GEOPHYSICS IN GROUNDWATER HYDROLOGY

SURFACE GEOPHYSICS

BOREHOLE GEOPHYSICS

BOREHOLE GEOPHYSICS

WHY LOG?

- BEHAVIOR OF GROUNDWATER IN SUBSURFACE IS A FUNCTION OF THE SUBSURFACE GEOLOGIC CHARACTER.

  -- WATER FLOWS IN POROUS & PERMEABLE UNITS

  -- WATER IS STORED IN POROUS & IMPERMEABLE UNITS

  -- WATER MAY BE ABSENT FROM NON-POROUS UNITS

- DRILL HOLES ARE ONLY MEANS OF DIRECT ACCESS TO THE SUBSURFACE

  -- SAMPLING OF ROCKS, FLUIDS, AND RELATED PHYSICAL PROPERTIES ARE THE ONLY WAYS INFORMATION CAN BE DERIVED FROM THESE HOLES

- LOGS ARE INTERPRETED TO DETERMINE AQUIFER & GEOLOGIC PROPERTIES

  -- LITHOLOGY

  -- GEOMETRY

  -- RESISTIVITY

  -- BULK DENSITY

  -- POROSITY

  -- PERMEABILITY

  -- MOISTURE CONTENT

  -- SPECIFIC YIELD

- PUMPING TESTS CAN FAIL IF DATA ARE IGNORED
  - -- HYDRAULIC CONDITIONS ALONG BOREHOLE
  - -- STORAGE CHARACTERISTICS OF AQUIFER
  - -- DEPTH TO AQUIFER
  - -- THICKNESS OF AQUIFER
- GEOPHYSICAL LOGS MAY BE ONLY MEANS OF AQUIRING DATA FROM <u>OLD</u> HOLES

AN "IDEAL" LOGGING APPROACH:

- PLAN THE LOGGING PROGRAM BASED ON REQUIRED DATA.
- DRILL HOLES CAREFULLY.
- TAKE FREQUENT FORMATION & FLUID SAMPLES.
- TAKE LOGS CAREFULLY.
- INTERPRET LOGS COLLECTIVELY.

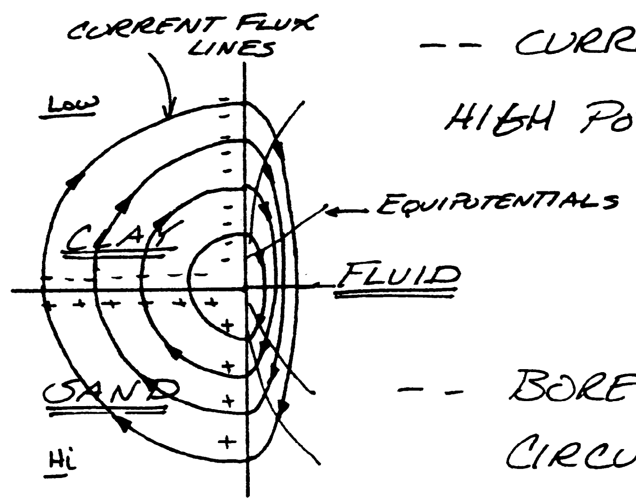
BOREHOLE TOOLS

- RESISTIVITY
- SPONTANEOUS POTENTIAL
- ACOUSTIC
- GAMMA; GAMMA-GAMMA
- NEUTRON
- CALIPER
- SPINNER (FLOWMETER)
- VIDEO
- TEMPERATURE

SPONTANEOUS POTENTIAL

- RECORD OF ELECTRIC POTENTIAL DEVELOPED BETWEEN BOREHOLE FLUID AND SURROUNDING ROCK

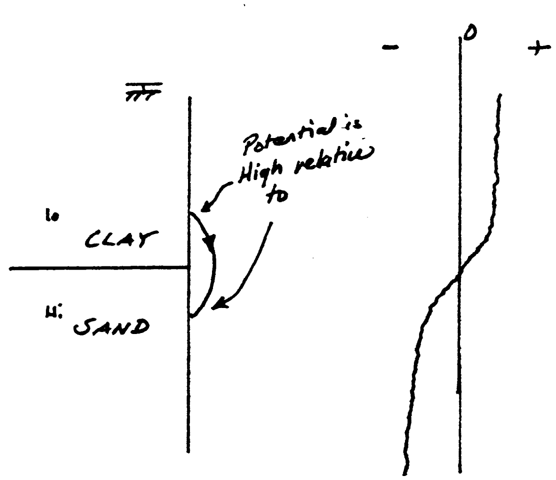
- "JUNCTION POTENTIALS"
  - -- TWO DISSIMILAR MATERIALS GENERATE A VOLTAGE POTENTIAL AT A JUNCTION



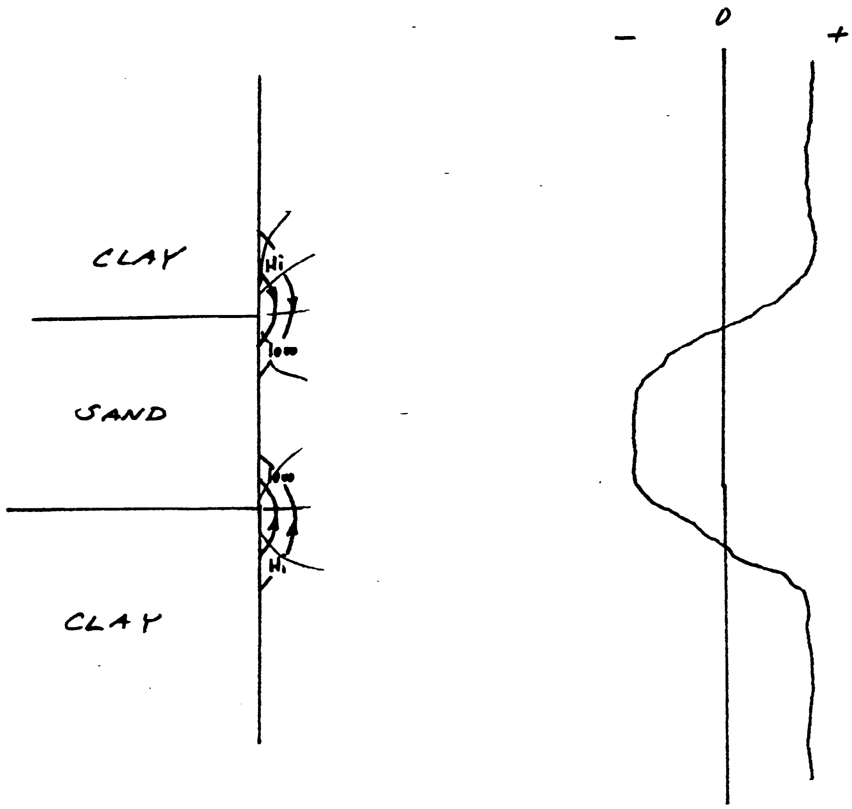
-- CURRENT FLOWS FROM HIGH POTENTIAL TO LOW POTENTIAL

-- BOREHOLE FLUID COMPLETES CIRCUID

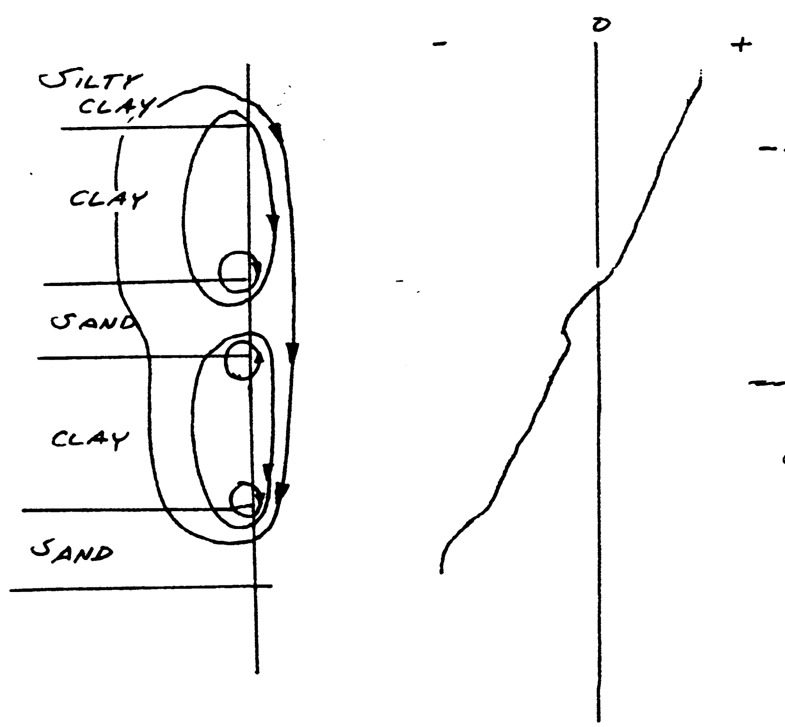
-- SONDE' MEASURES POTENTIAL IN FLUID



SIMPLE LAYERED SYSTEM



IN COMPLEX SYSTEMS - MULTIPLE CURRENT PATHS



-- GENERAL "DRIFT" DUE TO HIGH POTENTIAL FROM SILT GRADING TO SAND

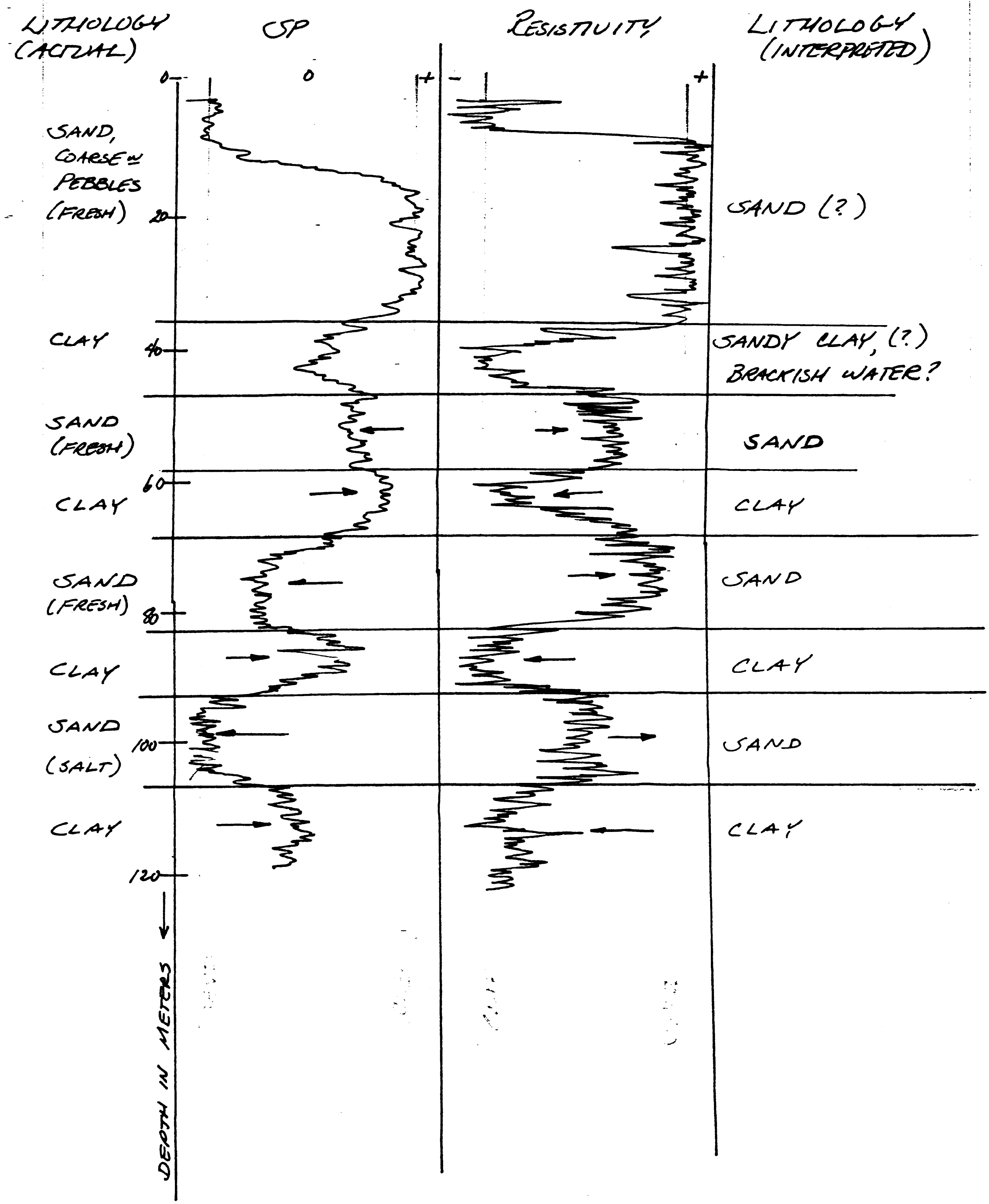
— "BUMPS" DUE TO INTERSPERSED SANDS & CLAYS

GENERALIZED CORRELATIONS (SP AND RESISTIVITY)

- SPONTANEOUS POTENTIAL TENDS TO BE HIGH (+) IN CLAYS, SHALES, & BASALT
- SPONTANEOUS POTENTIAL TENDS TO BE LOW (−) IN SANDS, LIMESTONES, AND OTHER PERMEABLE LAYERS
- RESISTIVITY TENDS TO BE LOW IN CLAYS DUE TO HIGH POROSITY AND HIGHLY MINERALIZED WATER (LOTS OF IONS IN SOLUTION)
- RESISTIVITY TENDS TO BE HIGH IN SANDS WITH FRESH WATERS.

INTERPRETATION (GENERALIZED APPROACH)

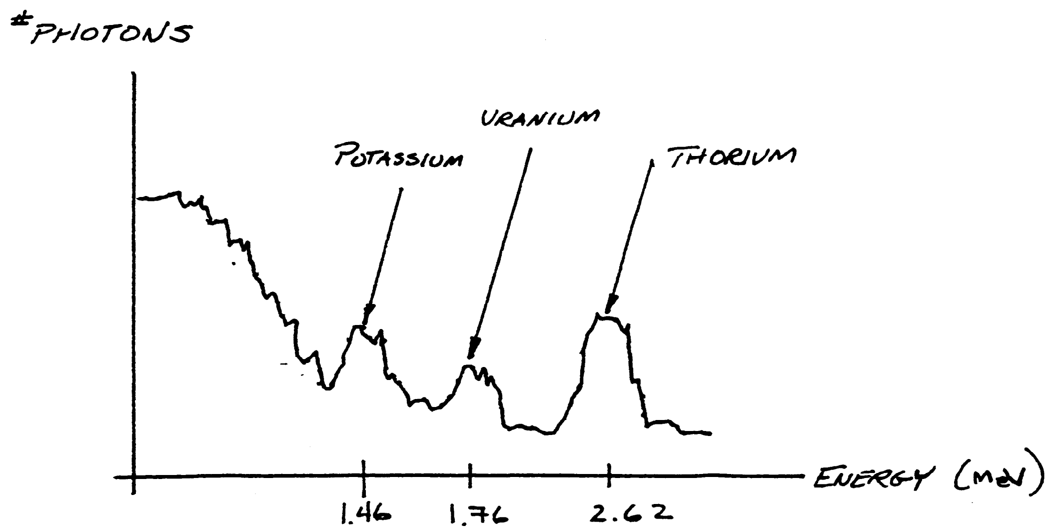
- PREPARE SP & RESISTIVITY LOGS SIDE BY SIDE
- PENCIL A "SAND" AND "CLAY" LINE ON EACH LOG
- IDENTIFY ZONES WITH GOOD CORRELATION ON BOTH LOGS
- COMPARE WITH LOCAL DRILLING LOGS FOR WHICH SIMILAR GEOPHYSICAL LOGS ARE AVALIABLE



LITHOLOGY (ACTUAL)
SP
RESISTIVITY
LITHOLOGY (INTERPRETED)
0
0
+
-
+
20
40
60
80
100
120
SAND, COARSE w PEBBLES (FRESH)
CLAY
SAND (FRESH)
CLAY
SAND (FRESH)
CLAY
SAND (SALT)
CLAY
SAND (?)
SANDY CLAY, (?) BRACKISH WATER?
SAND
CLAY
SAND
CLAY
SAND
CLAY
DEPTH IN METERS

NATURAL GAMMA

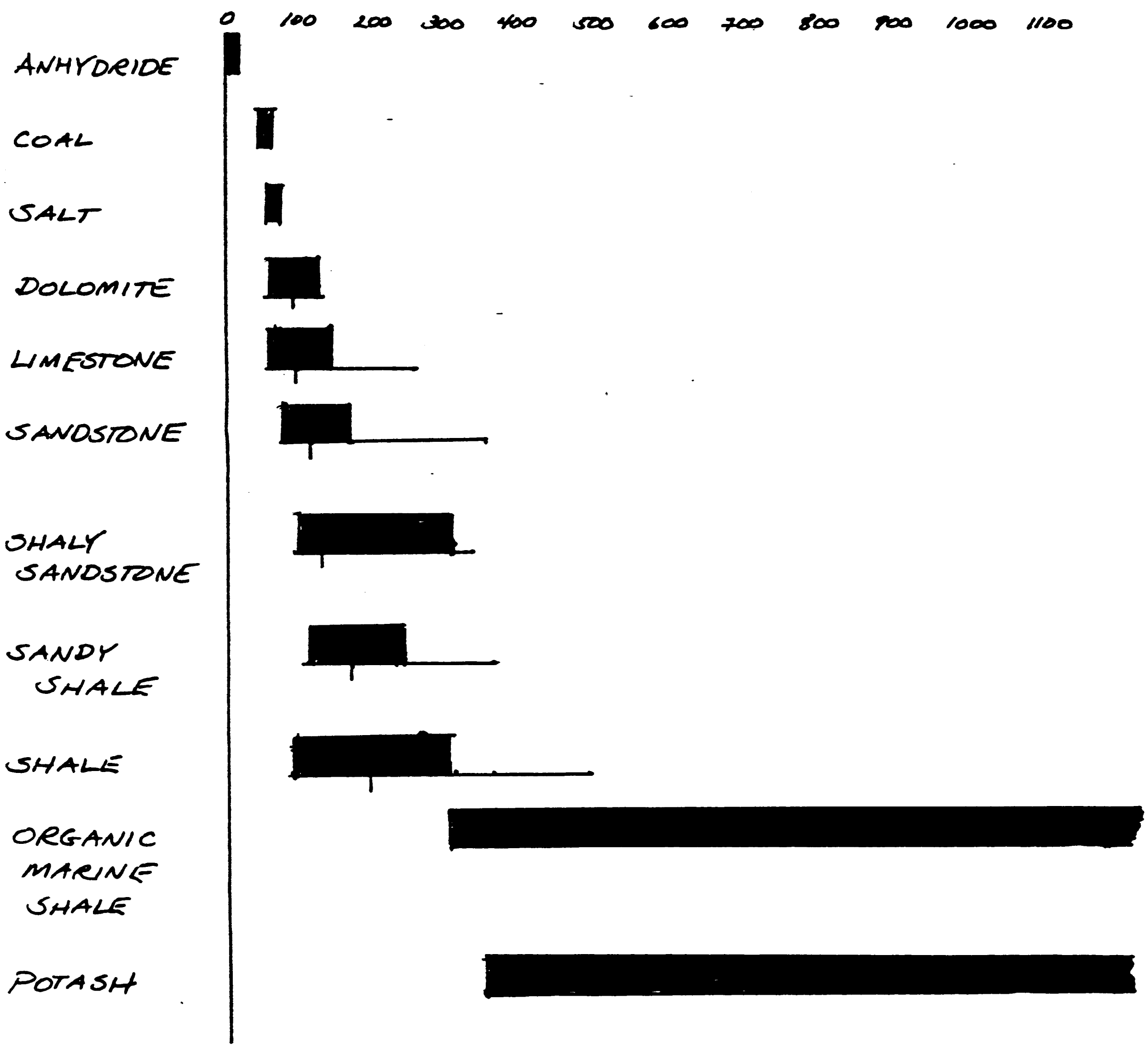
- DIFFERENT ROCK MATERIALS EMIT GAMMA PHOTONS AT DIFFERENT ENERGIES AND RATES
- NATURAL GAMMA MASS IS HIGHER IN CLAYS AND SHALES THAN IN SAND AND CARBONATES
- NATURAL GAMMA SPECTRUM CAN BE USED TO INTERPRET RELATIVE DISTRIBUTION OF MATERIALS

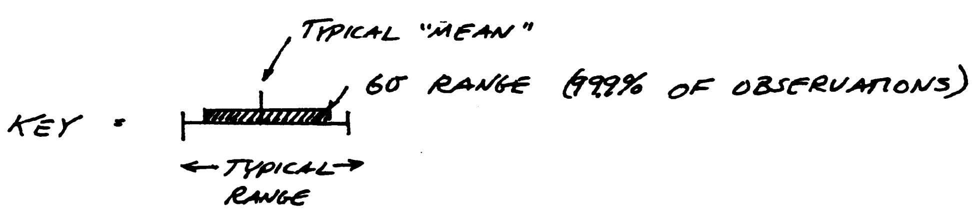


"SPECTRUM"

"MASS" = $\int$ #PHOTONS(MeV) · dMeV ("AREA OF SPECTRUM")

GAMMA — "MASS" (API - GAMMA UNITS)





- HIGH MASS ⇒ CLAYS, SHALES
- LOW MASS ⇒ CARBONATES, SANDS

REF: KEYS, W.S. AND MACCARY, L.M., APPLICATION OF BOREHOLE GEOPHYSICS TO WATER RESOURCE INVESTIGATIONS, U.S. GEOLOGICAL SURVEY, TECHNIQUES OF WATER RESOURCES INVESTIGATIONS, BOOK 2, CH. E1.

INDUCED GAMMA (GAMMA-GAMMA)

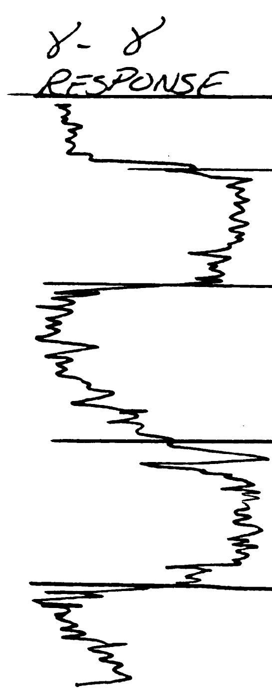
- MEASURE BACKSCATTERED GAMMA FROM AN ACTIVE SOURCE IN THE TOOL

- ACTIVE GAMMA IS ADSORBED IN DIRECT PROPORTION TO ELECTRON DENSITY OF MATERIAL

- SOLID HAS HIGH ELECTRON DENSITY
- WATER HAS LOW ELECTRON DENSITY

  - HIGH POROSITY ⇒ MOSTLY WATER
    HIGH TOOL RESPONSE
  - LOW POROSITY ⇒ MOSTLY SOLID
    ∴ LOW TOOL RESPONSE

- NEED IDEA OF LOCAL GEOLOGY TO INTERPRET



γ-γ RESPONSE	SAND-CLAY SYSTEM	BASALT-FRACTURE SYSTEM
	SAND	BASALT
	CLAY	FRACTURES
	SAND	BASALT
	CLAY	FRACTURES
	SAND	BASALT

NEUTRON

- HYDROGEN IS A GOOD NEUTRON MODERATOR
- WATER IS A DENSE SOURCE OF HYDROGEN (11% BY MASS)
- MEASURE NEUTRON BACKSCATTER

HIGH POROSITY ⇒ MOSTLY WATER
∴ HIGH BACKSCATTER

LOW POROSITY ⇒ MOSTLY SOLID
∴ LOW BACKSCATTER

- MUST BE CALIBRATED AGAINST LOCAL MEDIA
- CAN BE USED ABOVE WATER TABLE FOR MOISTURE CONTENT PROFILE

ACOUSTIC LOGS

- SOUND TRAVELS THROUGH FLUIDS AND SOLIDS AT VELOCITIES CHARACTERISTIC OF THE MATERIALS

- MEASURE TIME OF TRAVEL AND ENERGY ATTENUATION TO DETERMINE POROSITY

$$\frac{1}{V_{MEDIUM}} = \Delta t = \frac{\omega}{V_{FLUID}} + \frac{1-\omega}{V_{SOLID}}$$

(Δt ← TIME OF FLIGHT)

SOLID/FLUID	VELOCITY (FT/SEC)
SANDSTONE	15,000-18,000
SHALES	6,000-16,000
LIMESTONE	19,000-21,000+
DOLOMITE	21,000-24,000
CLAYS	5000 - 6000
WATER	5000 - 5400

SUPPOSE A $\Delta t = 78\mu sec/ft$ IS MEASURED IN LIMESTONE. ESTIMATE POROSITY.

$\Delta t_{MEDIUM} = 78\mu sec/ft$

$V_{FLUID} = 5000 ft/sec \; ; \; \frac{1}{V_F} = 200\mu sec/ft$

$V_{SOLID} = 20,000 ft/sec \; ; \; \frac{1}{V_S} = 50\mu sec/ft$

$$78\mu sec/ft = \omega(200\mu sec/ft) + (1-\omega)(50\mu sec/ft)$$

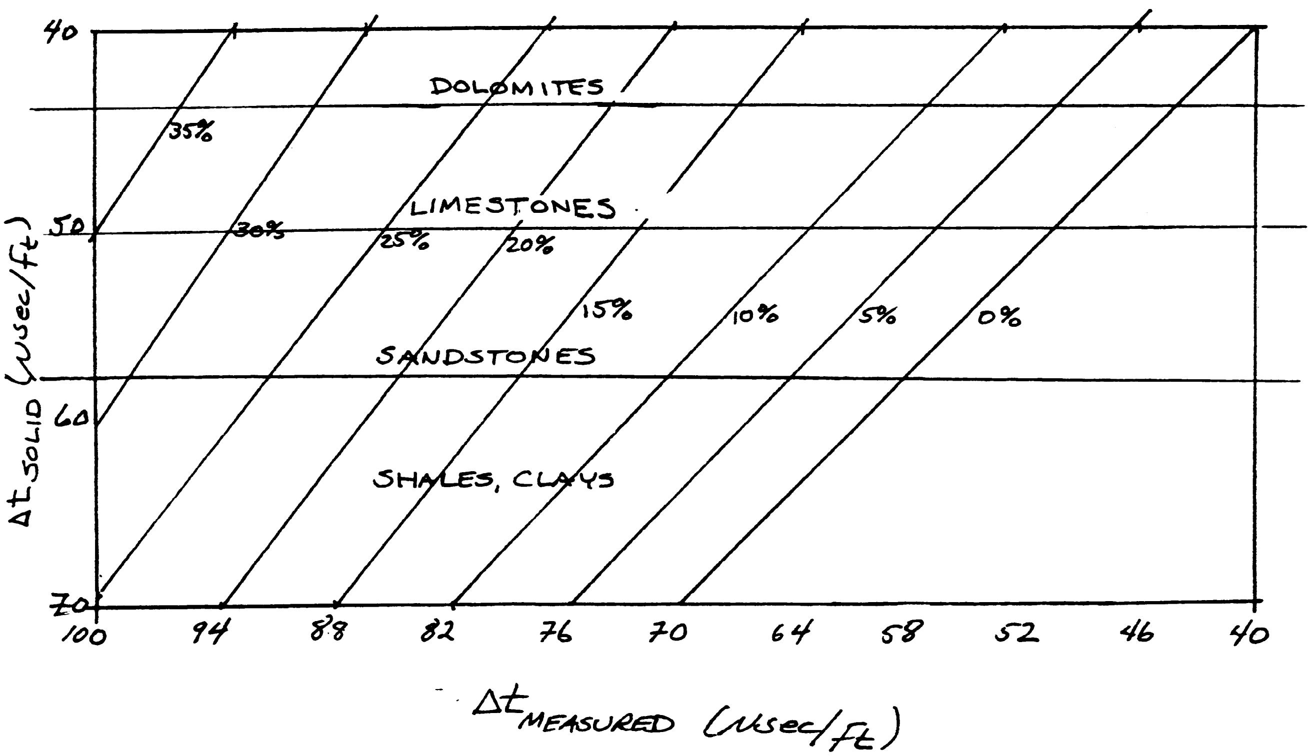
$$78 = 200\omega + 50 - 50\omega \; ; \quad 28 = 150\omega$$

$\therefore \frac{28}{150} = \omega = 0.186$ $\quad \therefore$ POROSITY IS ROUGHLY 18%

- ACOUSTIC LOGS ARE ALSO RELATED TO ENGINEERING PROPERTIES OF ROCKS.

- POROSITY FROM ACOUSTIC LOG

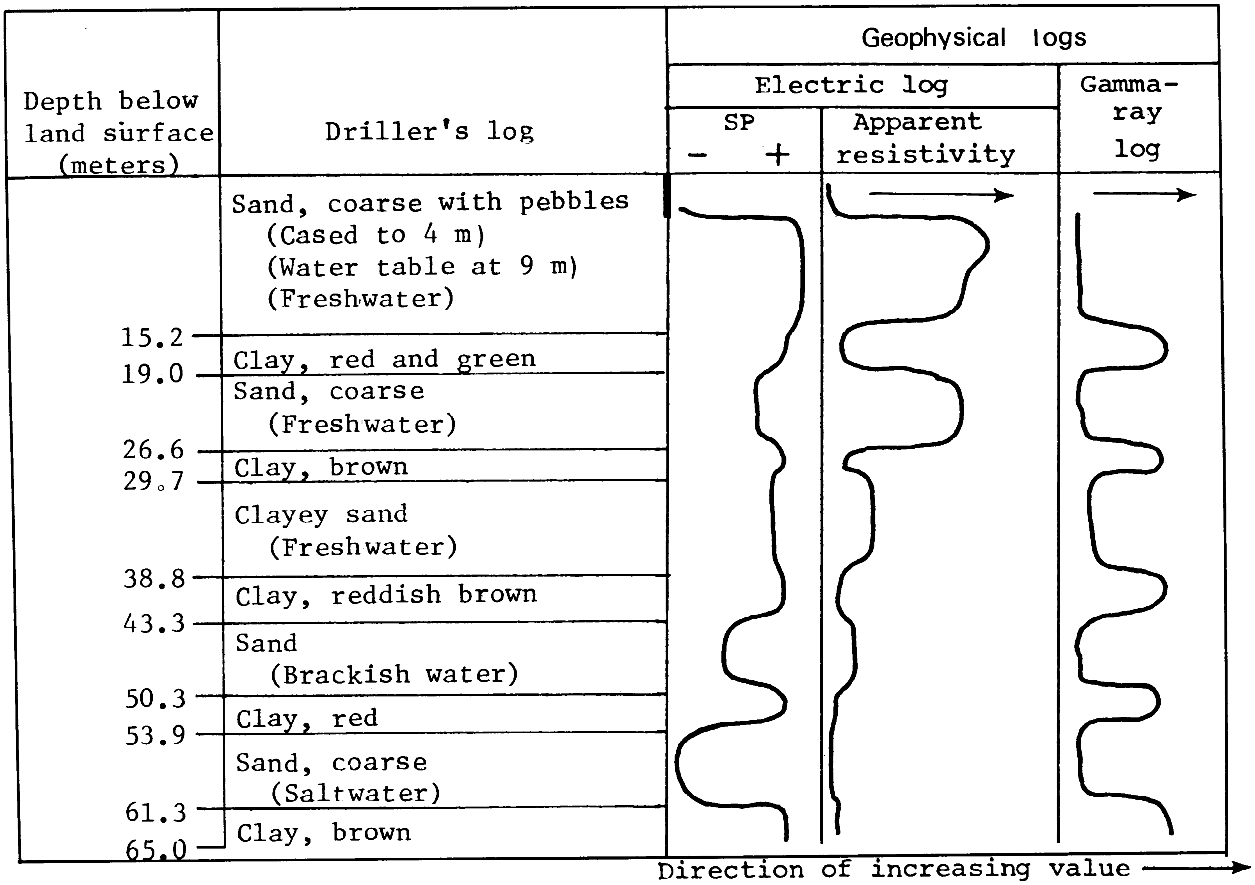
$$\omega = \frac{\Delta t_{MEASURED} - \Delta t_{SOLID}}{\Delta t_{LIQUID} - \Delta t_{SOLID}}$$



REF: ADAPTED FROM: U.S.G.S TWRI BOOK 2, CH. E1.
"APPLICATION OF BOREHOLE GEOPHYSICS TO WATER-RESOURCES INVESTIGATIONS"

INFORMATION	TOOLS
LITHOLOGY, STRATIGRAPHIC CORRELATION OF AQUIFERS	DRILLING LOG, ELECTRIC, SONIC, CALIPER NUCLEAR LOGS
TOTAL POROSITY BULK DENSITY	CALIBRATED SONIC, NEUTRON, γ-γ
EFFECTIVE POROSITY	CALIBRATED RESISTIVITY
CLAY OR SHALE CONTENT	γ
→ PERMEABILITY	PUMPING TEST, SLUG TEST
SECONDARY PERMEABILITY	CALIPER, SONIC, VIDEO
SPECIFIC YIELD	CALIBRATED NEUTRON, γ-γ
GRAIN SIZE	ELECTRIC (?)
MOISTURE CONTENT	CALIBRATED NEUTRON
INFILTRATION	TIME INTERVAL NEUTRON RADIOACTIVE TRACER TIME DOMAIN REFLECTROMETRY
→ GROUND WATER FLOW PATHS	TRACERS, TEMPERATURE VELOCIMETER
DISPERSION, DILUTION	FLUID CONDUCTIVITY, TEMPERATURE γ
PRODUCTION ZONES	SPINNER LOG, INJECTIVITY
PHYSIO-CHEMICAL	FLUID CONDUCTIVITY, TEMPERATURE, NEUTRON, RESISTIVITY, SAMPLING
COMPLETION	γ-γ, CALIPER, VIDEO

WELL LOGS



An important part of well construction is determining the character and the thickness of the different layers of material penetrated by the well and the quality of the water in the permeable zones. This information is essential for the installation of casing and for the proper placement of screens. Information on materials penetrated is recorded in the form of "logs." The logs most commonly prepared for supply wells are drillers' logs and geophysical (electric) logs. Copies of logs should be carefully preserved by the well owner as a part of the file on each well.

Drillers' logs consist of written descriptions of the material penetrated by wells. These descriptions are based both on samples of rock cuttings brought to the surface during drilling operations and on changes in the rate of penetration of the drill and in the vibration of the rig. The well driller may also collect samples of the rock cuttings for study by geologists on his staff or those on the staff of State geological surveys or Federal and State water-resources agencies. Descriptions of these samples made by utilizing a microscope and other aids are commonly referred to as a *geologic log* to differentiate them from the driller's log. If the well is to be finished with a screen, the well driller will retain samples of material from the principal water-bearing zones for use in selecting the slot size of screens.

Geophysical logs provide indirect information on the character of rock layers. The most common type of geophysical log, the type normally referred to as an *electric log,* consists of a record of the spontaneous electrical potentials generated in the borehole and the apparent electrical resistivity of the rock units. Several types of electric loggers are available, but nearly all provide continuous graphs of spontaneous potential and resistivity as a sensing device is lowered into and removed from the borehole. Electric logs can be made only in the uncased portion of drill holes. The part of the hole to be logged must also contain drilling mud or water.

The spontaneous potential log (which is usually referred to as the SP log) is a record of the differences in the voltages of an electrode at the land surface and an electrode in the borehole. Variations in voltage occur as a result of electrochemical and other spontaneous electrical effects. The SP graph is relatively featureless in shallow water wells that penetrate only the freshwater zone. The right-hand boundary of an SP log generally indicates impermeable beds such as clay, shale, and bedrock. The left-hand boundary generally indicates sand, cavernous limestone, and other permeable layers.

The *resistivity log* is a record of the resistance to the flow of an alternating electric current offered by the rock layers and their contained fluids and the fluid in the borehole. Several different electrode arrangements are used to measure the resistivity of different volumes of material, but the arrangement most commonly used by the water-well industry is referred to as the single-point electrode. The resistivity of water-bearing material depends primarily on the salt content of the water and the porosity of the material. Clay layers normally have a low resistivity because of their large porosity, and the water that they contain tends to be relatively highly mineralized. In contrast, sand layers saturated with freshwater tend to have a high resistivity. Sand layers containing salty water, on the other hand, tend to have a low resistivity resembling that of clay layers. Such layers tend to have a strongly negative spontaneous potential that, viewed together with the resistivity, aids in identification of the layers.

Several other types of geophysical logs are available, including gamma-ray logs that record the rate of emission of gamma rays by different rock layers. In fact, geophysical logging is a complex topic that has been developed, largely by the oil industry, into an advanced technical field. It is being utilized to an increasing extent by the water-well industry, especially in conjunction with the construction of large-yield wells by the hydraulic rotary method.

It is also important, either during well construction or following geophysical logging, to collect, for chemical analyses, water samples from the permeable zones that may supply water to the completed well. The chemical analyses made on these samples should include the concentration of any constituents that are known to be a problem in other supply wells drawing from the aquifer. These constituents might include iron, manganese, chloride, sulfate, nitrate, total dissolved solids, and others. (See "Quality of Ground Water.")