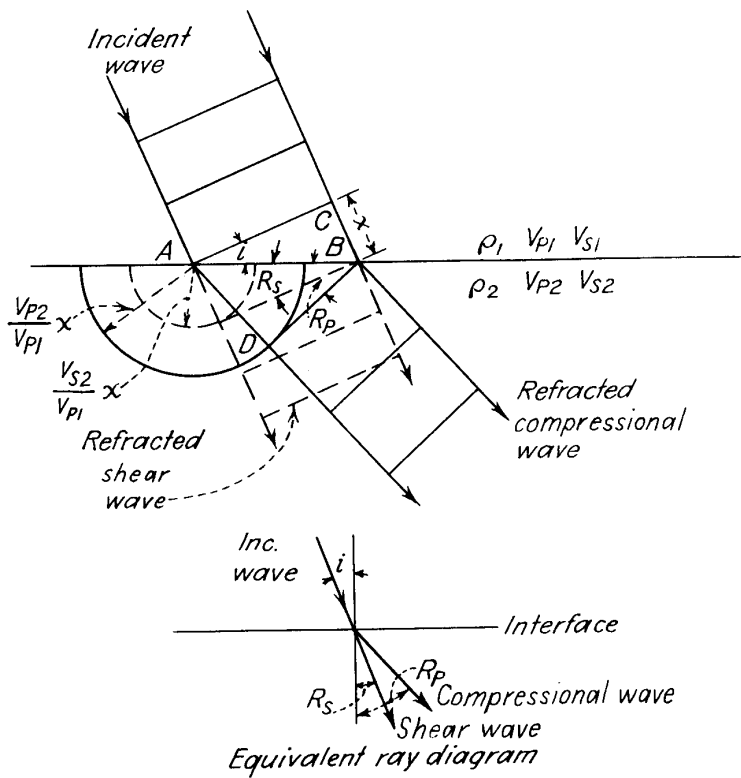


FIGURE 2-14 Refraction of plane compressional wave across interface.

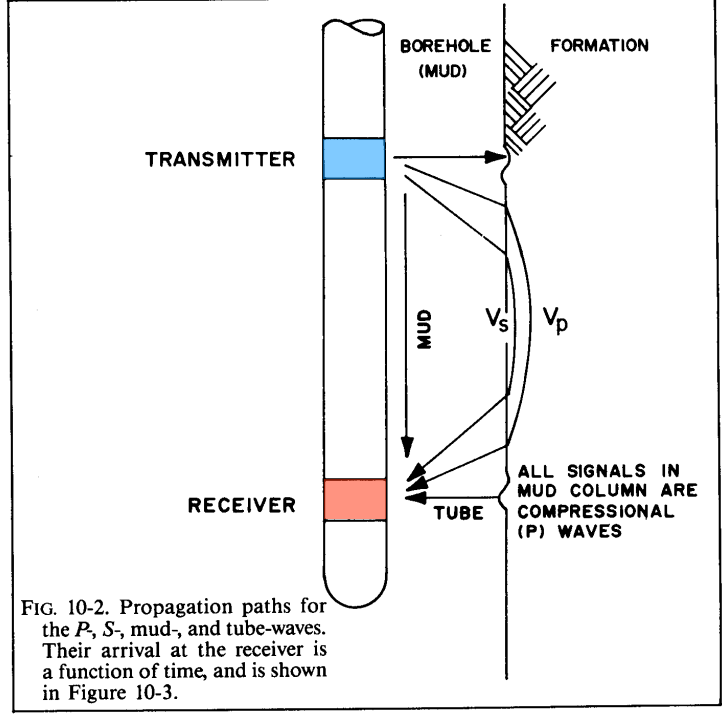
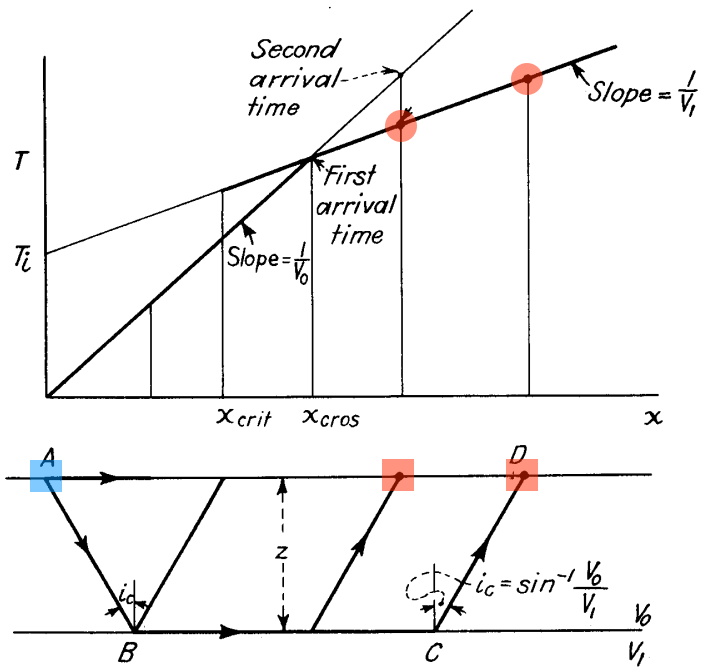
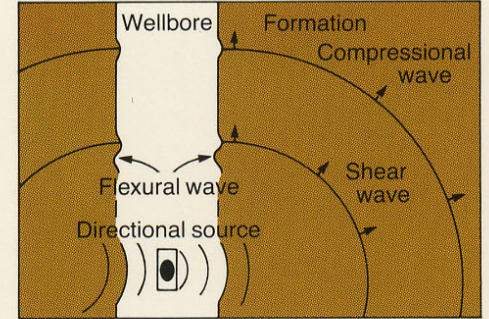
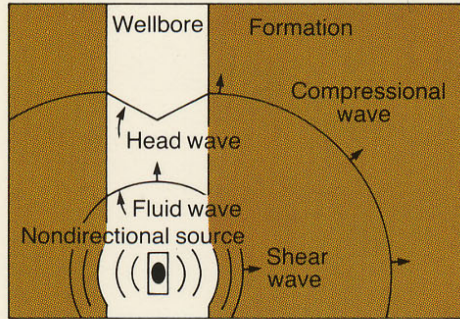
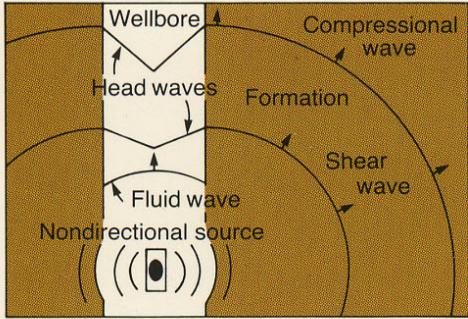


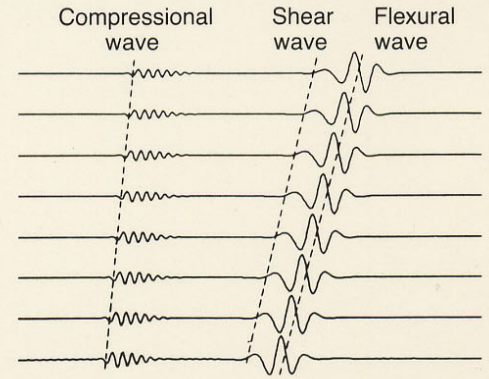
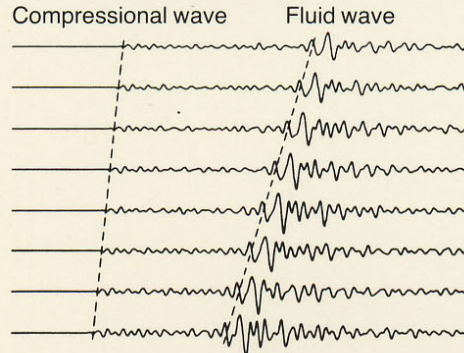
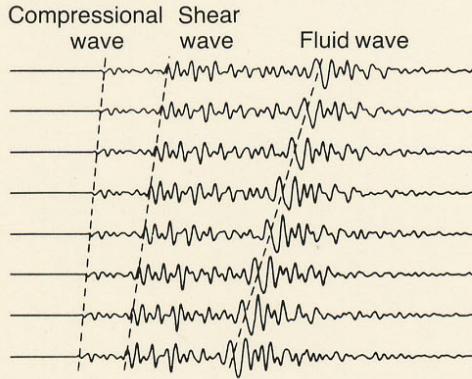
FIG. 10-2. Propagation paths for the P, S, mud-, and tube-waves. Their arrival at the receiver is a function of time, and is shown in Figure 10-3.



Sound Wave Propagation



Sonic Waveforms



“Fast” formation

“Slow” formation

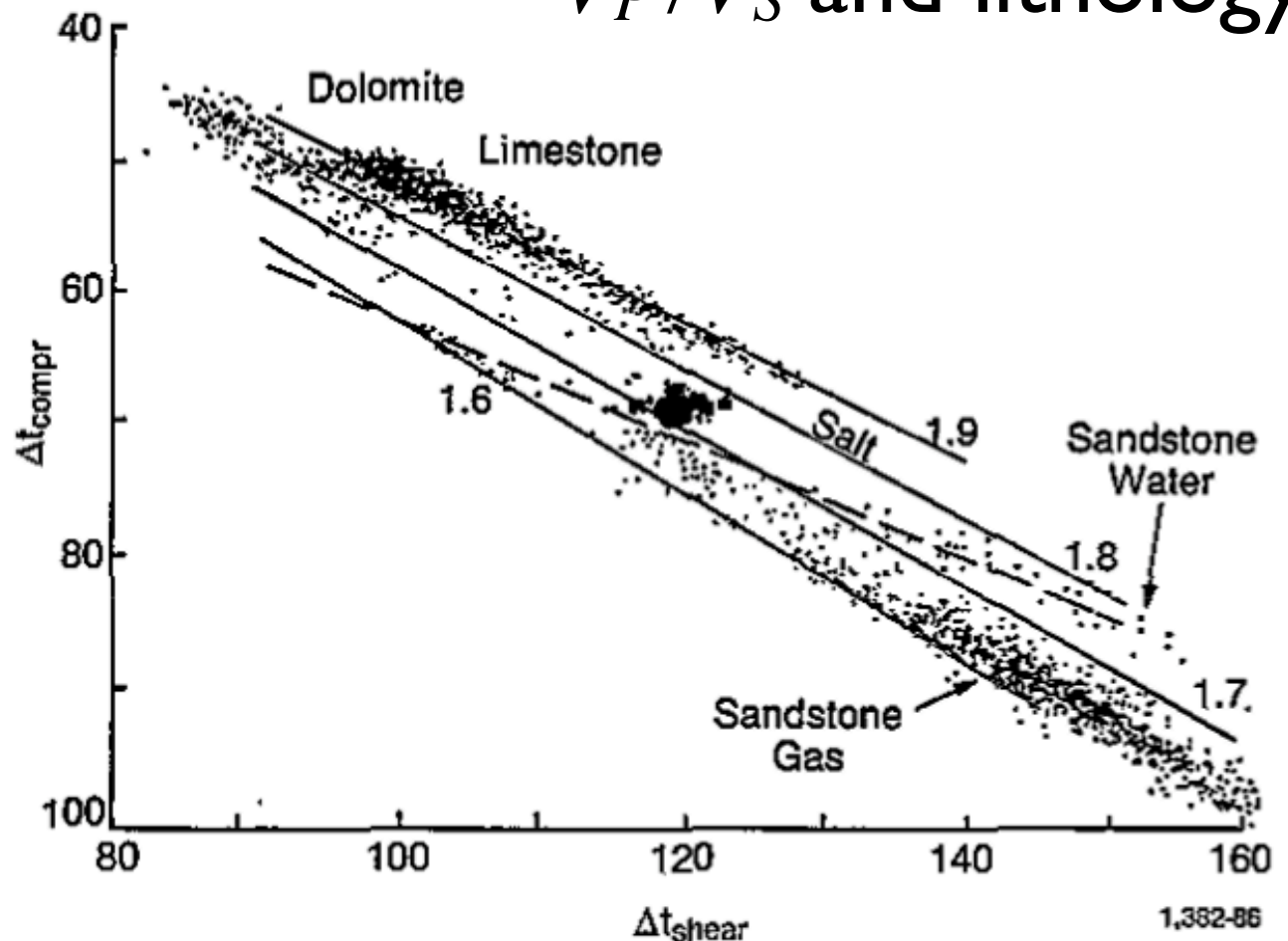
“Slow” formation

Wyllie's time-average

Slowness $u = 1/V_P$

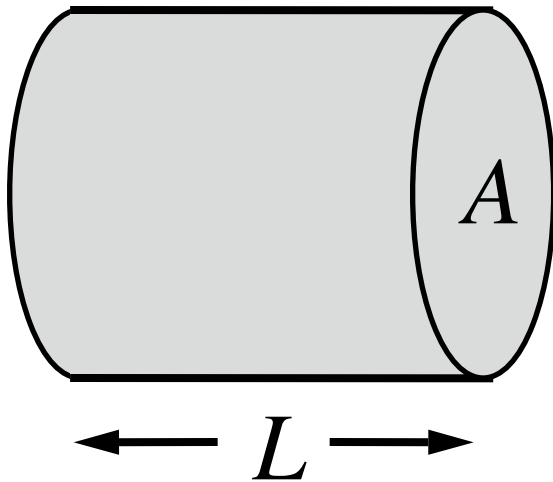
$$u = (1 - \phi)u_g + \phi u_f$$

V_P/V_S and lithology



- Nuclear Logs
- Sonic
- Electrical / magnetic
 - Resistivity
 - Electrode devices
 - Induction
 - Magnetic susceptibility
- Imaging
- Vertical seismic profile (VSP)
- Logging While Drilling
- Examples

Electrical properties



Ohm's law

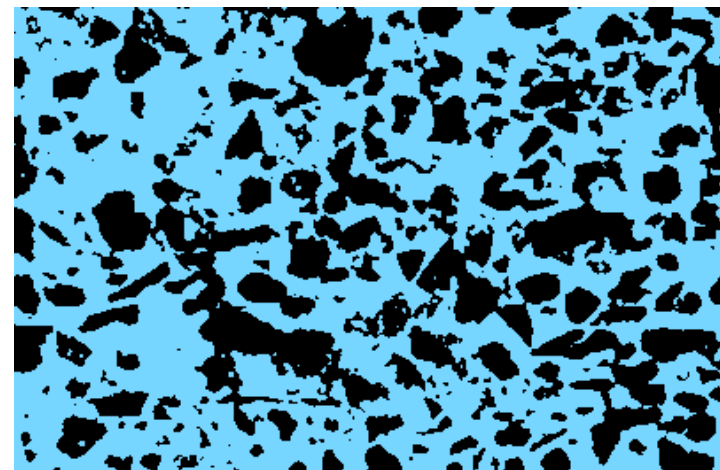
$$V = IR^*$$

Resistance R^*

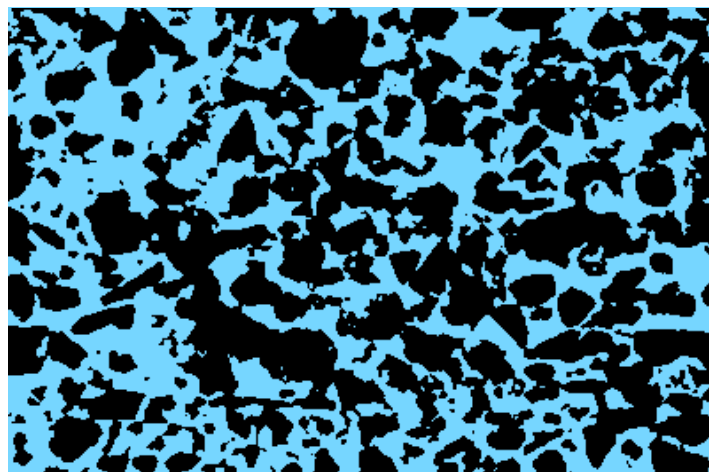
Resistivity R

$$R^* = R \frac{L}{A}$$

Units of resistivity are $\Omega \cdot \text{m}$ (ohm·m)

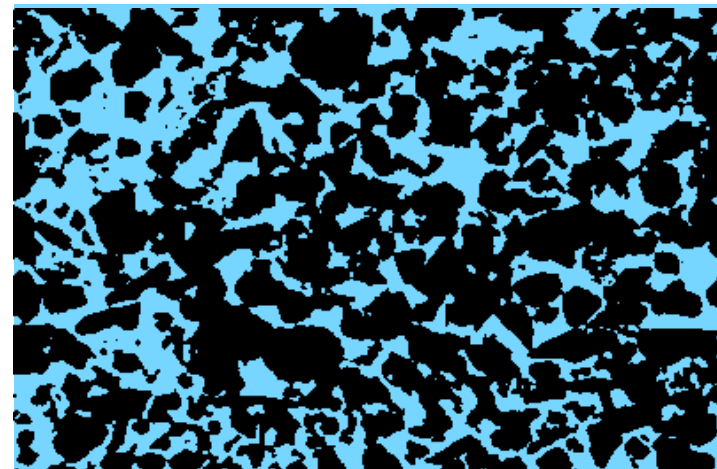





Water

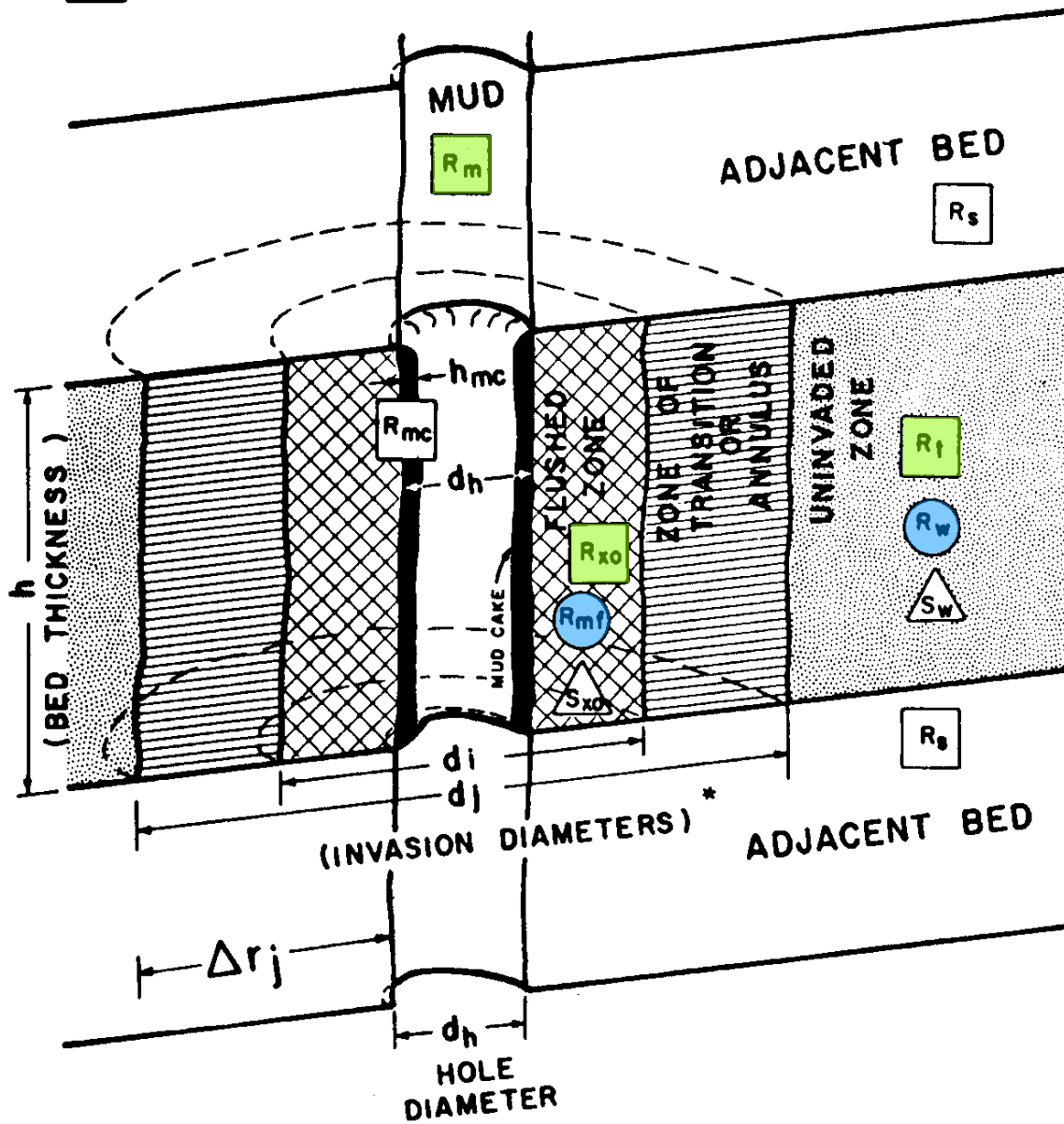


Resistivity

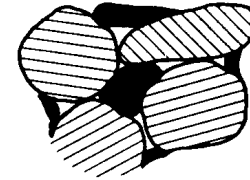
Porosity



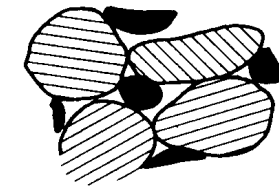
-  Resistivity of the zone
-  Resistivity of the Water in the zone
-  Water Saturation in the zone.



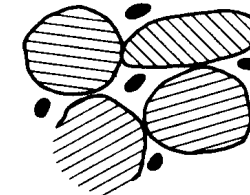
Water wet sand



(a)



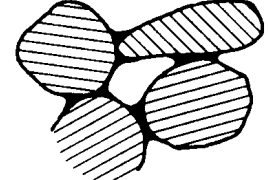
(b)



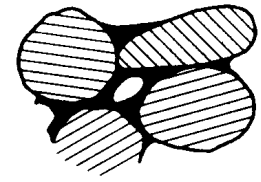
(c)

 Water

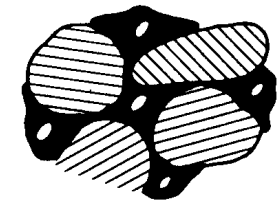
Oil wet sand



(d)



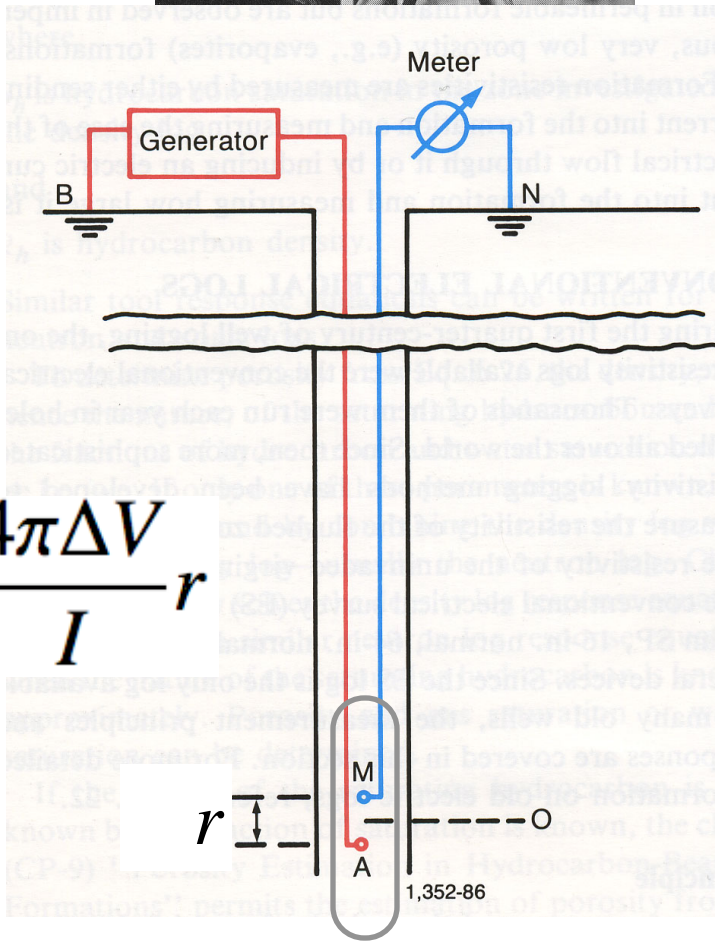
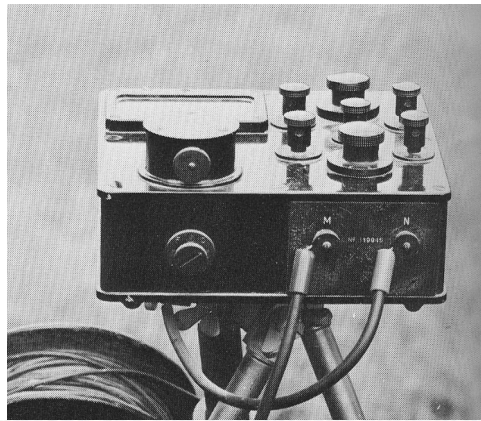
(e)



(f)

 Oil

1927



$$R_a = \frac{4\pi\Delta V}{I} r$$

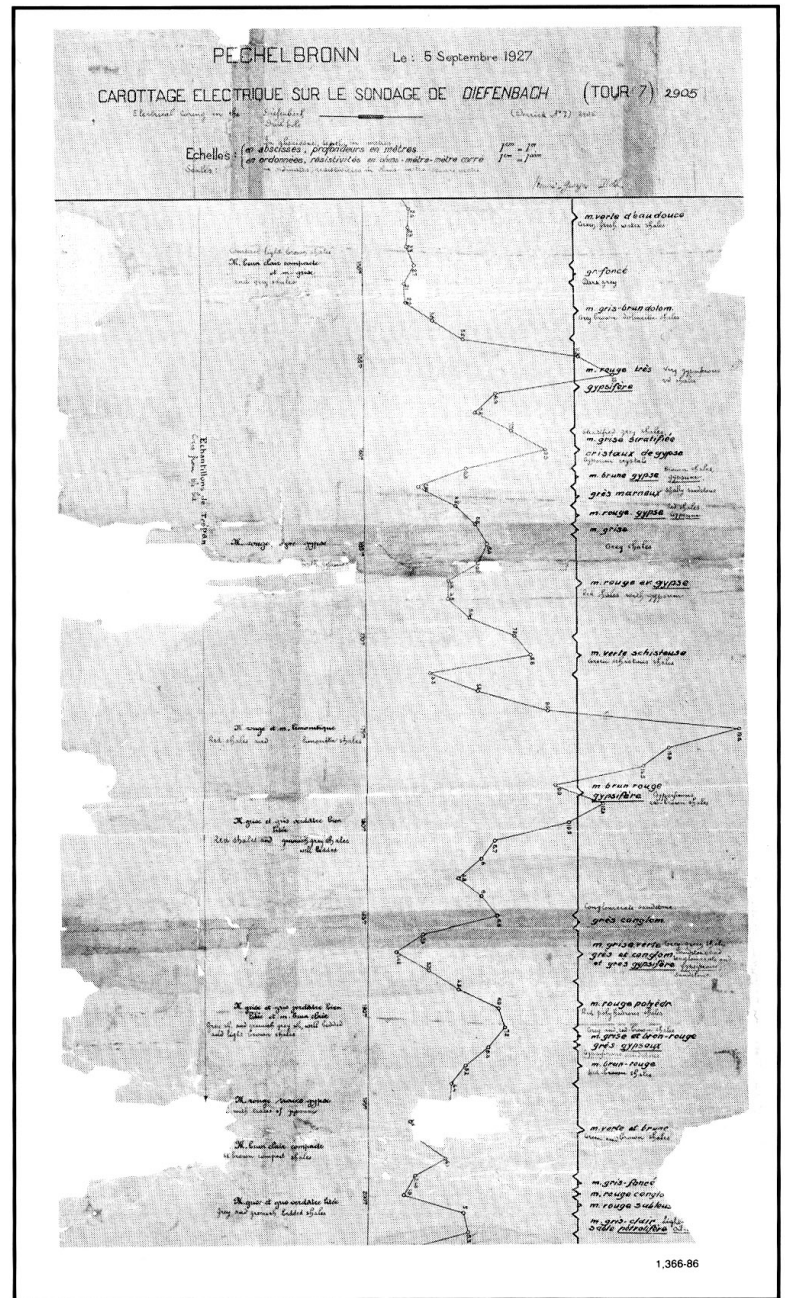


Fig. 1-1—The first log: points plotted on graph paper by Henri Doll.

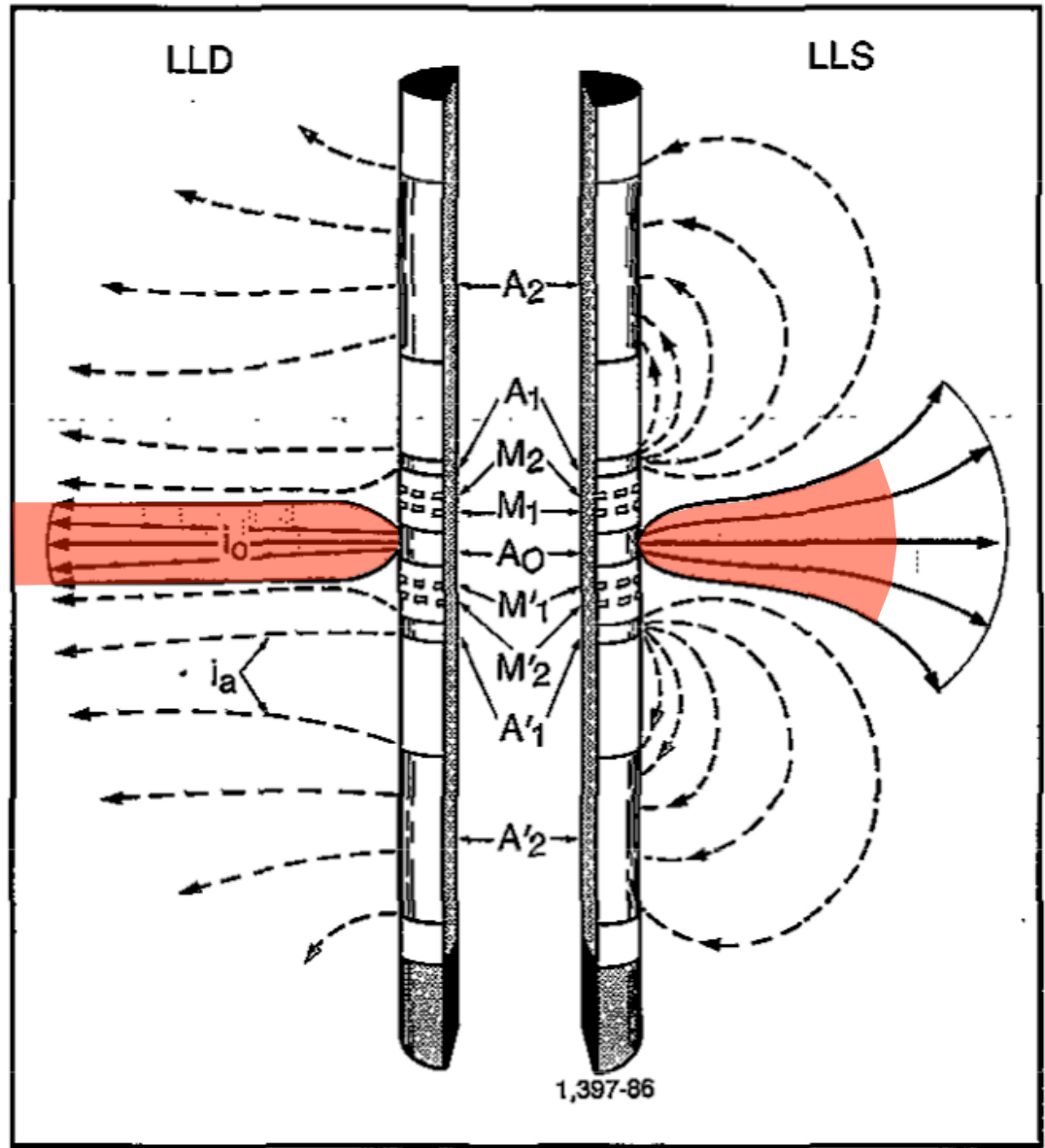
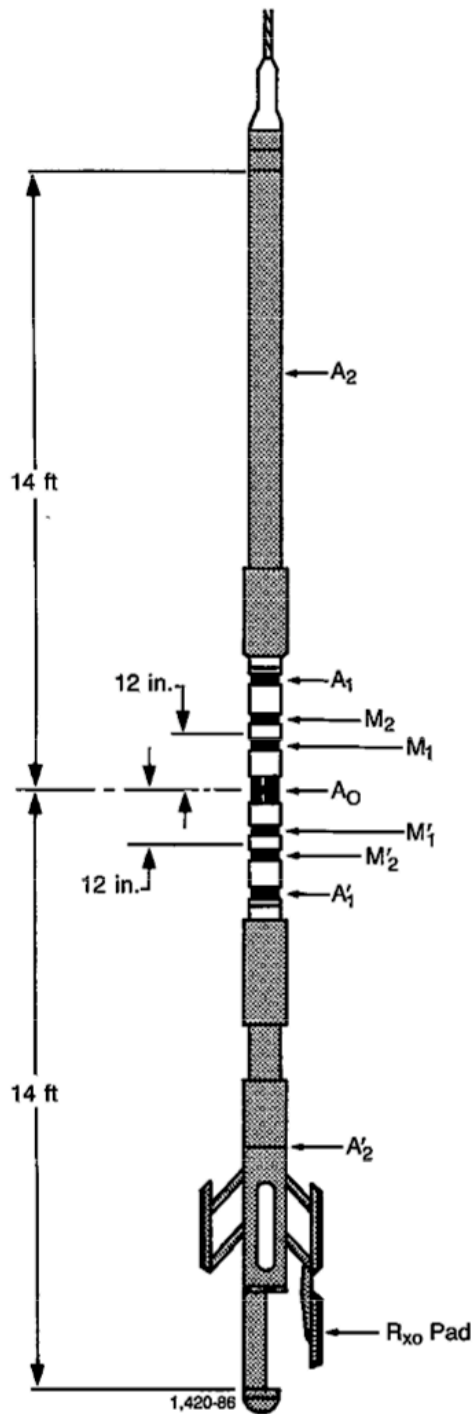


Fig. 7-13—Schematic of the Dual Laterolog.

Magnetic susceptibility χ

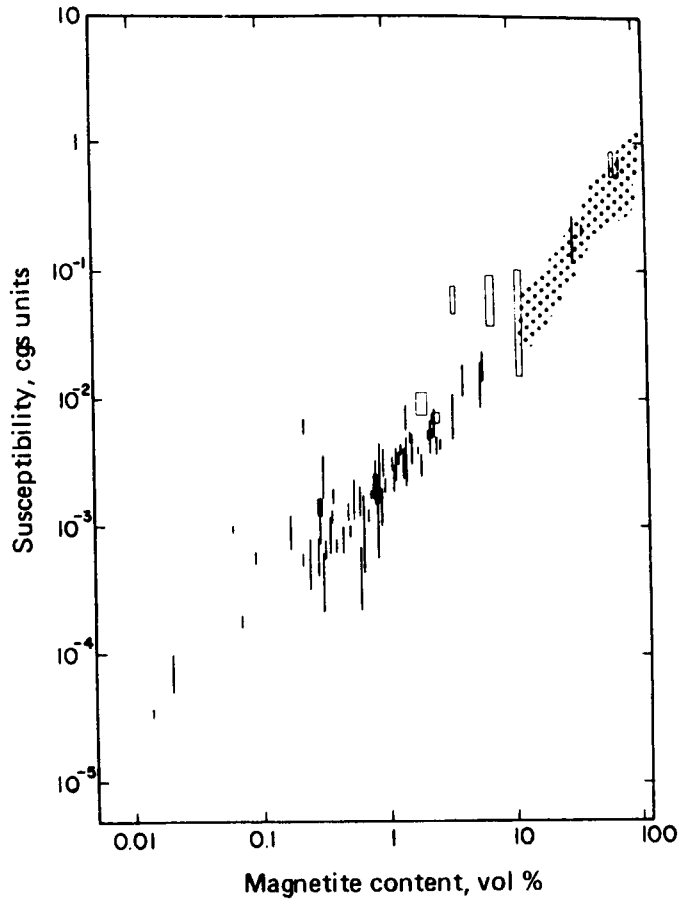
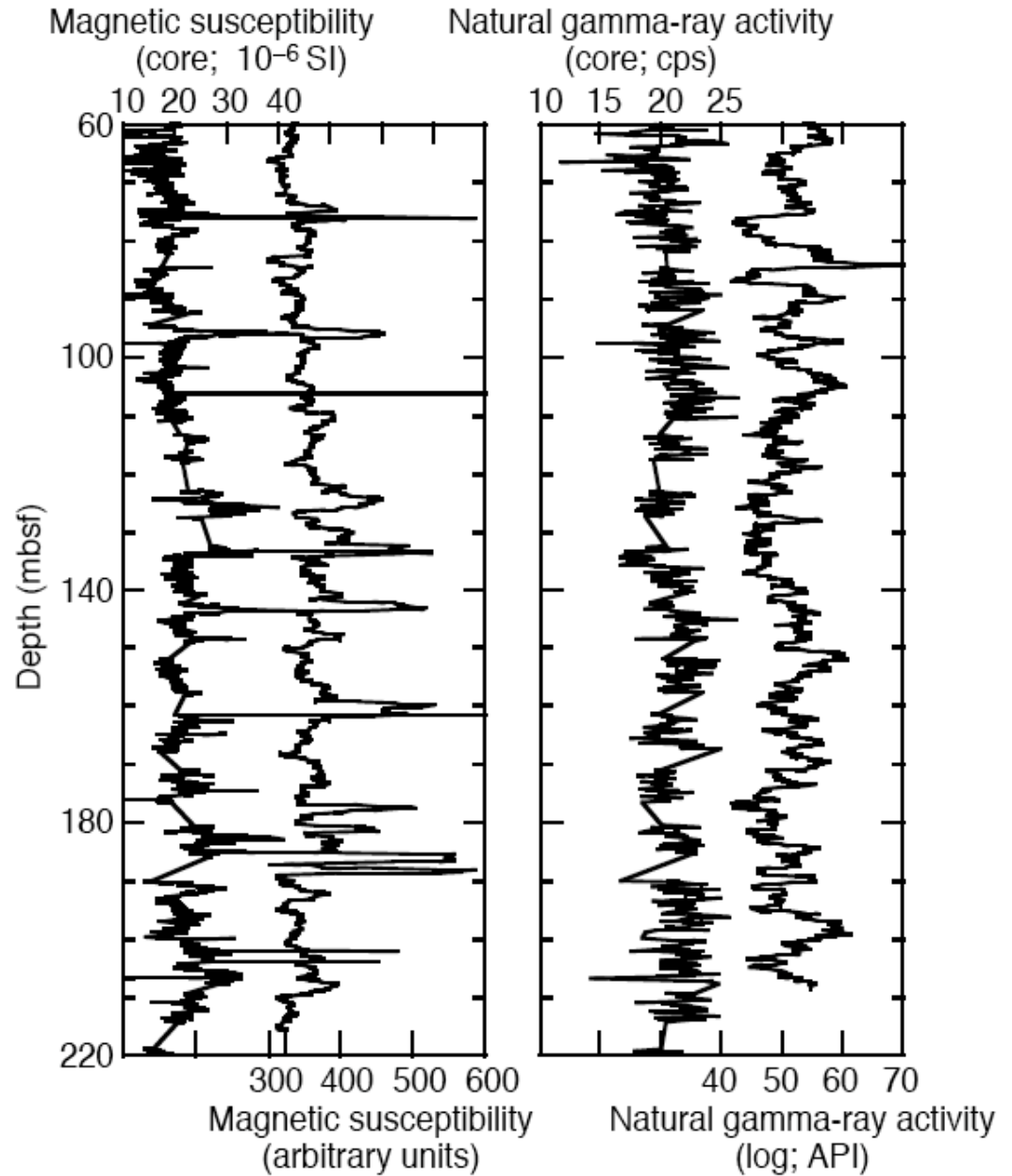
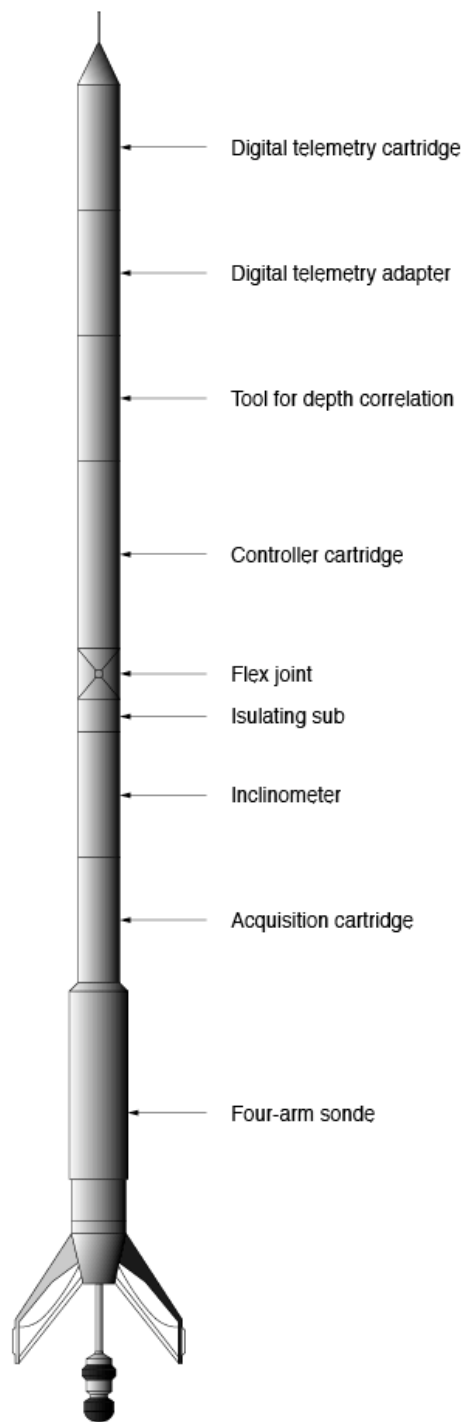


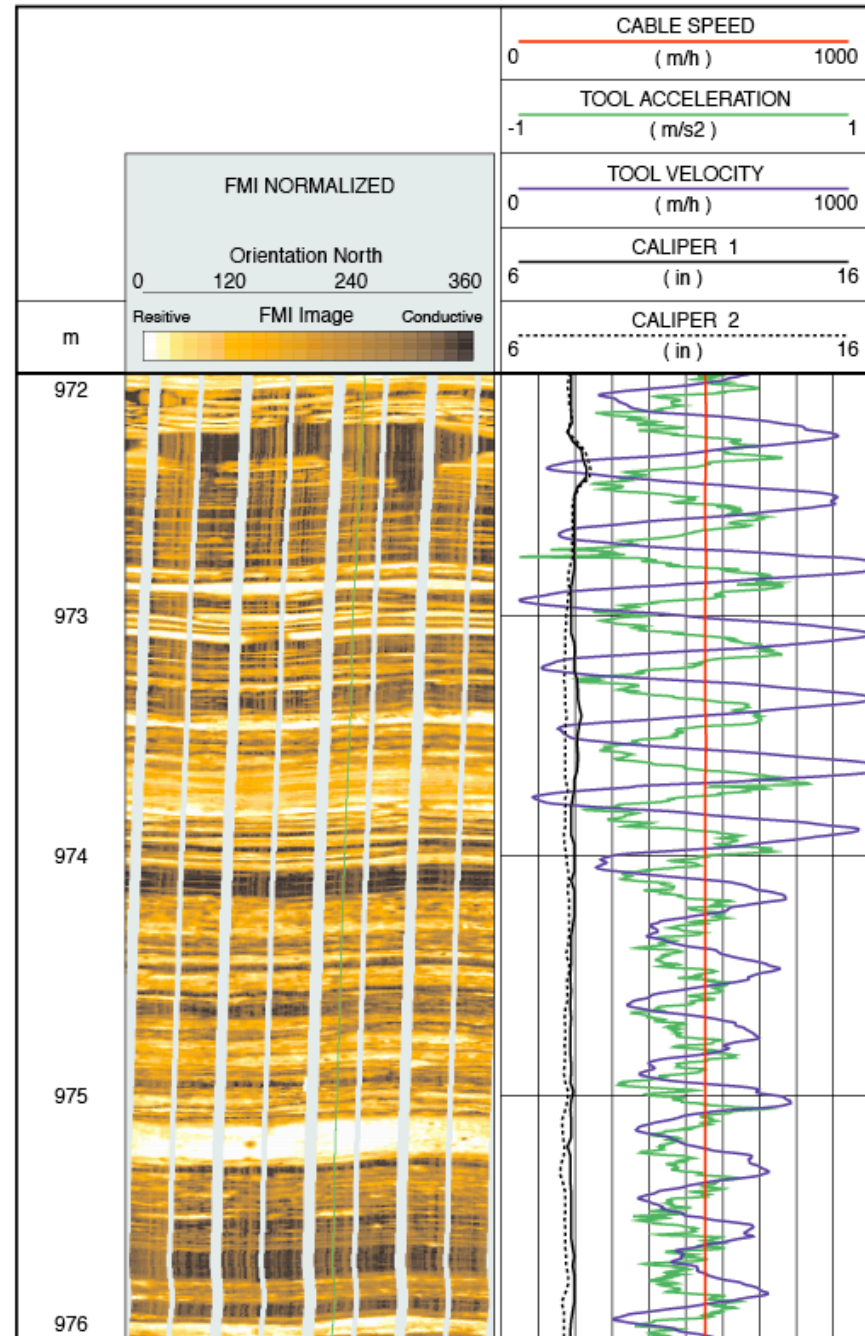
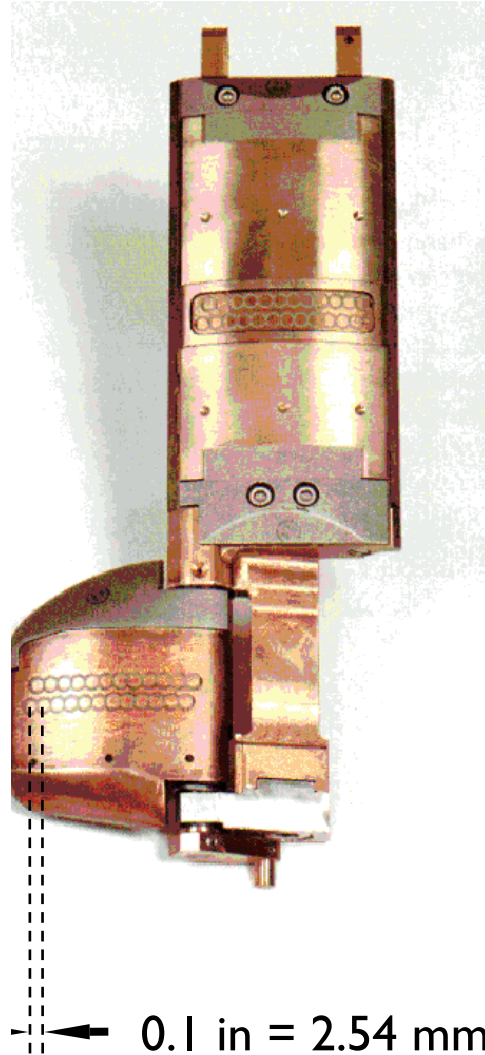
Figure 5.77 Relation between susceptibility and magnetite content of a variety of rocks and ores compiled by Lindsley et al. (1966). Vertical lines show range due to anisotropy; box widths show variation among samples



- Nuclear Logs
- Sonic
- Electrical / magnetic
- Imaging
 - Electrical
 - Acoustic
- Vertical seismic profile (VSP)
- Logging While Drilling
- Examples



192 electrodes



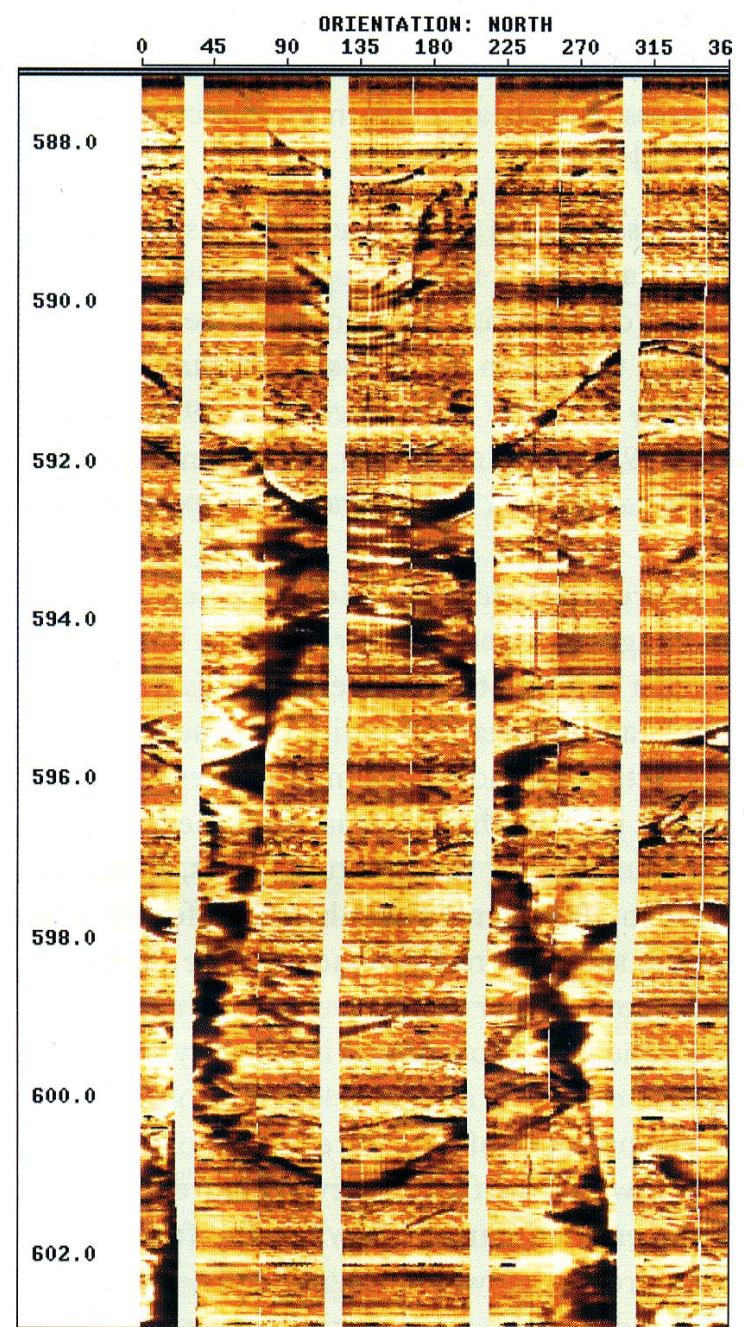
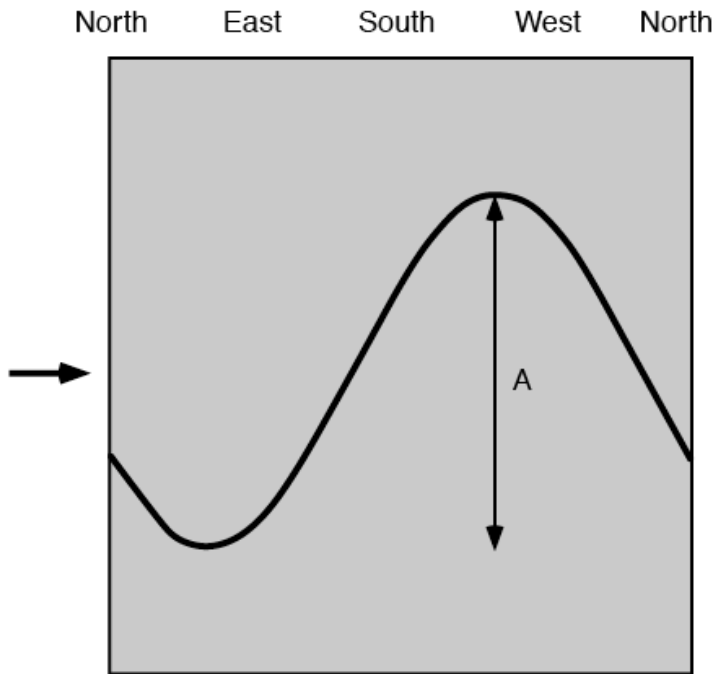
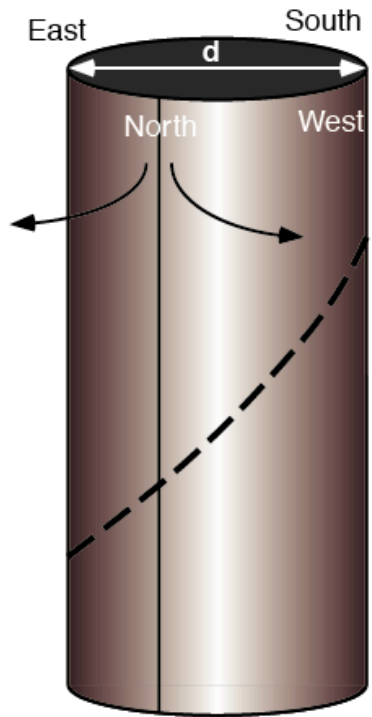
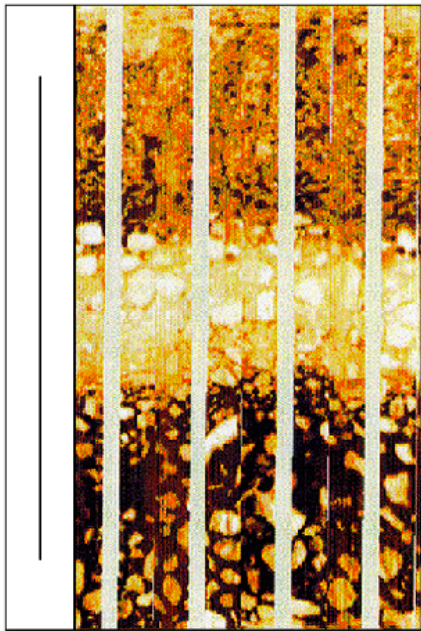


Figure 2.2.27. FMI images over a layered carbonate sequence with at least two distinct planar fracture sets, on dipping towards SSW, the other dipping steeply towards NNE.

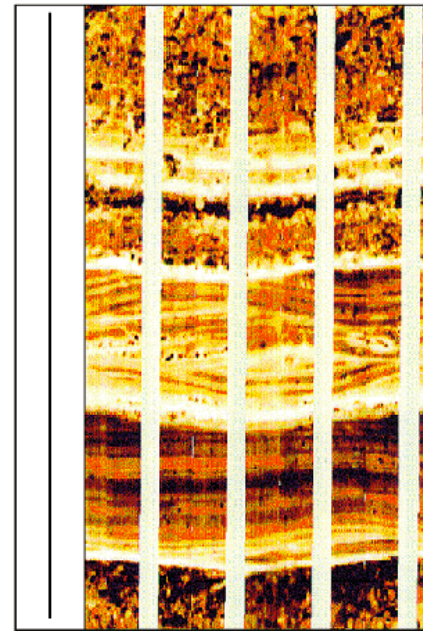
1m



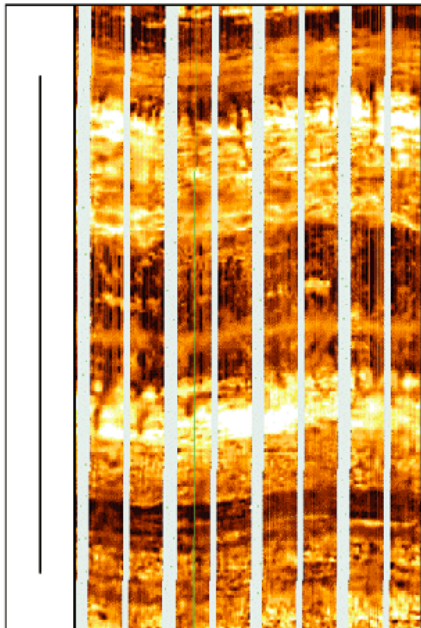
Conglomerate in debris flow



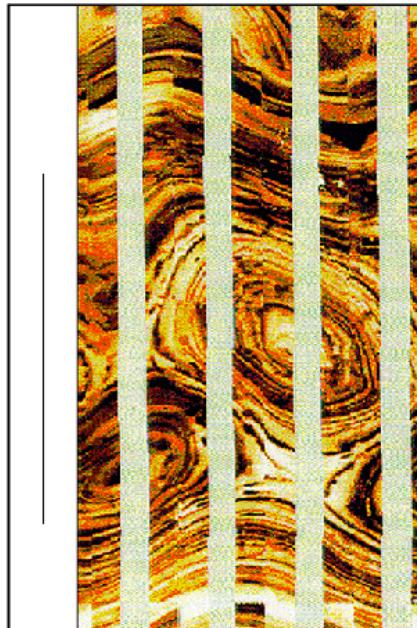
Rip-up clasts in fluvial channel



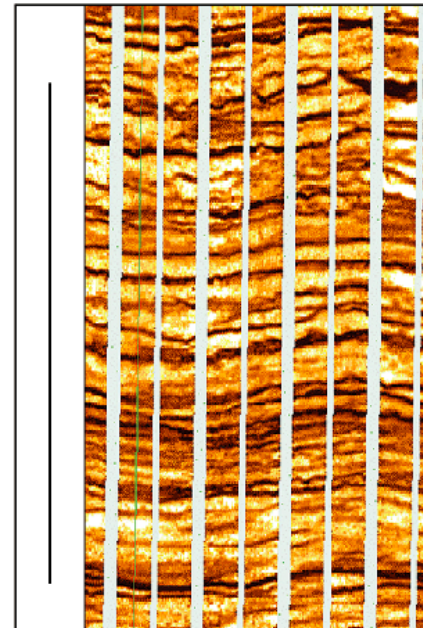
Cross-beds in tidal sandstone



Burrowing in shelf deposit



Overturned sand layers in slump



Stylolites in a limestone

are presented as a continuous record. Features are easily followed throughout any interval of the borehole.

TOOL DESCRIPTION

A schematic of the televiwer logging tool is shown in Figure 1. High frequency sound (about 2 megahertz) from an acoustic transducer, pulsed at a rate of about 2000 times a second, is used to survey the borehole walls. A flux-gate magnetometer senses the earth's magnetic field and provides orientation information in open hole. A motor

rotates the transducer and flux-gate magnetometer within the tool about three times a second.

Although the transducer has a diameter of only a half-inch, the sound emitted is confined to a very narrow beam because of the high operating frequency. Pulses of sound are directed toward the borehole wall where a portion of each pulse is reflected back toward the transducer. The transducer converts the reflected sound pulses into electrical signals; these are utilized at the surface for producing the televiwer log. The combination of transducer rotation with a continuous

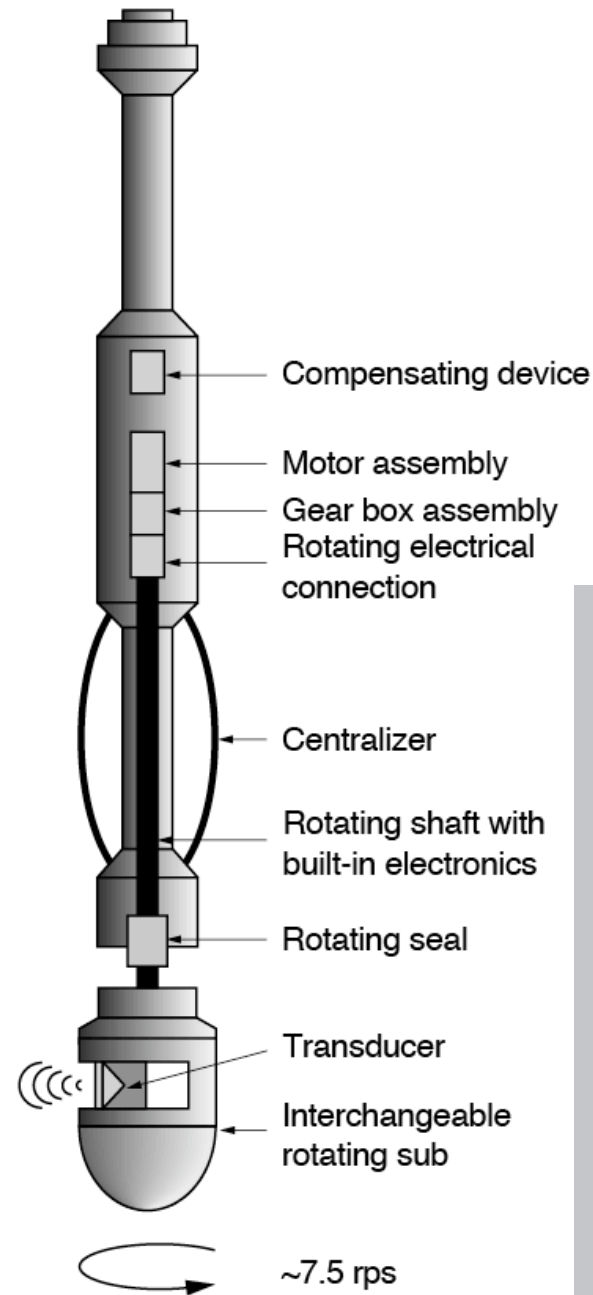
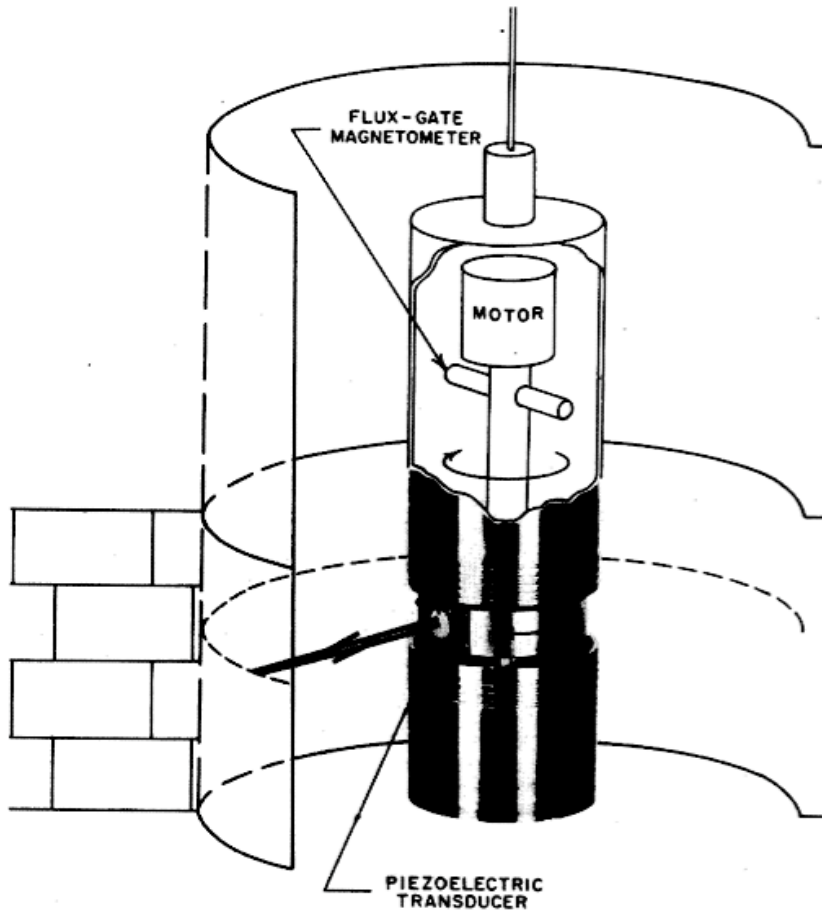
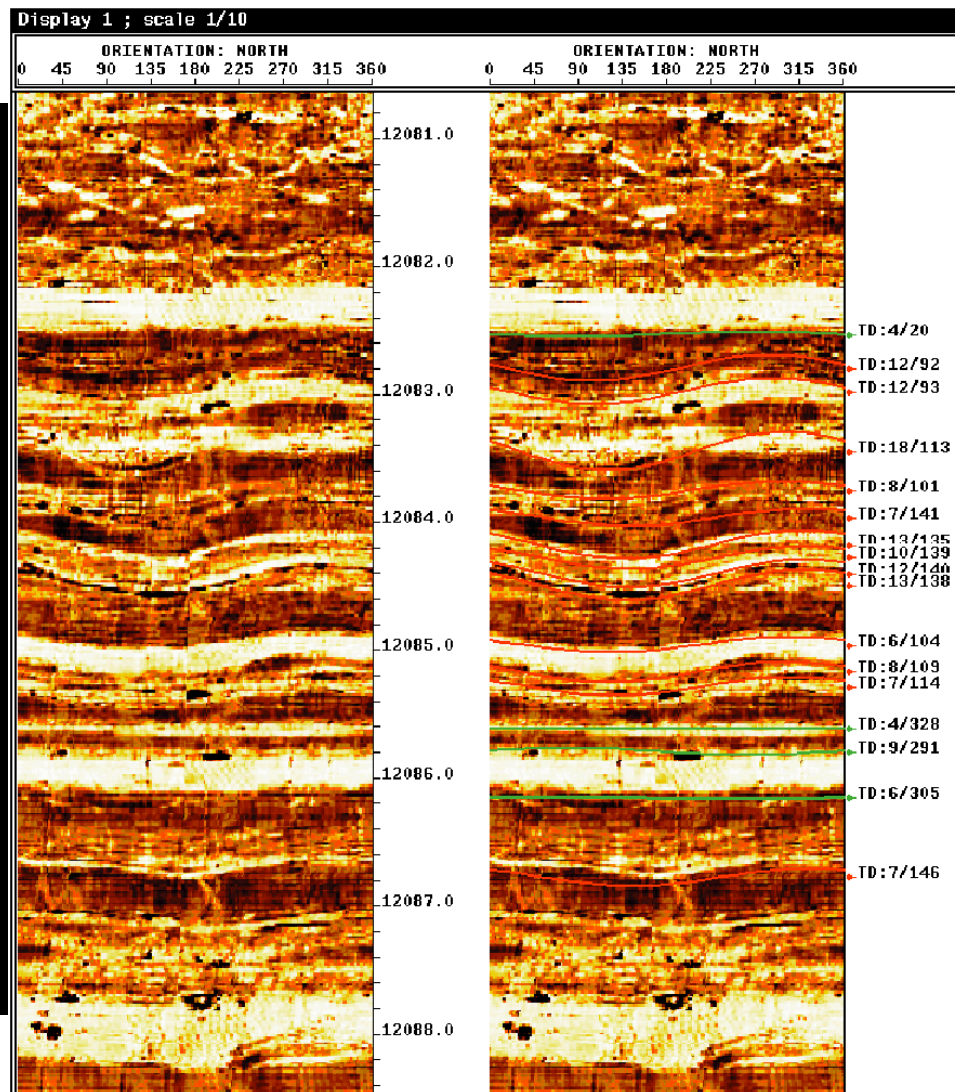
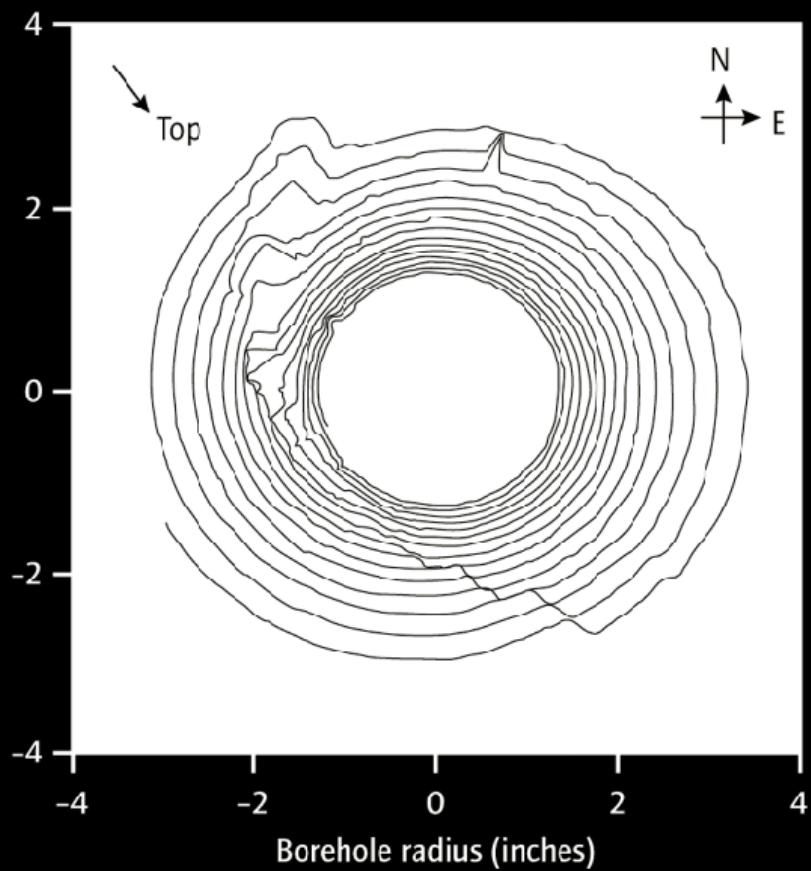
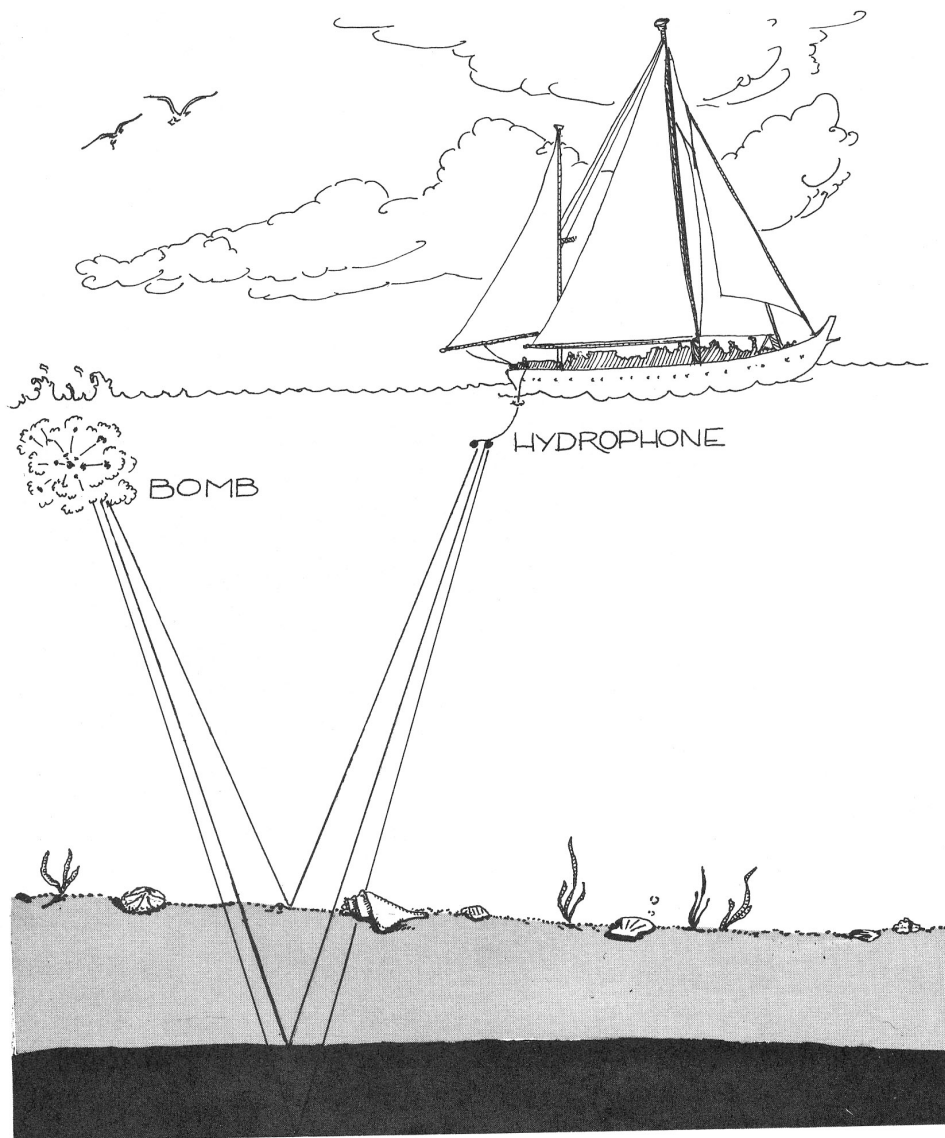


FIG. 1. Schematic layout of televiwer showing scanning acoustic transducer, magnetic north sensing magnetometer, and driving motor.



- Nuclear Logs
- Sonic
- Electrical / magnetic
- Imaging
- Vertical seismic profile (VSP)
- Logging While Drilling
- Examples

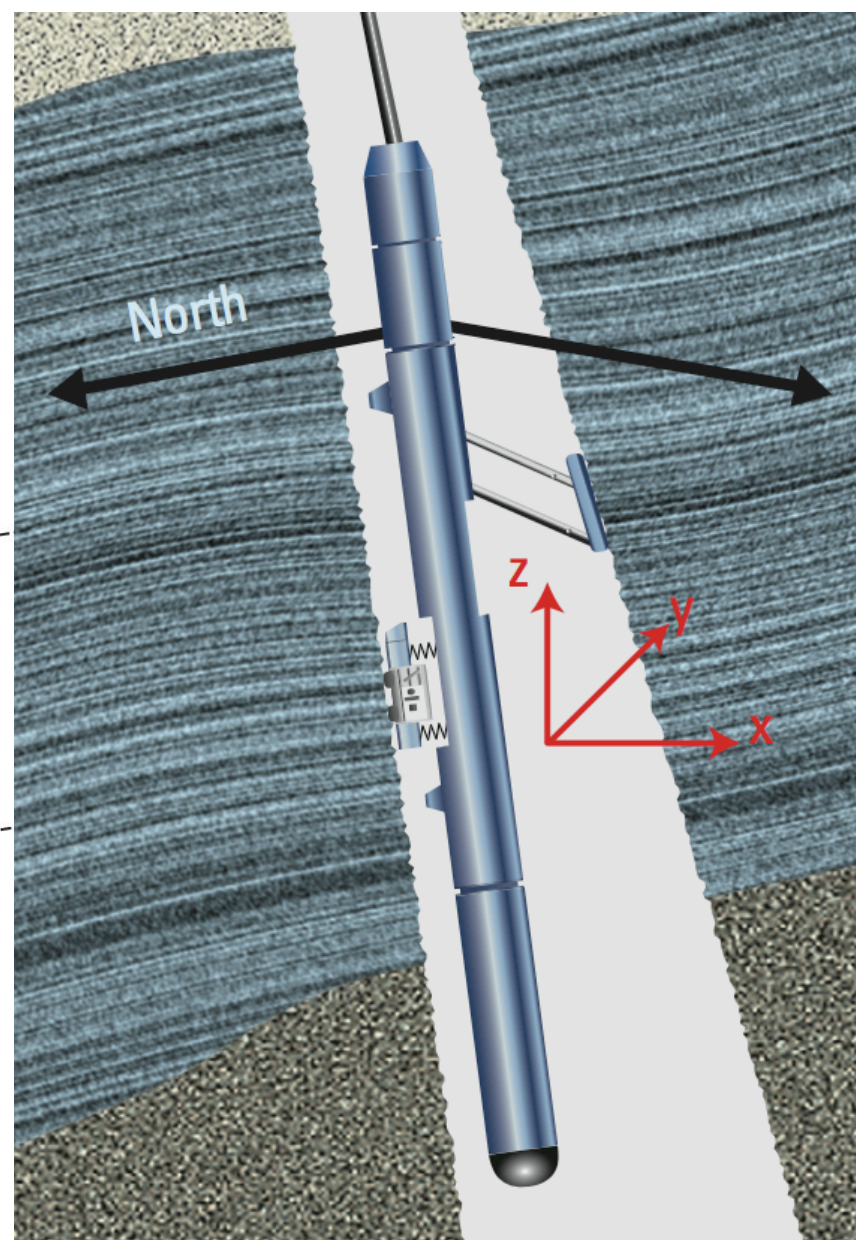
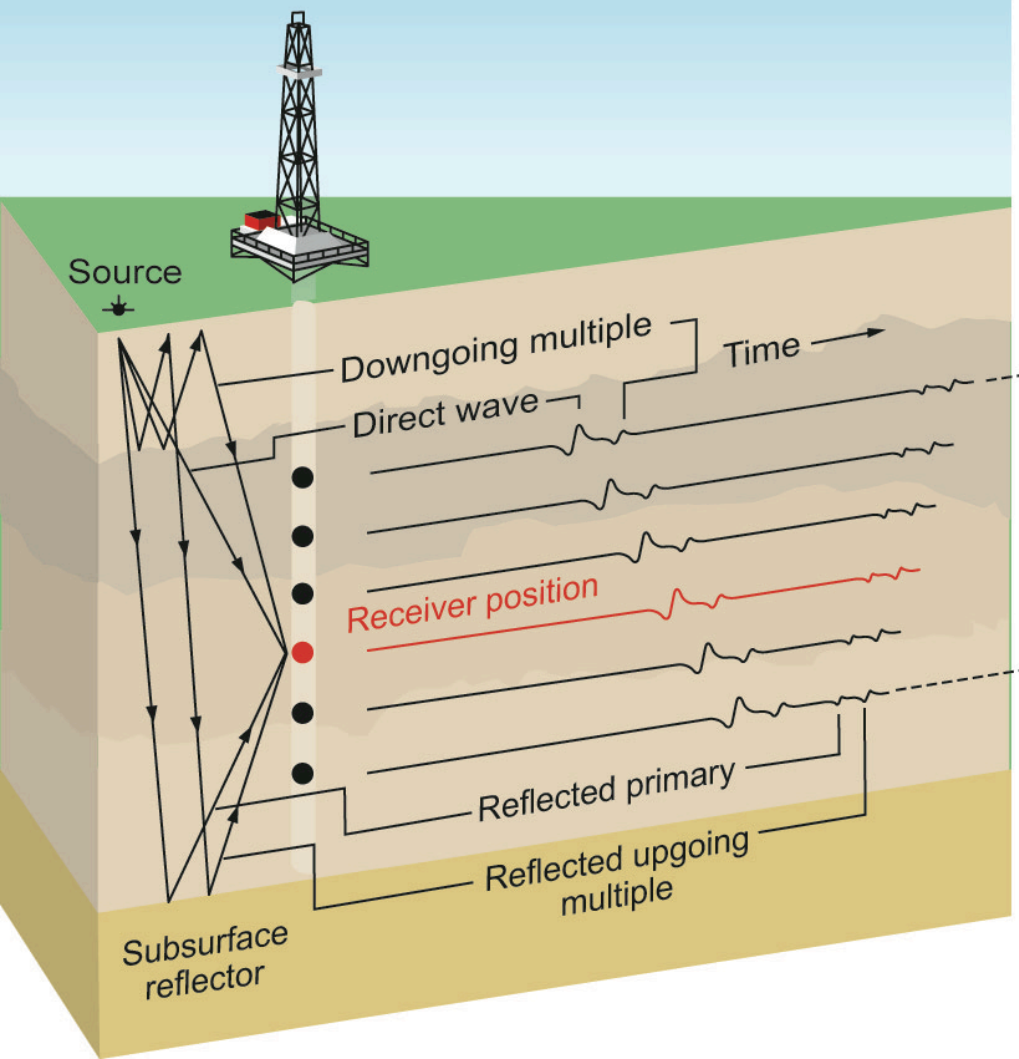


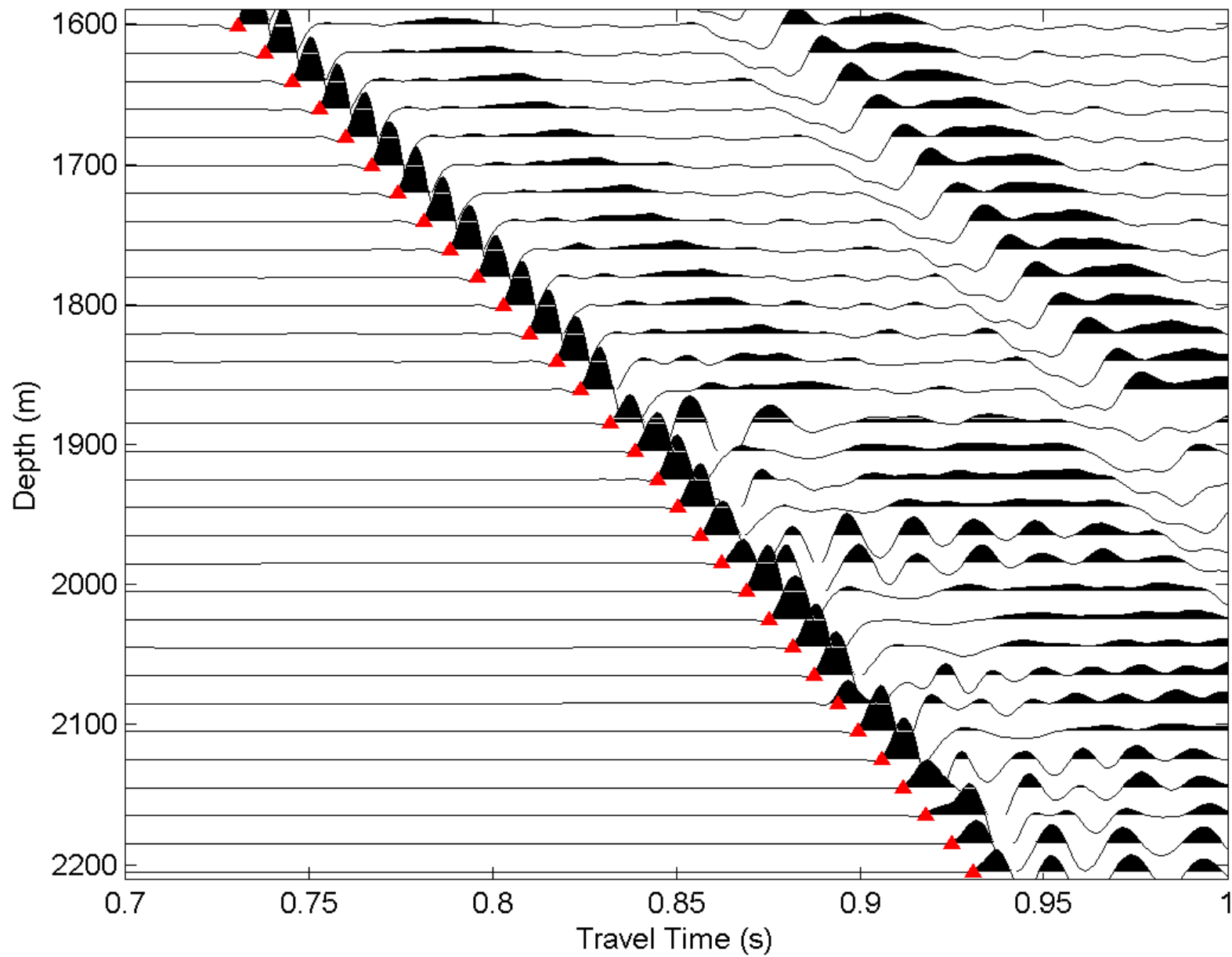
Explosion wave paths during seismic reflection.

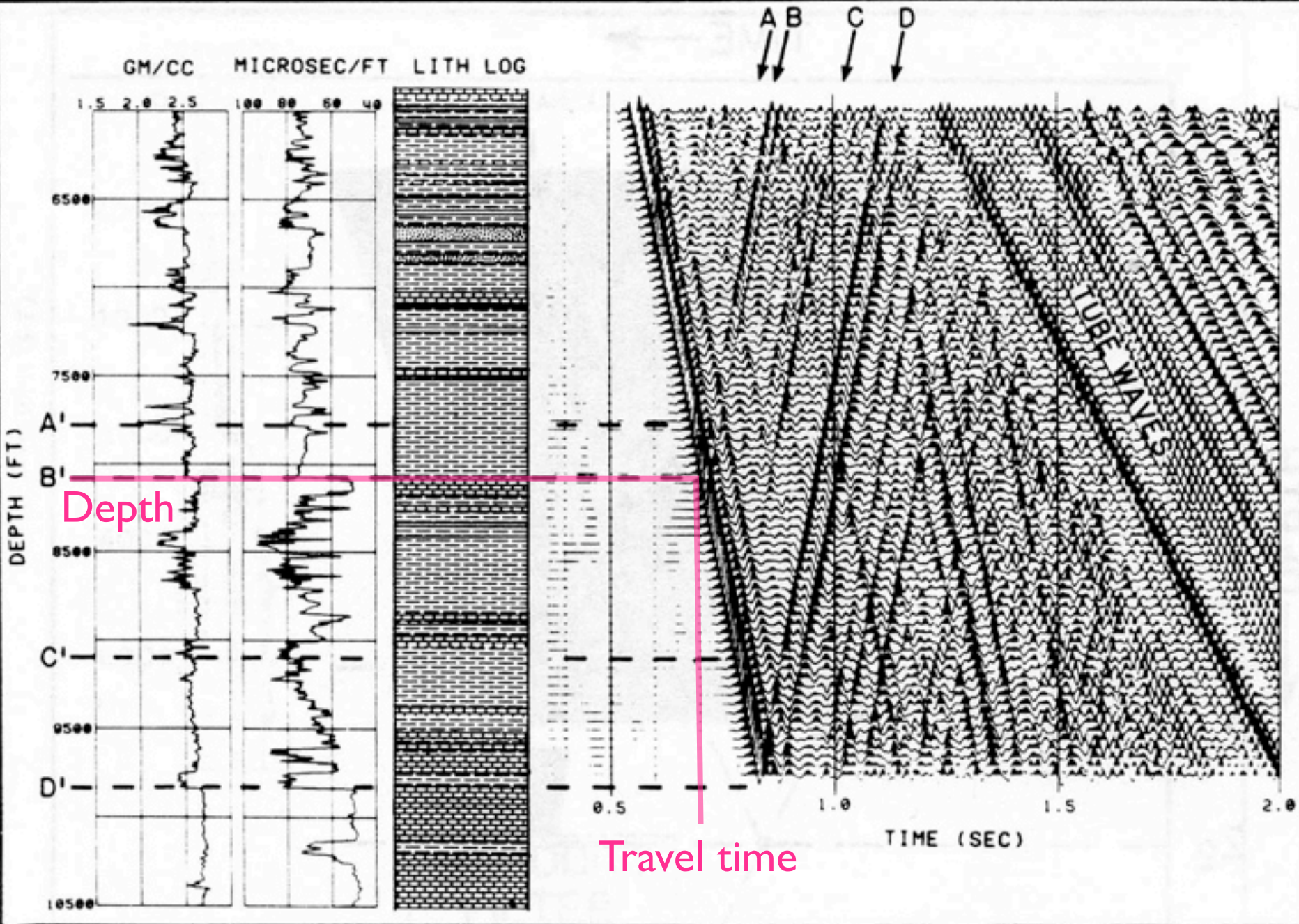


Seismic shooting went on at half-hour intervals.

Zero-offset VSP



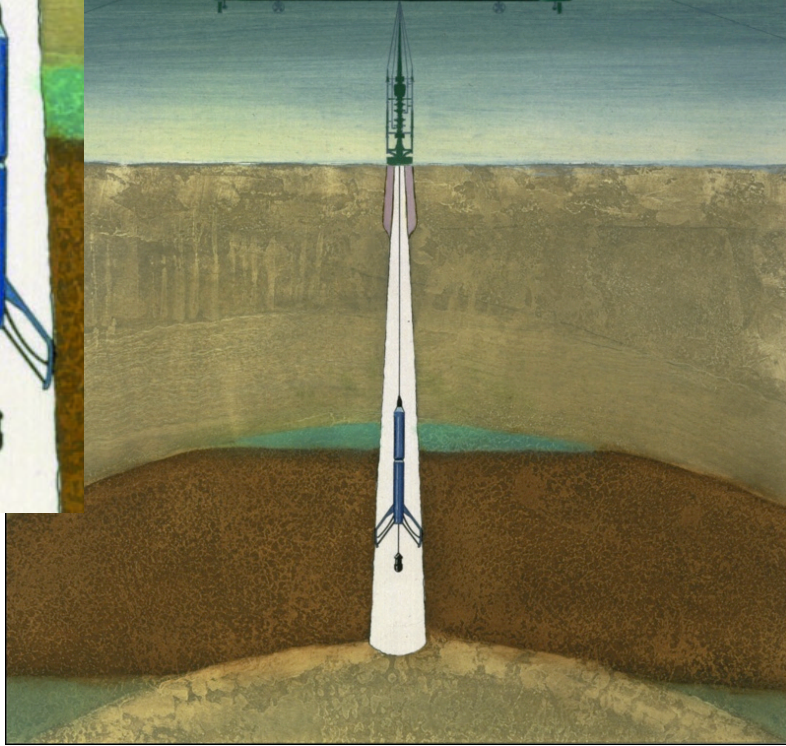
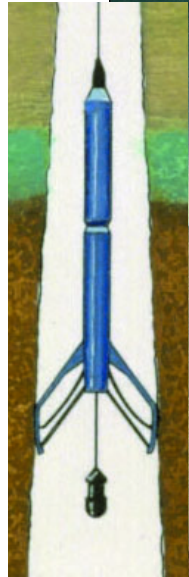




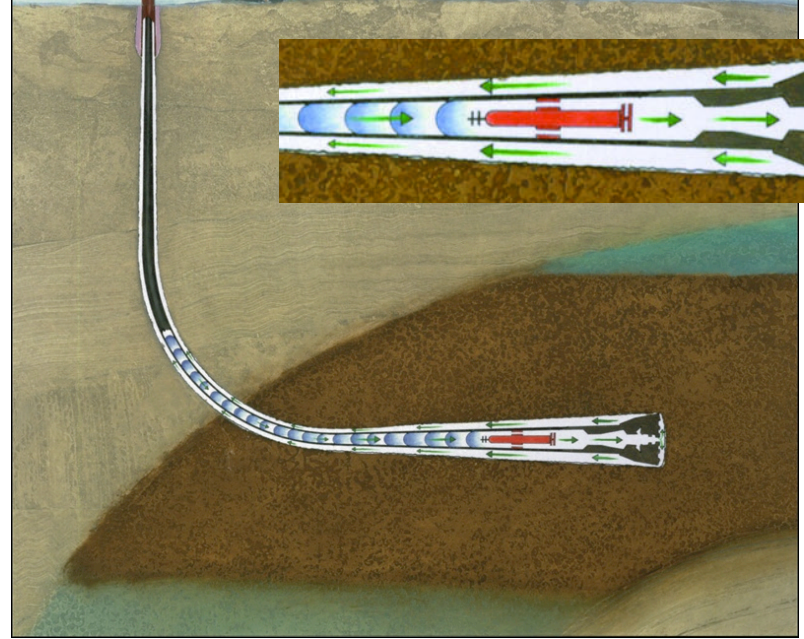
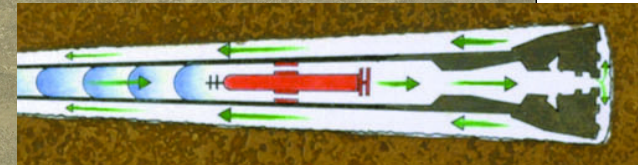
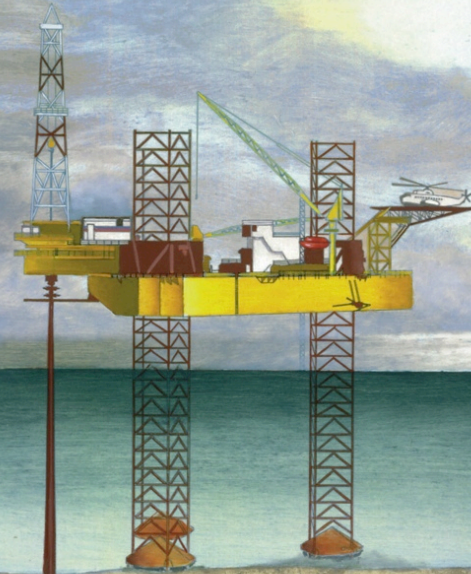
After Hardage (1985)

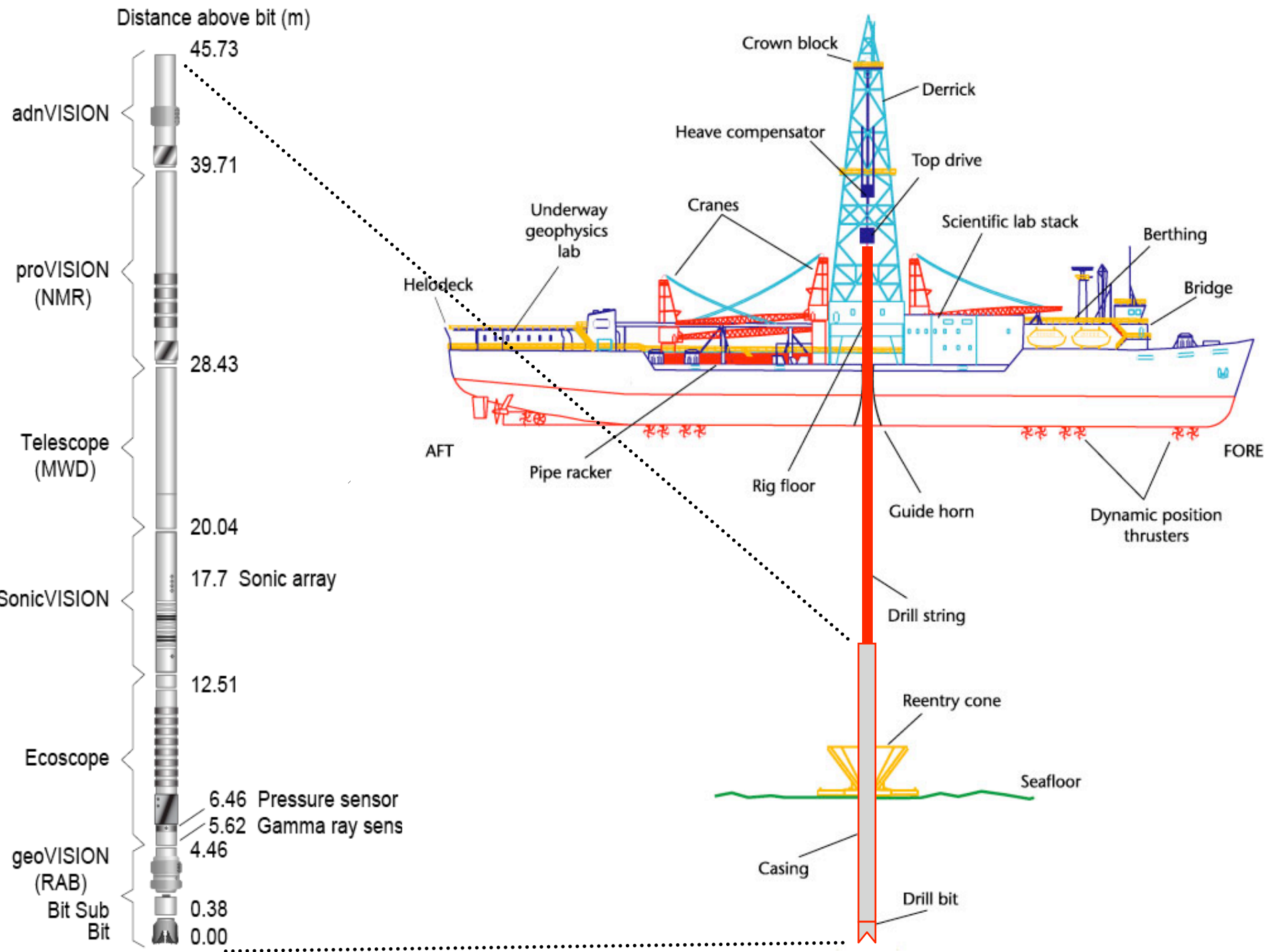
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Wireline logging

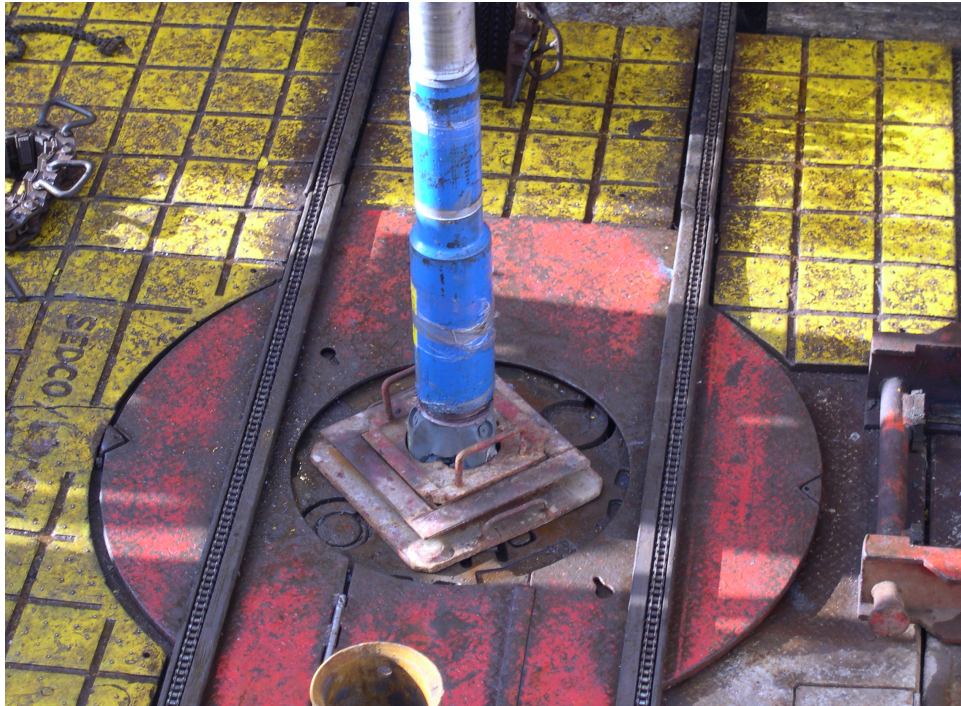


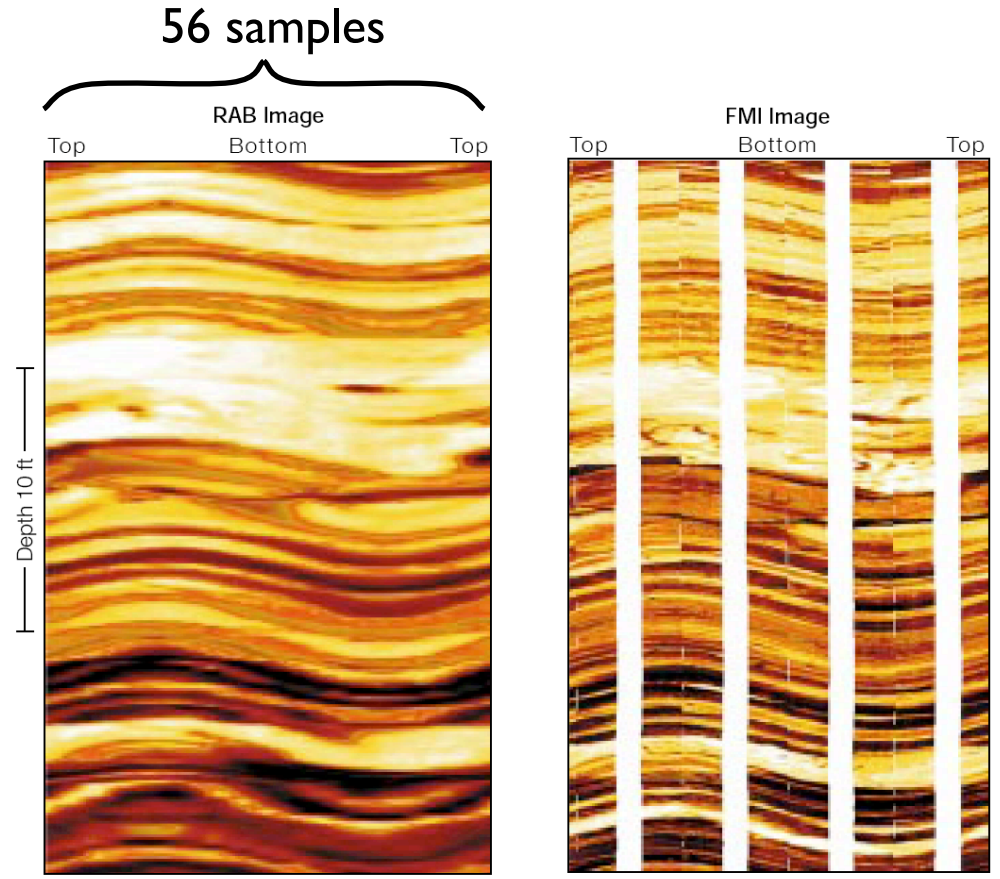
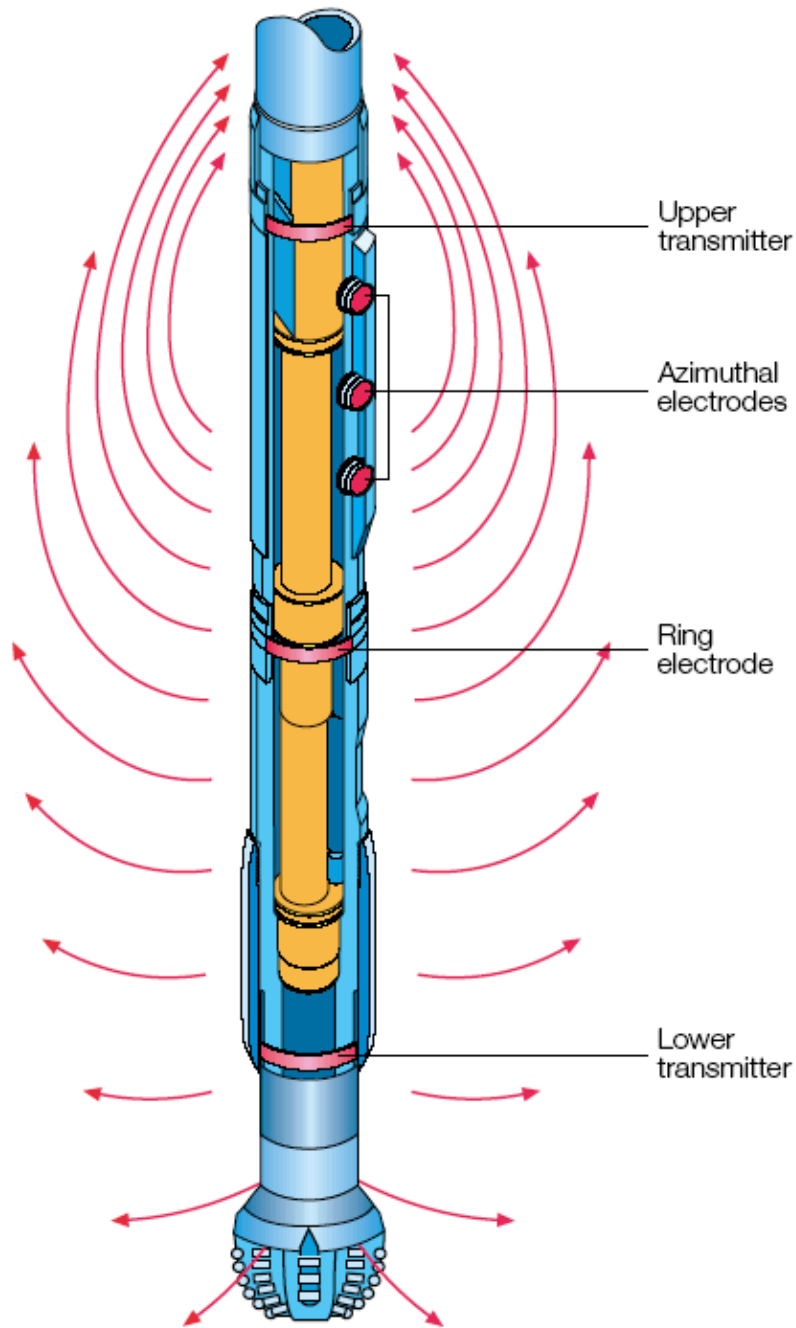
Logging while drilling (LWD)









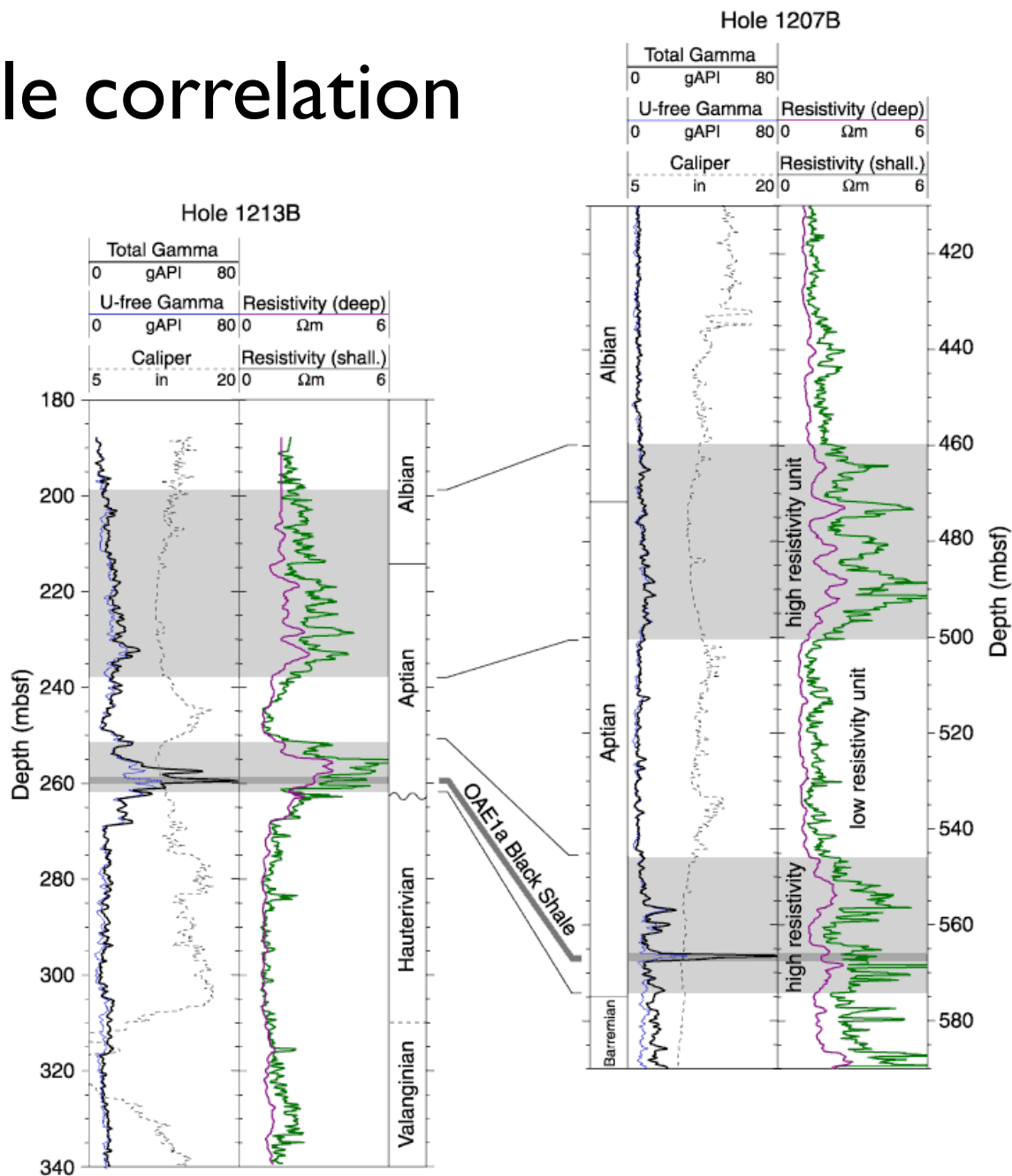


□ RAB and FMI images of dipping beds. Both RAB and FMI images show large-scale events that are several feet long. However, the resolution of the FMI image is much better. Beds less than about 4 in. [10 cm] thick are not clearly seen on the RAB image.

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Figure F45. Downhole gamma radiation and resistivity logs from Holes 1207B and 1213B illustrating the form and setting of the Aptian Oceanic Anoxic Event (OAE1a) black shale.

Hole-to-hole correlation



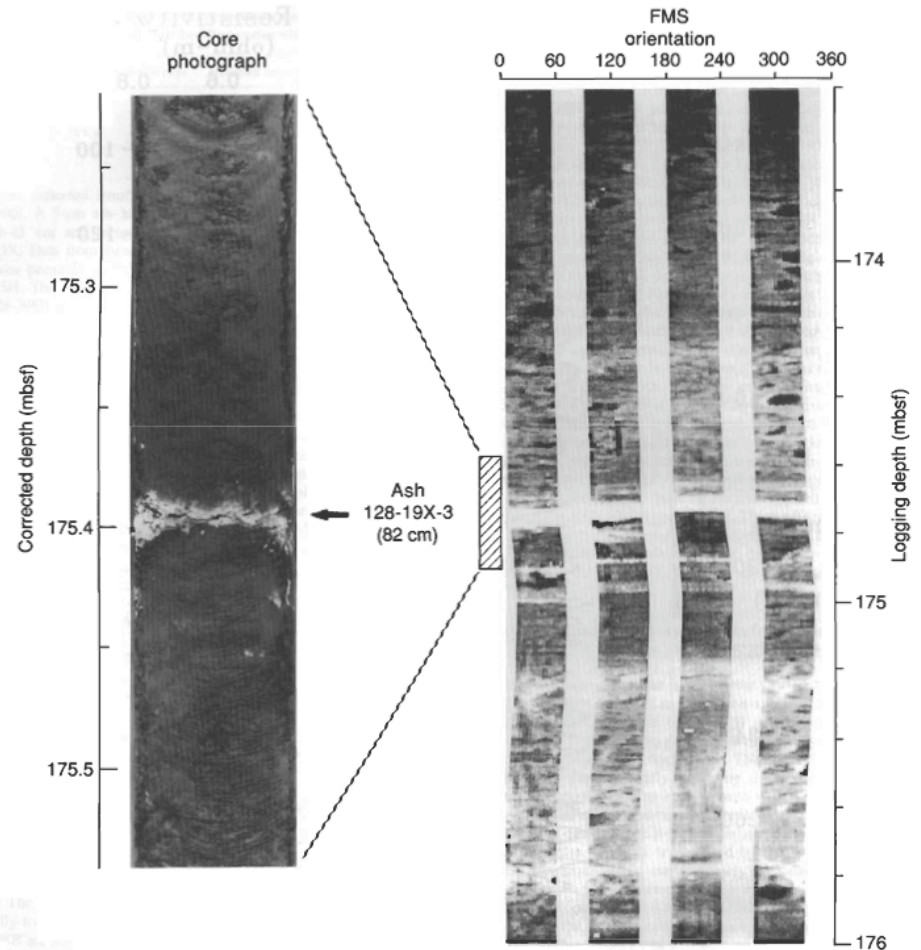
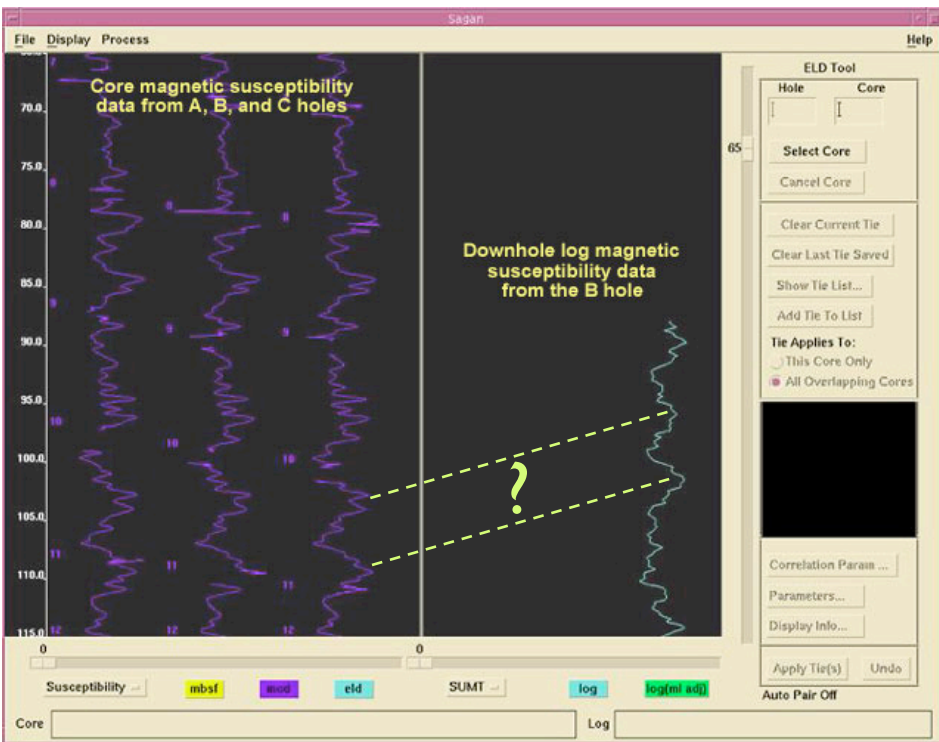
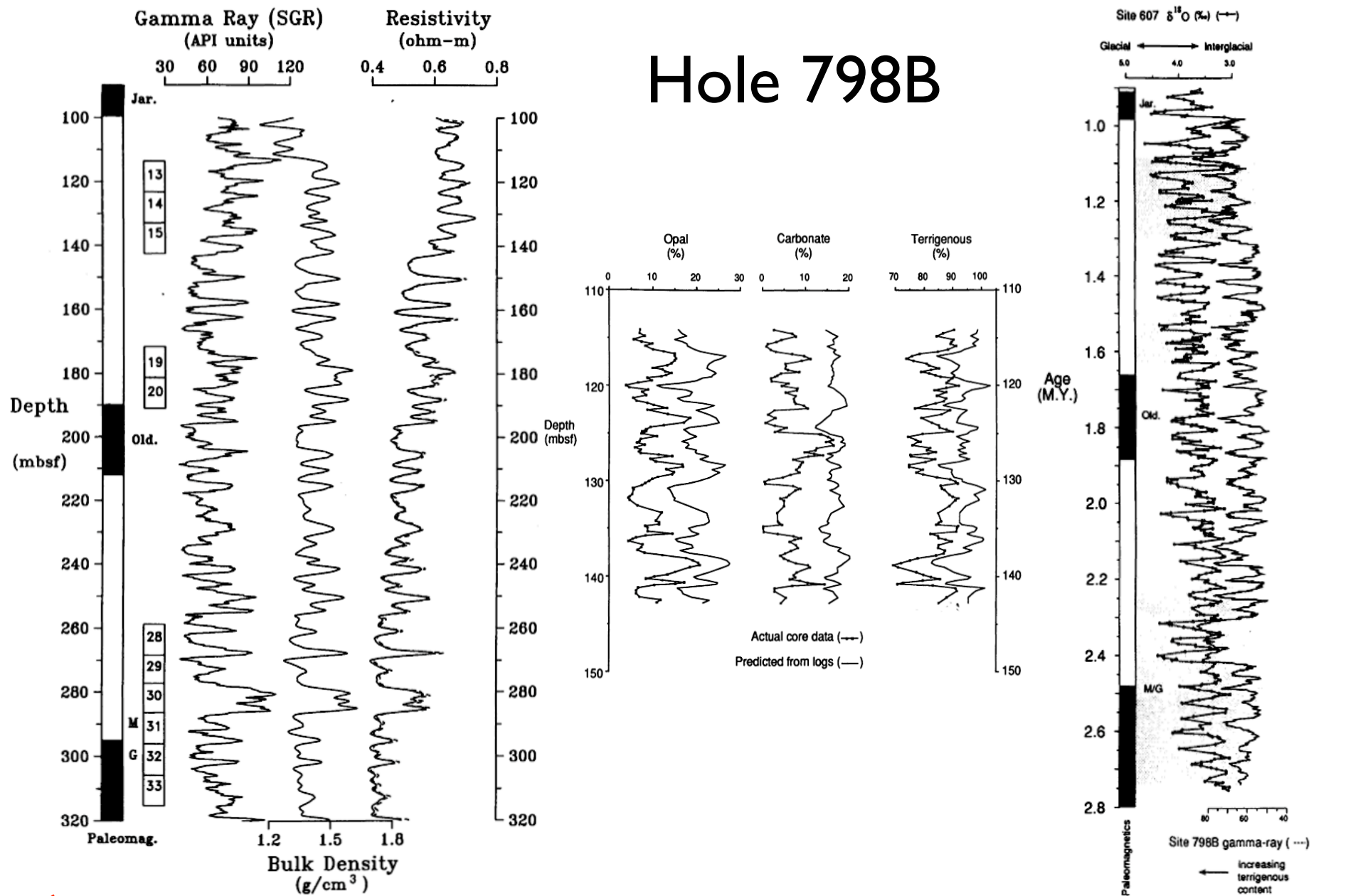


Figure 8. Example of core-log correlations using volcanic ashes. Core photograph is of ash layer in Core 128-798B-19X-3 (82 cm) at 175.40 mbsf (depths corrected for core expansion). The formation microscanner (FMS) microresistivity images of this interval are shown at right. The images are azimuthal (0° – 360° magnetic declination, left-to-right) traces of four orthogonal pads which are pressed against the borehole wall. The ash layer appears as a bright (highly resistive) band at a 174.70 mbsf logging depth.

Hole 798B



← Opal from diatoms (Glacial) Terrigenous material (Interglacial) →

Figure 14. Correlation of the Hole 798B SGR gamma-ray log with the marine $\delta^{18}O$ record from Site 607 in the North Atlantic (Raymo et al., 1989; Ruddiman et al., 1989). The SGR time series was initially constrained using the paleomagnetic reversal boundaries. Minor adjustments to the SGR time series were performed using the CORPAC correlation program to improve its alignment with the Site 607 $\delta^{18}O$ record. The age-depth plot resulting from this process is shown in Figure 15.

Equivalent Time Resolution of Logging Tool Apertures

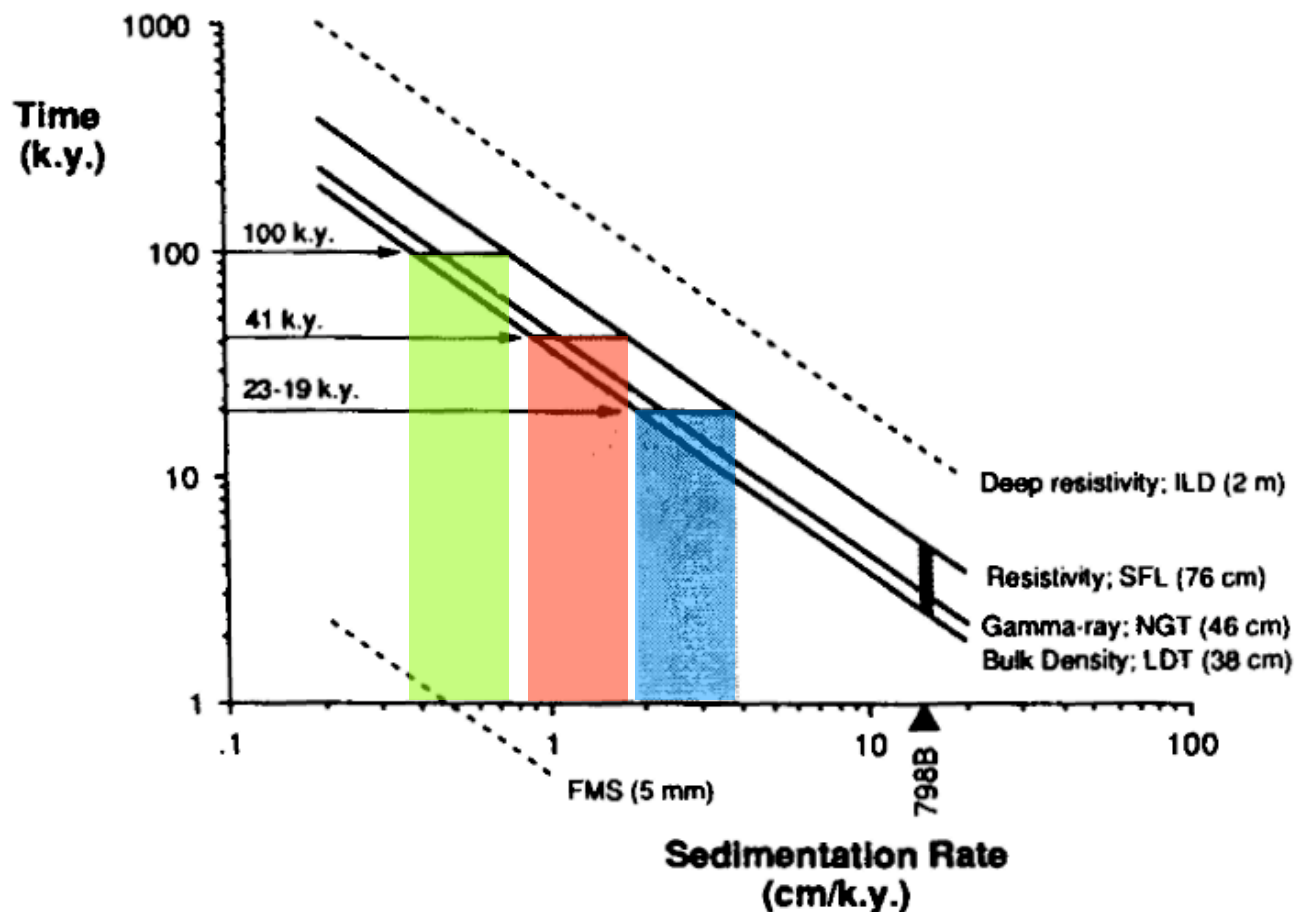


Figure 5. Plot of the temporal resolution of several logging tools as a function of sedimentation rate. Temporal resolution was calculated as vertical aperture/sedimentation rate. Minimum sedimentation rates required to resolve 100 k.y., 41 k.y., and 23–19 k.y. in time are shown as shaded columns. Note that these sedimentation rates are only sufficient to resolve a time interval (Δt) equivalent to 100 k.y., 41 k.y., and 20 k.y.

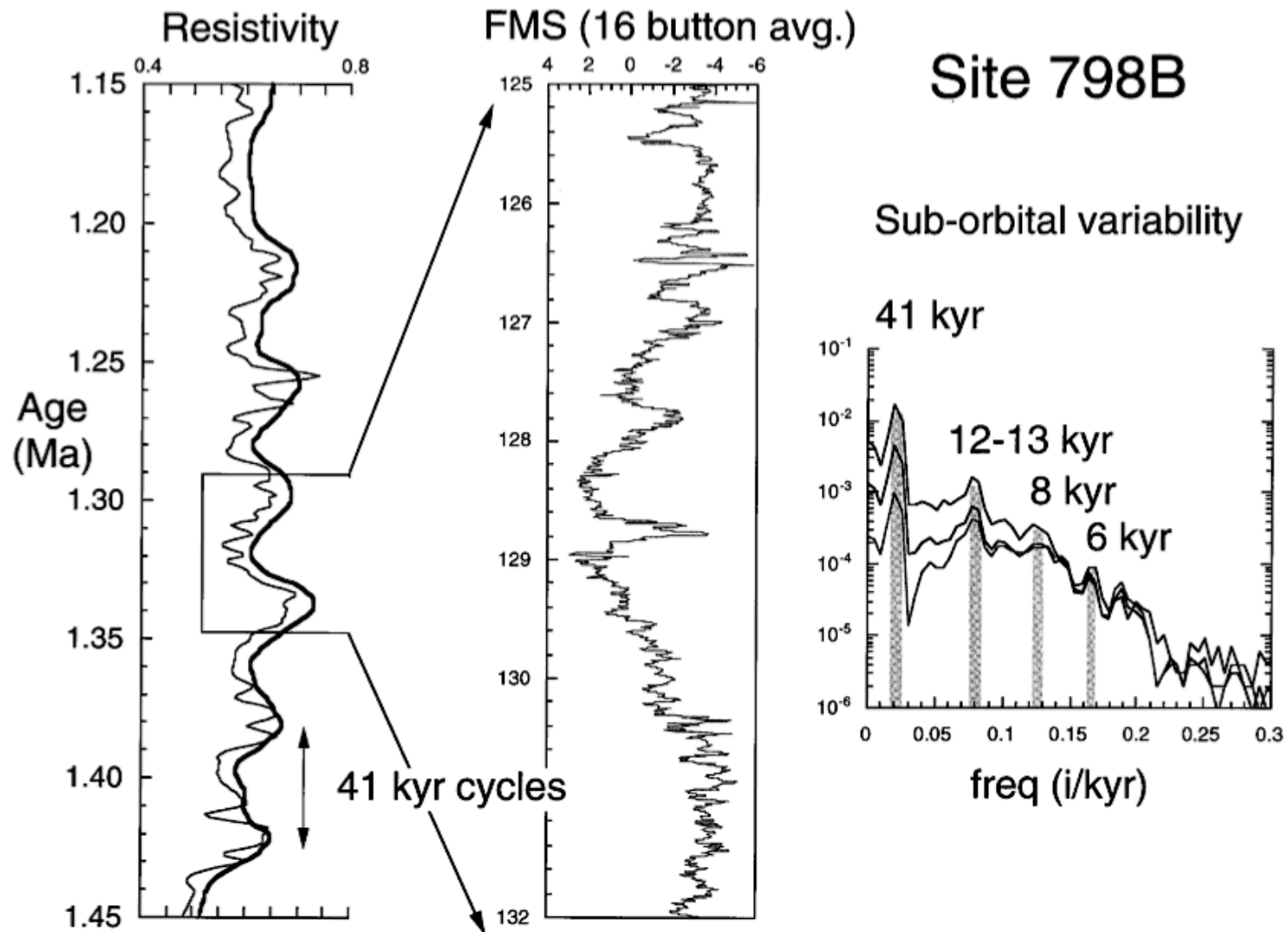


Figure 9. Comparison of data from three wireline resistivity tools: shallow and deep resistivity and the averaged FMS record that show cycles at a 41,000-year orbital period and below in the comparative power spectra [after *deMenocal and King, 1995*]. The resistivity logs have been converted to age, and the averaged FMS data are plotted on relative scale over a 7-m interval. The fine vertical resolution of the FMS data allows observation of periods as short as 6000 years.

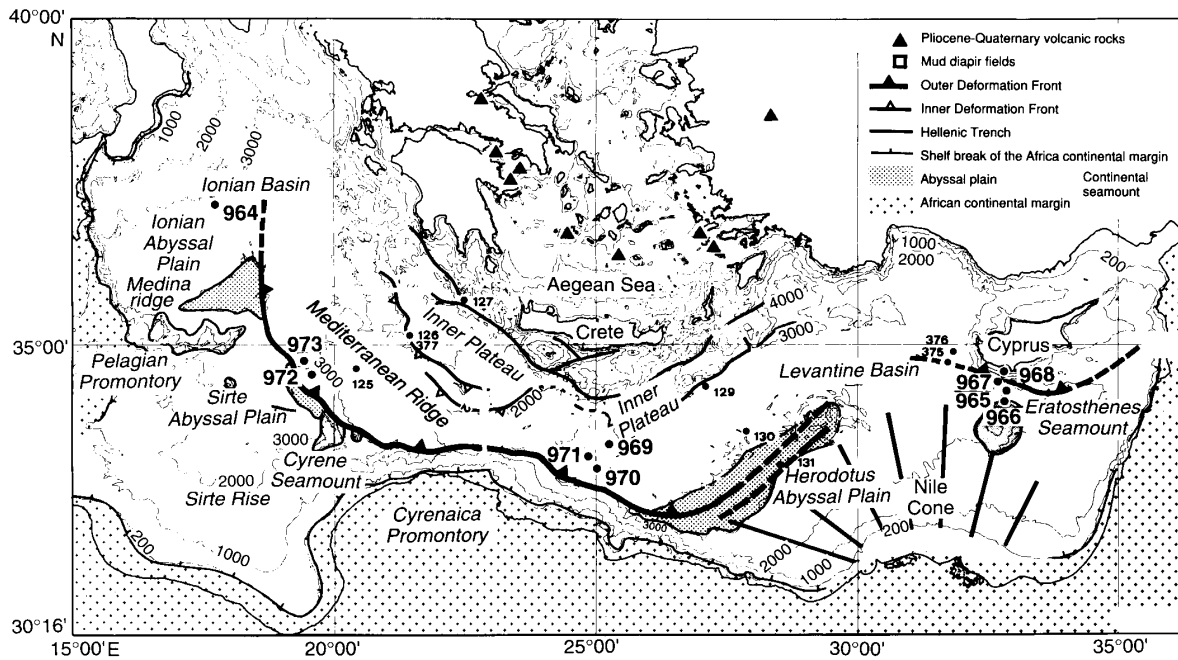


Figure 1. Outline map of the Mediterranean showing the main tectonic features and location of the sites drilling during Leg 160. DSDP sites are also shown.

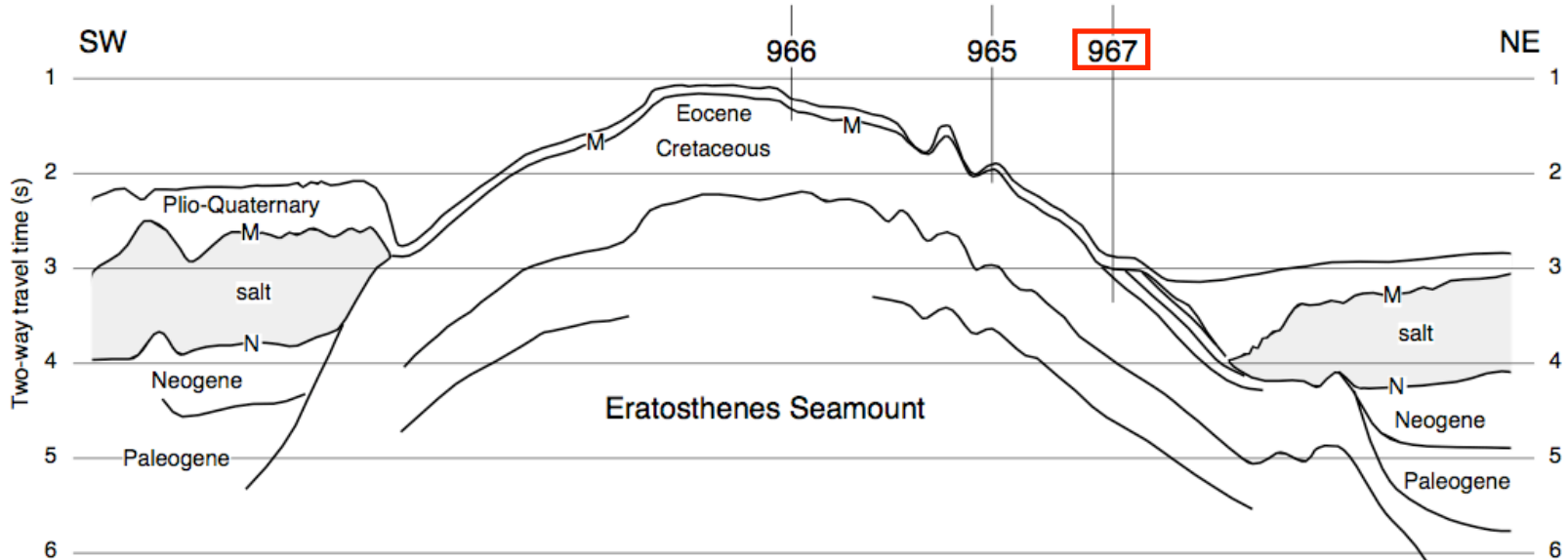


Figure 3. Interpreted multichannel seismic profile 10 (see Fig. 2 for location) extending across the Eratosthenes Seamount, illustrating the thick accumulations of Neogene and Paleogene sediments in the adjacent basin. The drill sites are projected onto the profile. Note that the seamount comprises mainly Cretaceous and older strata.

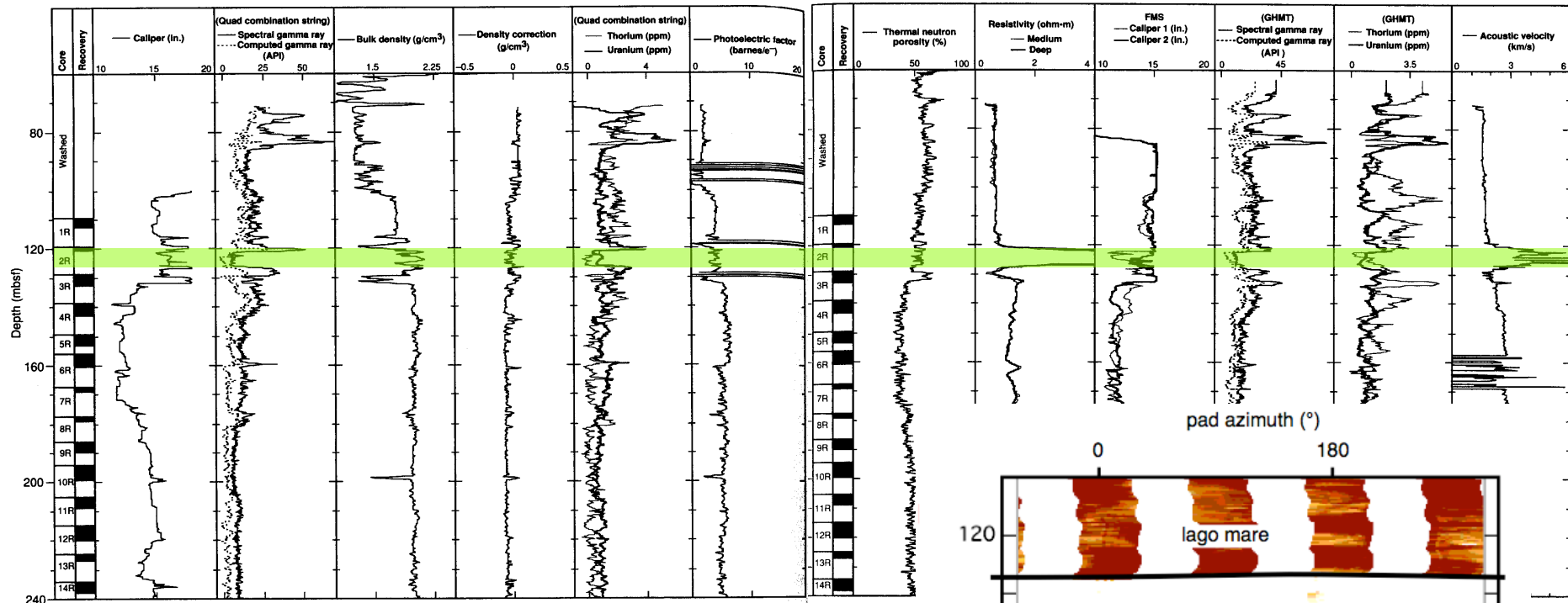


Figure 63. Hole 967E Quad combination tool and FMS (4-arm) caliper results.

Hole 967E
average
core
recovery
15%

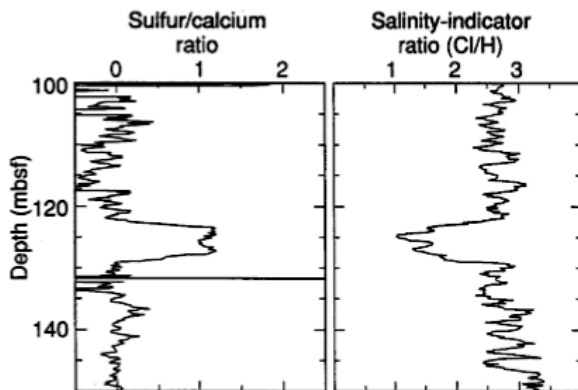


Figure 18. Example of a 4-m-thick layer with high sulfur/calcium and low chlorine/hydrogen ratios from the geochemical log, identifying it primarily as gypsum in ODP Hole 967C in the eastern Mediterranean Sea [from *Emeis et al.*, 1996]. The logs provided critical data in identifying this early basin deposit that was not recovered during coring operations.

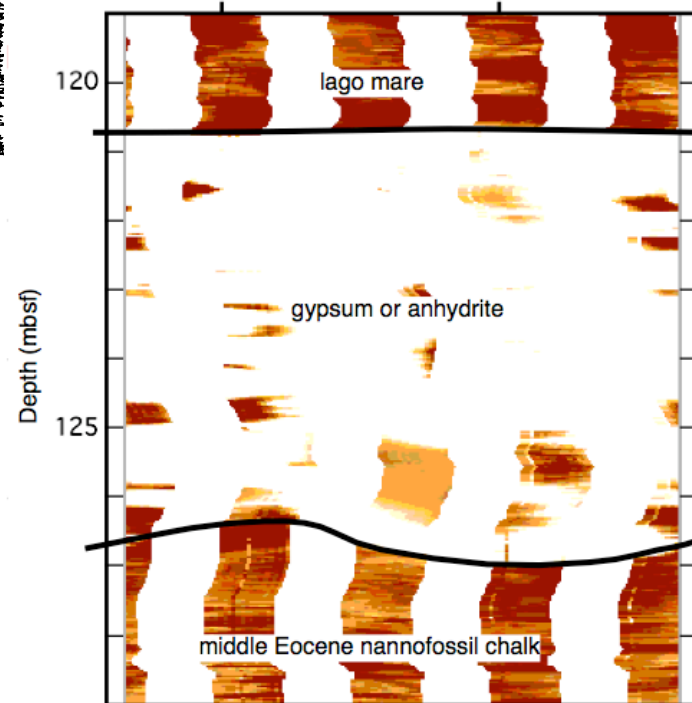


Figure 15. FMS image of the ~5-m-thick gypsum layer overlying upper Eocene foraminiferal nanfossil chalk. This erosional unconformity is quite irregular on a small spatial scale.