MP2400 Introduction to the physics of rocks

Name:………………………

Put your name and study number on each page Study number:………………

Year of entry:……………….

PART 1: CASE STORY (FIGURES 1, 1A)

At the west side of the Rhine Graben an old fault zone was reactivated by a small earth quake. After this event, as a result, a small hot spring with water erupting at intervals (geyser) manifested itself in the vicinity of one of the youngest volcanoes. The water was heated at a relatively shallow depth and originally supplied through a small but very elongated sand lens.

- In the cavity of the geyser, the water is heated up to 110 °C to steam, which erupts to the surface every 15 minutes.
- The amount of water is estimated at 6 m^3 of water (not steam), per session.
- The water contained about 50 g/l of NaCl of salt-ions.
- A heat resistant borehole televiewer recognised in the cavern a permeable zone of 6 m^2 in the sandbody, which allowed the water to come into the geyser cavity.
- The heat flow in this area is extraordinary: 230 °C/km

Lateral continuity

- At 300 meters from the geyser, at more or less the same depth, the sand lens produces spring-water for a Kurort.
  - Here the temperature down hole is (35°C).
  - This loose sandbed has a cementation exponent of 1.6.
  - Further a laterolog reading showed a formation resistivity (R_o) of 0.6 Ωm.
  - The water is assumed to have a viscosity of 10^{-3} Pa.s (Pa = $kg.m^{-1}.s^{-2}$)
  - From the Kurort well to the geyser a linear pressure drop was measured, with a total of $8.4*10^5$ Pa.
- Away from the Kurort, after a tight fault, the sand-layer slowly rises to 400 m depth.
  - The geothermal gradient is the same as near the Kurort.
  - The sand porosity is the same as near the Kurort.
  - Here some oil and water are detected in a well.
  - This loose sand bed has the same a saturation exponent of 2.
  - Further a laterolog reading showed a formation resistivity (R_t) of 0.92 Ωm.

Note: average surface temperature is 0°C

1: Environment

a) At what depth do we find the cavity.

b) Give the bottomhole fluid pressure.

c) Calculate or read the water conductivity at the surface and bottomhole of the geyser

d) Calculate or read the water conductivity near the Kurort.

e) Give the inflow of water in the cavity in m^3/s.

f) Give the geothermal gradient near the Kurort.

g) Give the bottom hole temperature and water resistivity in the water/oil well.

2: Porosity and saturation

a) Give the first Archie equation and unities to define the formation factor F and the porosity near the Kurort.
- R_o
- R_w
- ϕ
- m

b) What is the difference between Ro and Rt and give the second Archie equation with its unities to define the resistivity index I_R.
- I_R
- Ro
- Rt
- Sw
- n

c) Why is it not possible to use the Ro that is measured in the water well, to calculate I_R.
Give the combined Archie equation, in order to define the water saturation Sw in the mixed oil/water well.
- Rt
- Rw
- Sw
- n
- m
- ϕ

d) How much are the water saturation and the related oil saturation.

3: Flow through a porous medium

a) Give the Darcy formula in SI-units.
- Q
- ΔP
- L
- A
- η
- k

b) Calculate the permeability of the sand bed in D. (1 D = 10^{-12} m^2)

c) If the permeability was measured in hydrological terms, what will be the unit of permeability and which terms are neglected, when compared with the Darcy-equation?

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PART 2: GENERAL QUESTIONS

4a: Permeability predictions can be characterised with a simple logk = a+blog(ϕ) relation. This relation can be extended with a rock property that is found in cuttings or with a porosity parameter derived from a log. Name one of these two.

4b: With the use of image analysis the van Baaren equation can be applied on cuttings or unprepared faces and on polished thin sections. Which parameters have to be measured in the binary images to use the formula. What will be the consequence on the result, when the raw face is compared with a thin section?

5a: The capillary rise of a water level in a sand is in the opposite with two parameters; which one?

5b: Give in figure 2 the route for mercury injection, withdrawal and reinjection and show the places that define the maximum withdrawal (S_{imin}) and maximum saturation (S_{imax})

5c: Why starts the mercury saturation at a level far above $P_c = 0$?

6a: What is the difference in application for a neutron log and a density or γ–γ log.

6b: Many nuclear devices (density neutron tools) do have two detectors; near the source and away from the source. Give an explanation why.

7: The natural gamma-ray- , the spontaneous potential- and the combined neutron-/density-measurements can be used to calculate the shale volume. Give one of the three V_{shale} relations and name the parameters.

8: The acoustic travel time is depending on regular parameters and disturbing aspects. Name four items and give arguments in their relation to the travel time.

$$k = 10.D_{dom} \cdot C^{-3.64} \cdot j^{\,m+3.64}$$

1.
2.
3.
4.

LOG INTERPRETATION

9: Gamma-ray:

- Draw the gamma-ray line from 1110 to 1225 m.
- Define the sand line and the shale line.
- Which isotopes define the differences between the different types of clay minerals.

10: Laterolog deep

- Draw the laterolog line from 1110 to 1225 m.
- If the bottom sand contains fresh water instead of brine, what will happen to the resistivity. Draw with a dotted line.

11: Nuclear tools

- Draw the FDC and CNL lines straight and dotted, according to the header, from 1165 m downward. Assume the density of salt to be 1.7 g/cc.
- Draw in the FDC-CNL cross plot of figure 4 roughly the places of the different lithologies, mentioned in figure 3.

12: Sonic tool

- Draw the sonic line over the entire interval.
- If the bottom sand contains fresh water instead of brine, what will happen to the interval travel time. Draw with a dotted line.

- Will there be a difference in velocity between a wet coal and a dry coal? Base your answer on the densities.

Figure 1

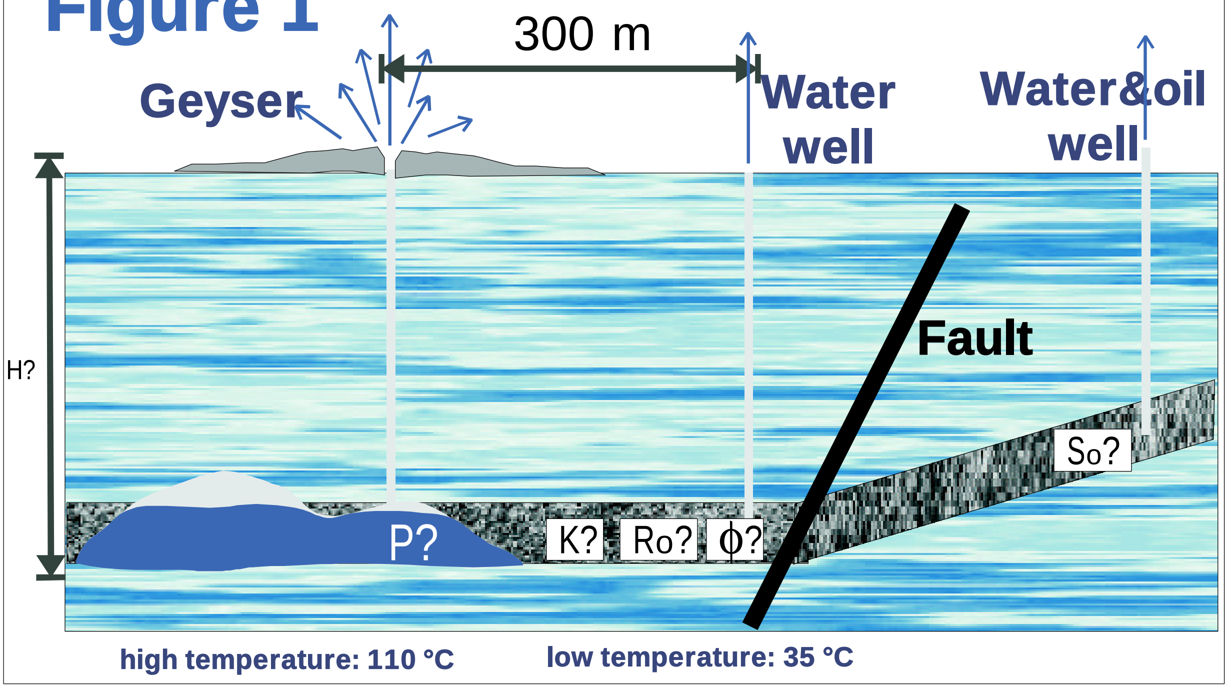


Figure 2

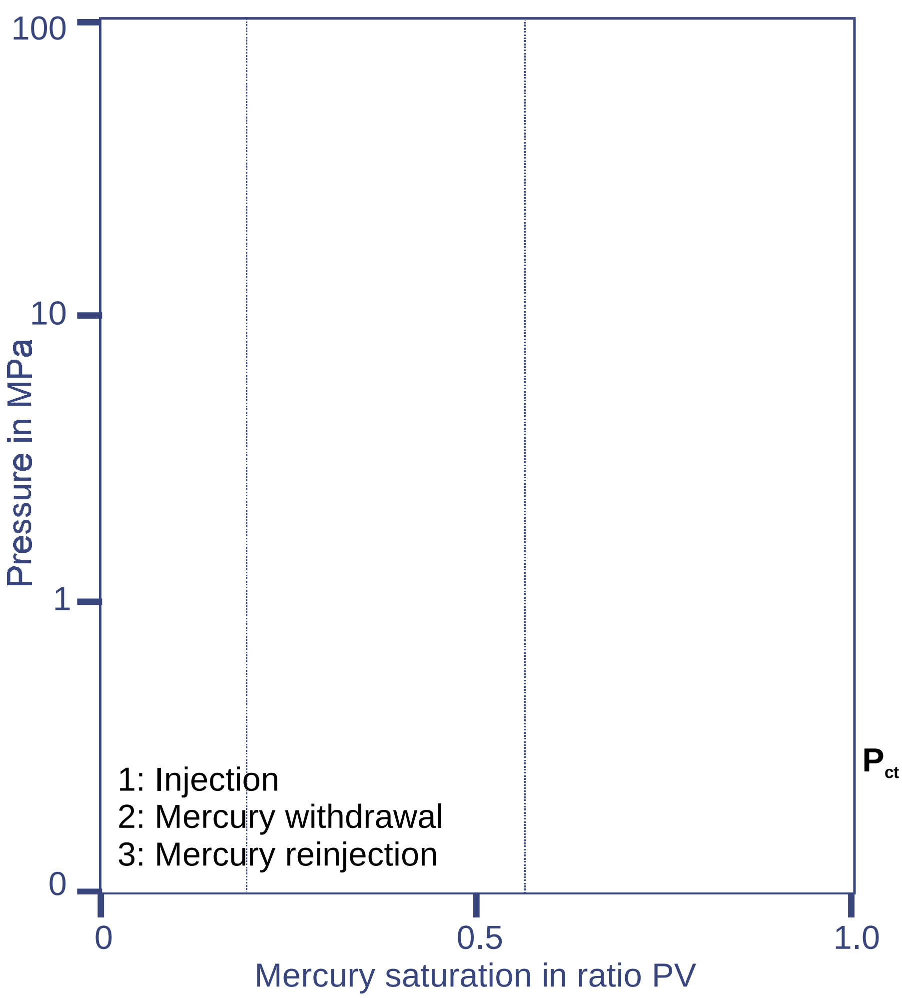


Figure 3

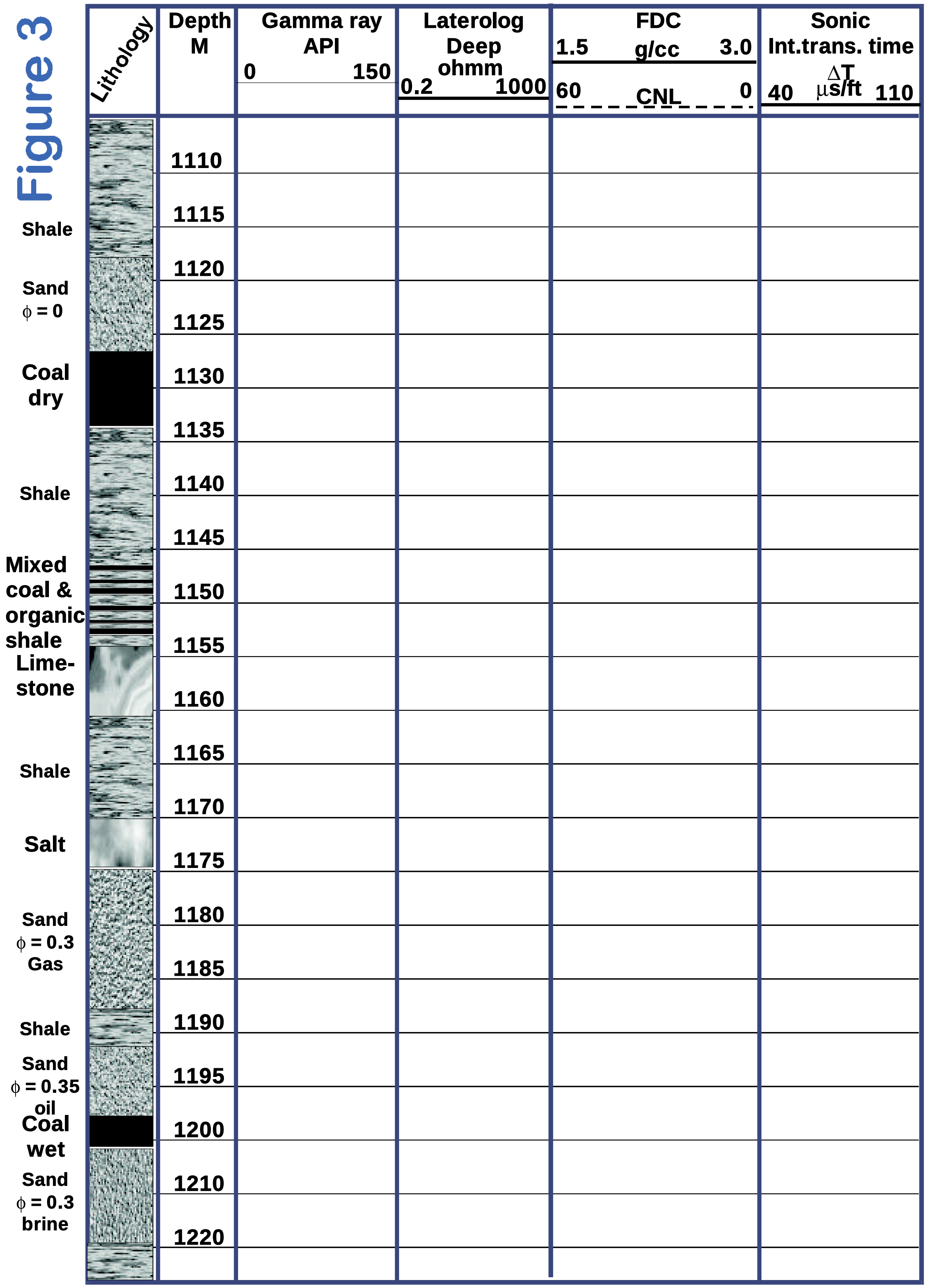

Lithology
Depth M
Gamma ray API
0 150
Laterolog Deep ohmm
0.2 1000
FDC
1.5 g/cc 3.0
60 CNL 0
Sonic Int.trans. time
ΔT
40 µs/ft 110
1110
1115
1120
1125
1130
1135
1140
1145
1150
1155
1160
1165
1170
1175
1180
1185
1190
1195
1200
1210
1220
Shale
Sand
ϕ = 0
Coal
dry
Shale
Mixed
coal &
organic
shale
Lime-
stone
Shale
Salt
Sand
ϕ = 0.3
Gas
Shale
Sand
ϕ = 0.35
oil
Coal
wet
Sand
ϕ = 0.3
brine

Figure 4

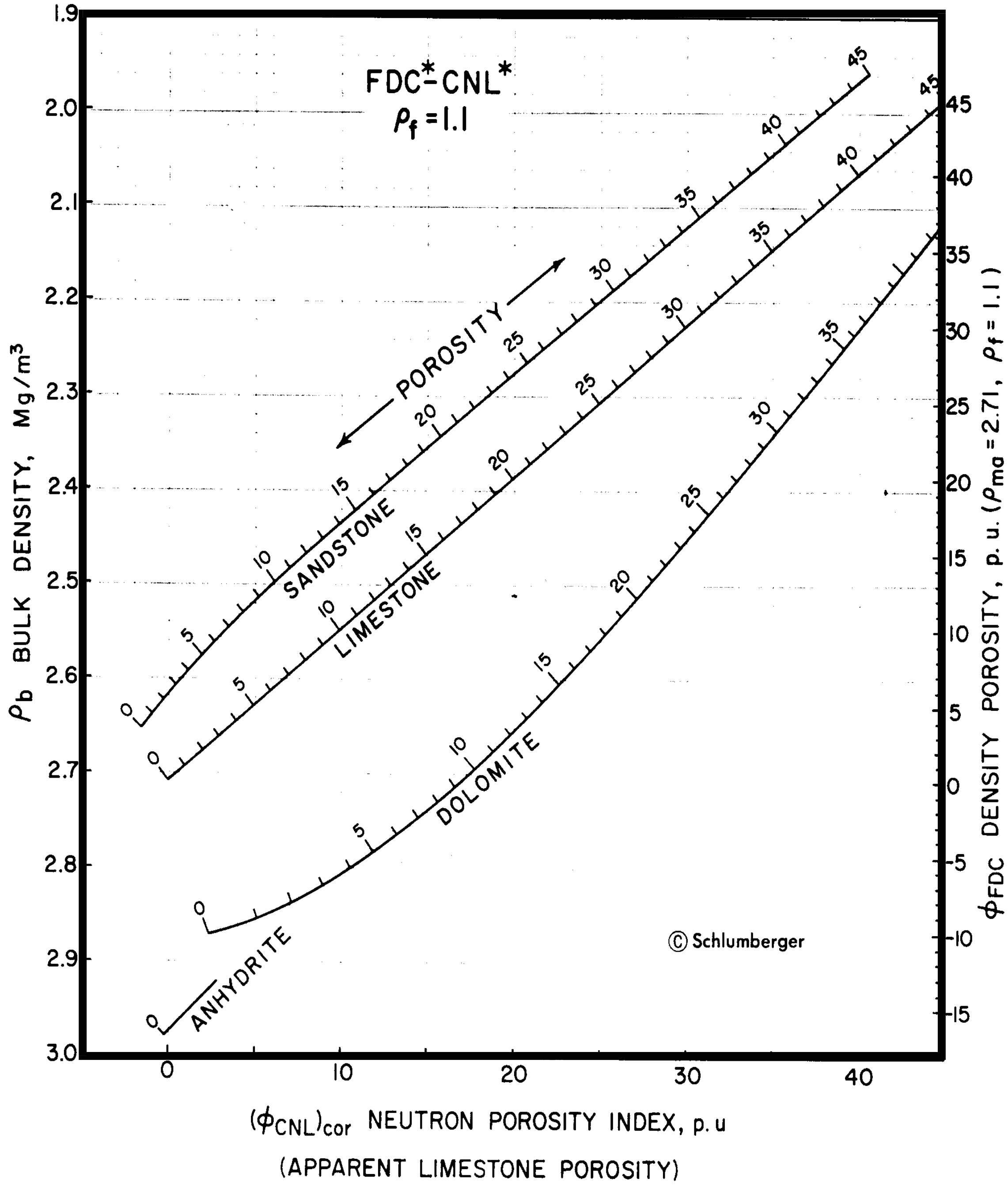
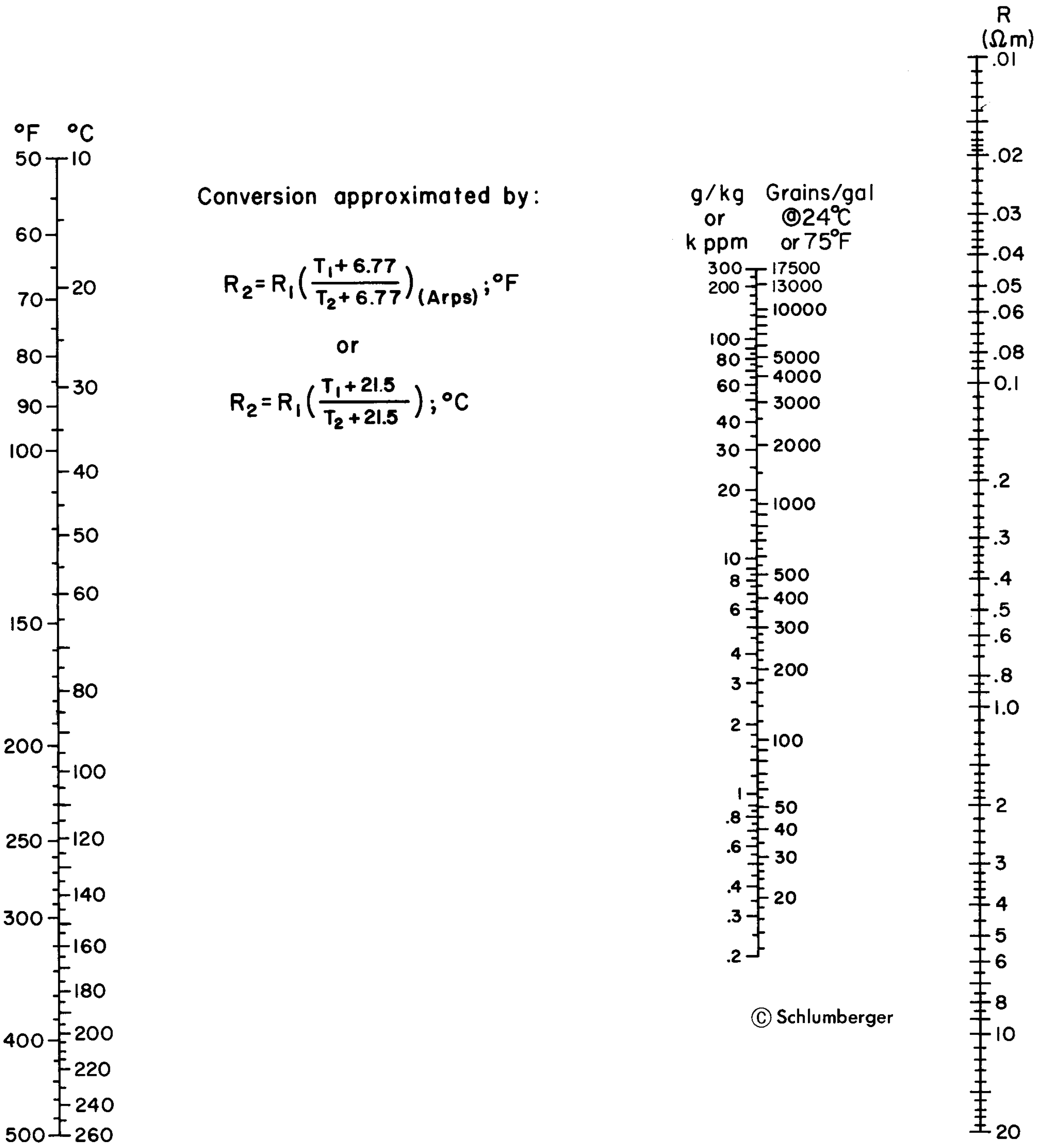

FDC*-CNL*
$\rho_f = 1.1$
POROSITY
SANDSTONE
LIMESTONE
DOLOMITE
ANHYDRITE
© Schlumberger
ρ_b BULK DENSITY, Mg/m³
$(\phi_{CNL})_{cor}$ NEUTRON POROSITY INDEX, p.u
(APPARENT LIMESTONE POROSITY)
ϕ_{FDC} DENSITY POROSITY, p.u. (ρ_{ma} = 2.71, ρ_f = 1.1)
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
0
10
20
30
40
45
35
25
15
5
-5
-10
-15

Figure 1A


°F °C
Conversion approximated by:
R2 = R1 ((T1 + 6.77)/(T2 + 6.77)) (Arps) ; °F
or
R2 = R1 ((T1 + 21.5)/(T2 + 21.5)) ; °C
g/kg or k ppm
Grains/gal @24°C or 75°F
R (Ωm)
© Schlumberger

ANSWERS

Part 1: Case story (figure 1, 2)
In Ruhlermoor (Germany) a fragmented clean sandstone reservoir is recognised at a depth of 2.2 km. The tight sandstone bodies (m = 2, n = 2) are divided by impermeable clay-shale zones and tight faults. Two exploration drillings provided the laboratory with core samples. The regional geothermal gradient is about 4°C/100 m and the yearly average surface temperature is 10 °C.
Core samples are used in the laboratory to measure the porosity, permeability and conductivity. The test samples had a length of 5 cm, a circular diameter of 2 cm and an average dry weight of 27.1 gram. The matrix density is 2.65 g/cm$^{3.}$ Permeability tests showed a pressure drop of 15 bar at a flow rate of 3.6 cm^3/s. In the formation water samples a salinity of 20.000 ppm was measured at a lab temperature of 20°C. The viscosity of the brine is 1,01*10^{-3} Pa.s.

A: Give the formula for the geothermal gradient and estimate the bottom hole temperature.
Formula: °C/km = **(Tdepth-Tsurface)/Depth**

Bottom hole temperature: **10 + 22 * 4 = 98 °C**

B: Give the density of the formation fluid and calculate the bottom hole fluid pressure.
Fluid density: **1020** kg/m^3. (20.000 ppm ~ 20 g/kg)

Bottom hole pressure: **224,4 bar or 22.44 Mpa (In bar or MPa). Depth 2.2 km; 2200 * 0.102 = 224.4 bar**

C: Give the Darcy-equation, name the parameters and calculate the porosity and permeability.

$$Q = \frac{k \cdot A \cdot DP}{h \cdot L} \Rightarrow k = \frac{Q \cdot h \cdot L}{A \cdot DP}$$

Parameter	Definition	Units	Values
k	**Permeability**	**m^2**	**?**
dP	**Pressure drop over the flow path**	**1 bar = 10^5 Pa = 10^5 N/m^2**	**1.5 Mpa or 1.5*10^6 N/m^2**
L	**Shortest length of the flow path**	**m**	**5*10^{-2}**
A	**Cross area of the flow path**	**m^2**	**3.14*10^{-4}**
η	**Viscosity pof the fluid or gas**	**Pa.s or kg/m.s**	**1.01*10^{-3}**
Q	**Flow rate**	**m^3/s**	**3.6*10^{-6}**

Porosity: **0.35 or 35 %: diameter; 2 cm, length; 5 cm, Area; 3.14 cm^2, V; 15.71 cc, ρ_{matrix} ; 2.65 g/cc, Weight$_{bulk}$ 27.1 g, so: (27.1/15.71) gives ρ_{bulk}. $\rho_{bulk}/\rho_{matrix}$ gives the fraction matrix volume: 0.65, so pore volume is 1-0.65 = 0.35**

Permeability: **See values and units in previous table: 0.4 D or 3.86*10^{-13} m^2**

D: Give the first Archie relations, name the parameters and calculate Ro at bottom hole conditions.

$$F = j^{-m} = \frac{R_o}{R_w}$$

Parameter	Definition	Units
φ	**Porosity (0.35)**	**ratio**
R_o	**Resistivity of porous sandstone rock with S_w =1 (?)**	**Ohm.m**
R_w	**Resistivity of water (0.22 ohm.m at 98 °C)**	**Ohm.m**
m	**Cementation factor (2)**	**number**
F	**Formation factor**	**number**

Ro = R_w * φ^{-m} ➔ 0.11 * 0.35^{-2} =0.9 Ohm.m

The second sand lens appears to contain water and methane gas. The in-situ P,T, matrix and pore properties of this sandstone are the same as for the water-saturated sandstone.
F: Give the second Archie relations, name the parameters and calculate Sw at bottom hole conditions.

I = S_w^{-n} = R_t/R_o

Parameter	Definition	Units
I	**Saturation Index (?)**	**number**
S_w	**Water saturation (?)**	**ratio**
n	**Saturation exponent (2)**	**number**
R_t	**True resistivity in a porous sand(stone) (1.7)**	**Ohm.m**
R_o	**Resistivity of porous sandstone rock with S_w =1 (0.9)**	**Ohm.m**

The Laterolog provided information about the virgin zone: Rt = 1.7 ohm.m. What is the hydrocarbon saturation?

HC = ? ➔ $S_w = \sqrt[n]{\frac{R_o}{R_t}}$ **or $(0.9/1.7)^{1/2}$ =0.72 so Hc = 1-S_w thus 1 - 0.72 = 0.28**

G: Now knowing that at 2.2 km depth a mixture of gas and water is present, one likes to know the water column, rising above the free water level. By using and completing the equations below, one can calculate the capillary rise.

Complete: $$DP = P_1 - P_2 = P_C = \frac{2 \cdot g \cdot cosq}{r} = \left(r_{water} - r_{air}\right) \cdot g \cdot h$$

Parameter	Definition	Units
DP	**Pressure difference**	**N/m^2**
P_1	**Pressure at the free water level**	**N/m^2**
P_2	**Pressure at the top water column**	**N/m^2**
P_c	**The capillary pressure**	**N/m^2**
g	**Surface tension**	**83 dyne/cm (or 83*0.001 N/m)**
q	**Interface angle**	**COS*q* =1**
r	**Radius tube**	**10^{-5} m**
r_w	**Density water**	**1020 kg/m^3**
r_g	**Gravity**	**In situ: 385 kg/m^3**
g	**Specific gravity**	**9.8 m/s^2**
h	**Column hight**	**? m**

The pore necks of the sandstone can be seen as a tube diameter of 10 micron (10^{-5} m)

Capillary rise h: **5.22 m** ➔

$$h = \frac{2 \cdot g \cdot \cos q}{r \cdot g \cdot Dr_{water-air}}$$

or (2*83*10^{-3}*1)/(5*10^{-5}*635) = 5.22 m

Part 2: General questions
A: What is the difference between oil wet and water wet pores.

SEE LECTURE NOTES

- What is the relation between the rock porosity and the interval transit time

SEE LECTURE NOTES

B: What is an empirical relation.

SEE LECTURE NOTES

- Give an example.

SEE LECTURE NOTES

C: Describe the relation between grain sorting and porosity.

SEE LECTURE NOTES

D: Describe the principal physics of the Laterolog ***or*** the induction log.

SEE LECTURE NOTES

- In which types of borehole fluids are these tools to be used?

SEE LECTURE NOTES

E: Which kinds of elements are creating the radioactivity needed for natural gamma ray measurements?

SEE LECTURE NOTES

- Quality of GR-borehole measurements is often depending on logging speed. How?

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G: Name two methods to define the shale volume of a clastic water, oil or gas reservoir.

SEE LECTURE NOTES

- Give one relation: V_{sh} = ---------------------------

Part 3: Log analysis (figure 3, 4)

A: Name the layers from log readings (figure 3) and motivate your choice of sediment type and pore content.

Layer number	Depth range	Sediment type + pore content
1	1500-1507	Shale / claystone
2	1507-1510	Sandstone + pores + gas
3	1510-1517	Shale / claystone
4	1517-1522	Sandstone + pores + oil
5	1522-1527	Shaly sandstone
6	1527-1531	Sandstone + pores + water
7	1531-1536	Shaly sandstone
8	1536-1542	Sandstone + pores + water
9	1542-1545	Shaly sandstone
10	1545-1550	Shale / claystone

B: Use the "Neutron porosity - density" plot to define the shale point, the shale content, the total porosity and effective porosity.

Layer number	Depth range	Shale volume Ratio	Total porosity-%	Effective porosity-%		GR Shale Volume Ratio
1	1500-1507	1	12	0		1
2	1507-1510	0	22	22		0
3	1510-1517	1	12	0		1
4	1517-1522	0.32	12.5	8		0
5	1522-1527	0.8	21	20		0.1
6	1527-1531	0	9	9		1
7	1531-1536	0.30	15	12		1.25
8	1536-1542	0	6	6		0
9	1542-1545	0.55	9	2		0.4
10	1545-1550	1	12	0		1

C: Give the shale volume by using the natural gamma-ray readings in the table above.
The small changes between the outcomes of the neutron/density method and the gamma-ray method can be explained. Name one of the possibilities.

FIGURE 1

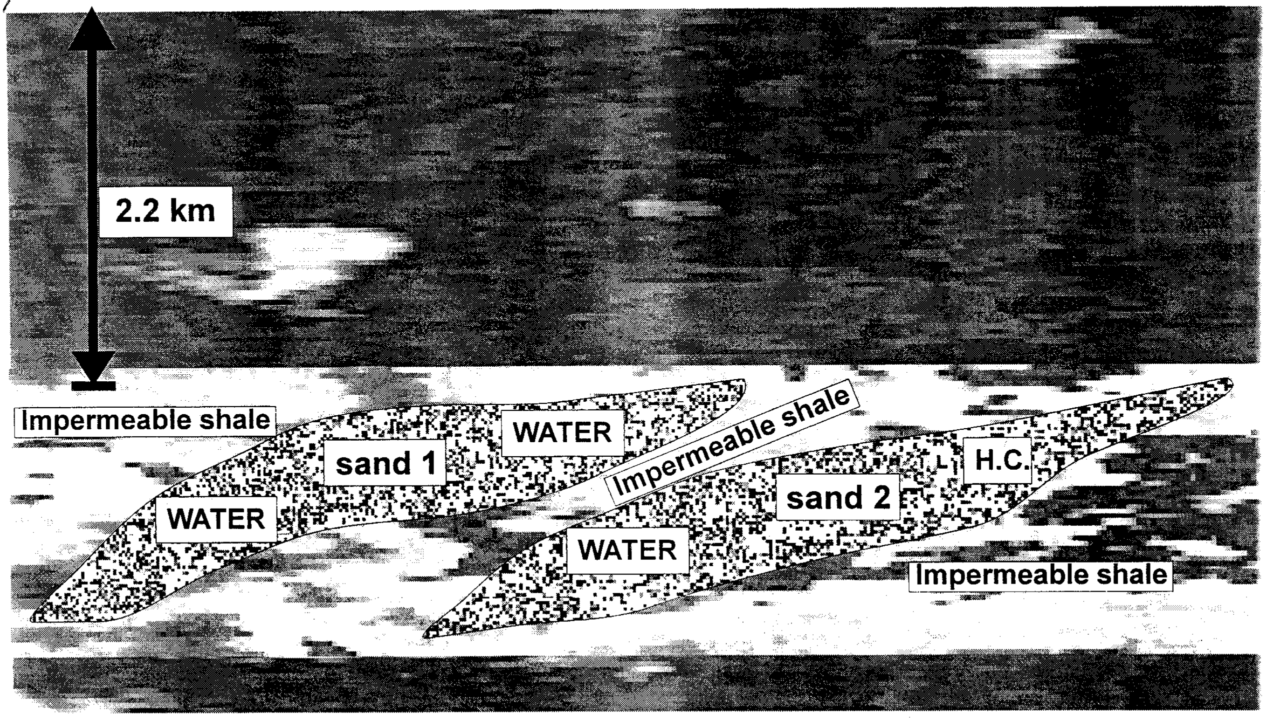
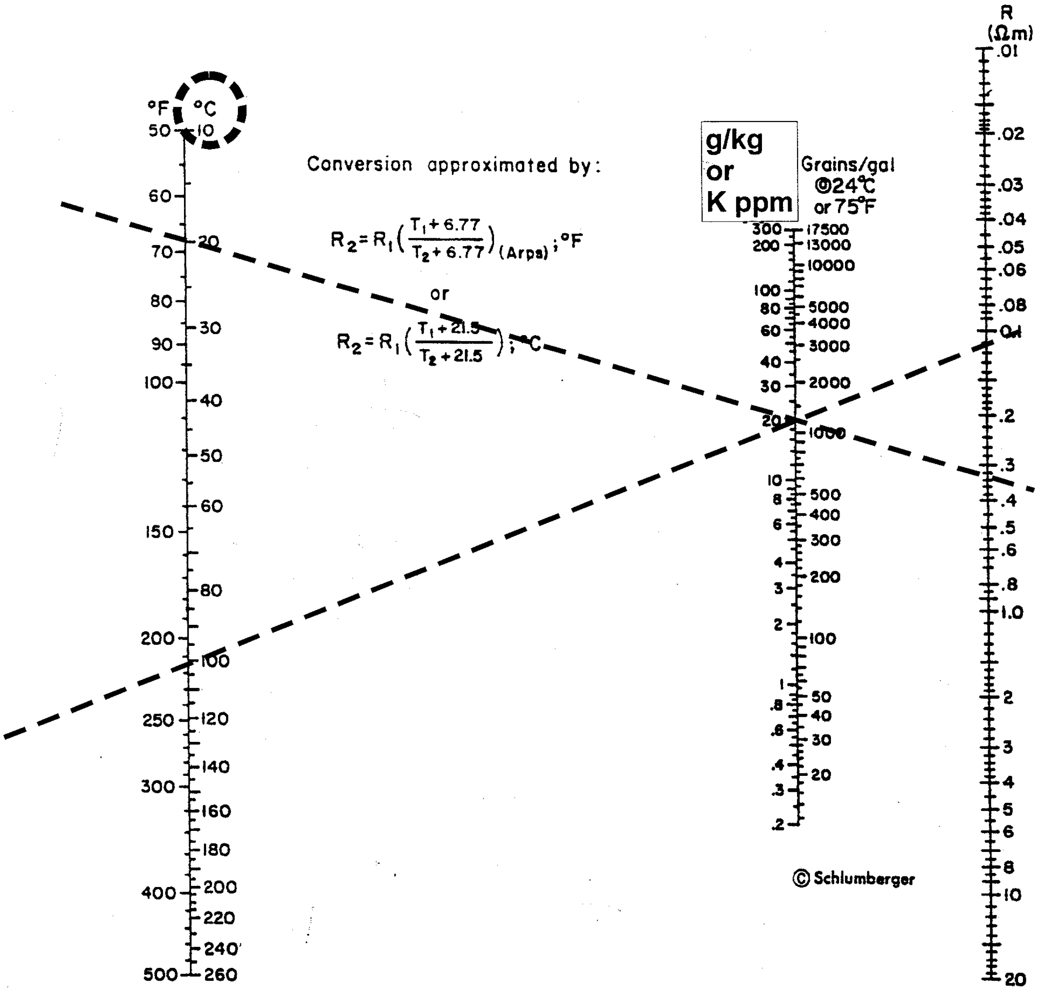


FIGURE 2



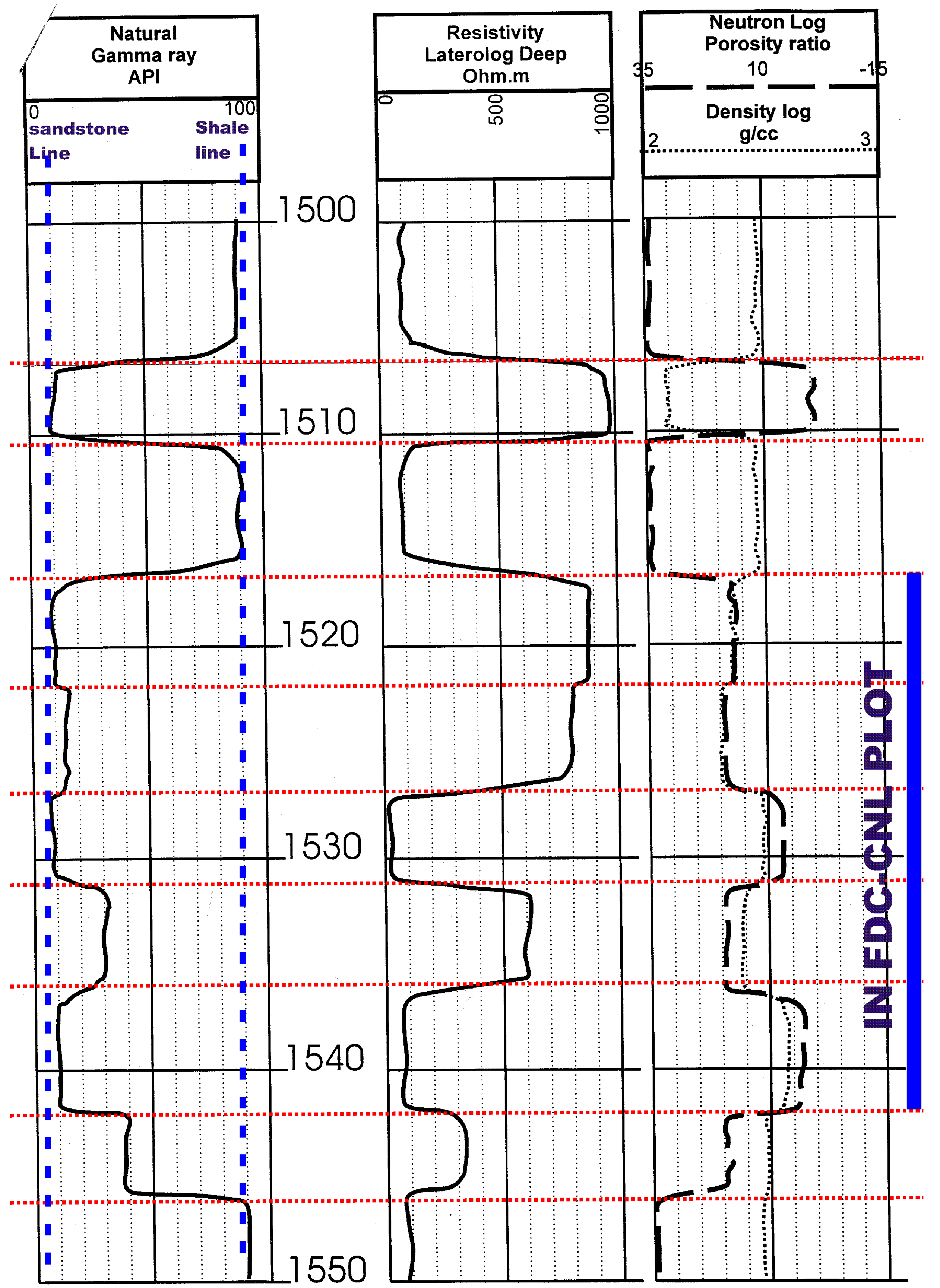
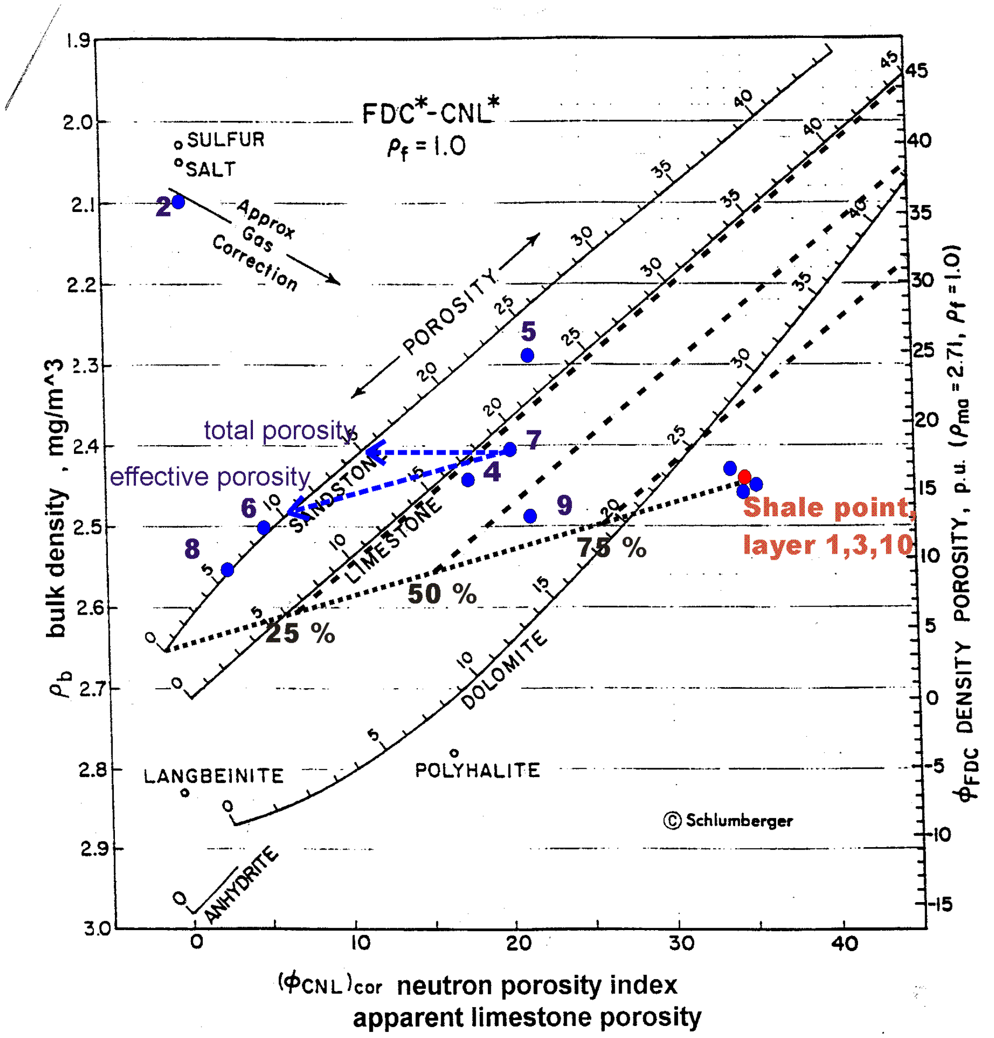

Natural
Gamma ray
API
0
100
sandstone
Line
Shale
line
Resistivity
Laterolog Deep
Ohm.m
0
500
1000
Neutron Log
Porosity ratio
35
10
-15
Density log
g/cc
2
3
1500
1510
1520
1530
1540
1550
IN FDC-CNL PLOT

FIGURE 3

FIGURE 4



Most relevant minerals, composition, density and main occurrence (from Carmichael, 1985 and Schlumberger 1989)

Name	Composition	Density kg/m³ x 10³	Occurrence *
Silicates			
Olivine	$(Mg,Fe)_2 SiO_4$	3.2 - 4.14	i, v
Garnet	$(Fe,Mg,Ca)_3.(Fe,Al)_2.(SiO)_3$	3.75 - 4.25	i, m
Pyroxenes	$(Ca,Mg,Fe,Al).[(Al,Si)O_3]_2$	3.2 - 3.5	i, m
Amphiboles	$Ca_{0-2}.(Mg,Fe,Al)_{5-6}.[(Al,Si)_4O_{11}]_2.(OH)_2$	3 - 3.2	i, m
Quartz	SiO_2	2.65	i, (v), m, s-cl/ch, d
Feldspar	$(Na,K,Ca).Al.(Al,Si)_3.O_8$	257 - 2.76	i, m, v, d, s-cl
Micas	$K_{0-1}.(Mg,Fe,Al)_3.(Al,Si)_3.O_{10}.(OH)_2$	2.7 - 3.2	i, m, (d)
Clay minerals	$(K,Na,Ca,Mg)_{0-2}.[(Al,Si)_8.O_{20}].(OH)_{2-4}.n(H_2O)$	2.5 - 2.65	s-cl/ch, m, d
Carbonates			
Calcite	$Ca.CO_3$	2.72	s-ch/cl, d (i)
Dolomite	$(Ca,Mg).CO_3$	2.85	s-ch/cl, d (i)
Siderite	$Fe.CO_3$	3.96	s-ch/cl, d
Sulphides & sulphates			
Pyrite	FeS	5.02	i, m, d, s-cl
Galena	PbS	7.6	i, m, d, s-cl
Sphalerite	ZnS	4.1	i, m, d, s-cl
Gypsum	$CaSO_4.n(H_2O)$	2.31	d
Anhydrite	$CaSO_4$	2.96	s-ch, d
Oxides			
Haematite	Fe_2O_3	5.28	i, m, (v), d, s-ch/cl
Magnetite	Fe_3O_4	5.20	i, m, (v), d, s-cl
(Hydro)-Carbons			
Coal	C:H:O - Antracite: 93:3:4, Bituminous; 82:5:13	1.8 - 1.2	s-cl/ch, d
Oil	$n(CH)_2$	0.85	d
Natural Gas	$C_{1.1}H_{4.2}$	$0.83 \cdot 10^{-3}$	d
Fresh water		~1	
Sea water or brine		> 1	

i - igneous; v - volcanic; m - metamorphic; d - diagenetic; s - sedimentary; cl - clastic; ch - chemical