Problem 1

In Figure 1 you find two geological cross sections through a salt dome, overlain by a gas bearing sandstone reservoir, which is fully encased in shale. Figure 1A depicts the situation 20 million years ago, Figure 1B shows the present-day situation.
As the salt dome rises, the reservoir is pushed upward as well. The reservoir is closed and completely encased in shale. In the "paleo-situation" of 20 million years ago, the aquifer is subjected to a hydrostatic pressure regime. The gas gradient is 0.9 MPa/km.

Question 1: construct the present-day pressure profile of the gas bearing layer in point "A". (Figure 2)

In the 'paleo-situation', the GWC is located at 2500m. From the hydrostatic pressure at this point we can draw the gas gradient upward to the top of the accumulation at 2000m (see fig 1). Since the reservoir is completely closed, the pressure regime is maintained unchanged during uplift and we can construct the present-day situation by shifting the pressure profile upward by 500m.

As the salt is moving upward, it creates a horizontal, extensional stress field of 20 MPa in the reservoir and its top seal which might create fractures. The overburden stress gradient is 30 MPa/km. From laboratory experiments it appears that the seal has an "angle of internal friction" of 30° and a "cohesion" of 8 MPa.

Question 2: determine with the help of Mohr circles (Figure 3) the maximum pore pressure level in the reservoir at which 'seal breach' is still avoided.

The critical point is the present-day top of the structure at 1500m. Vertical stress is here 45 MPa. Together with the horizontal stress of 20 MPa we can now draw the Mohr circle (fig.2). The Mohr Coulomb failure line is determined by the cohesion and angle of internal friction. In order to determine the maximum allowable pore pressure before breach, we shift the circle to the left until it touches the line. This shift is 22 Mpa, which is then the maximum pore pressure

Problem 1

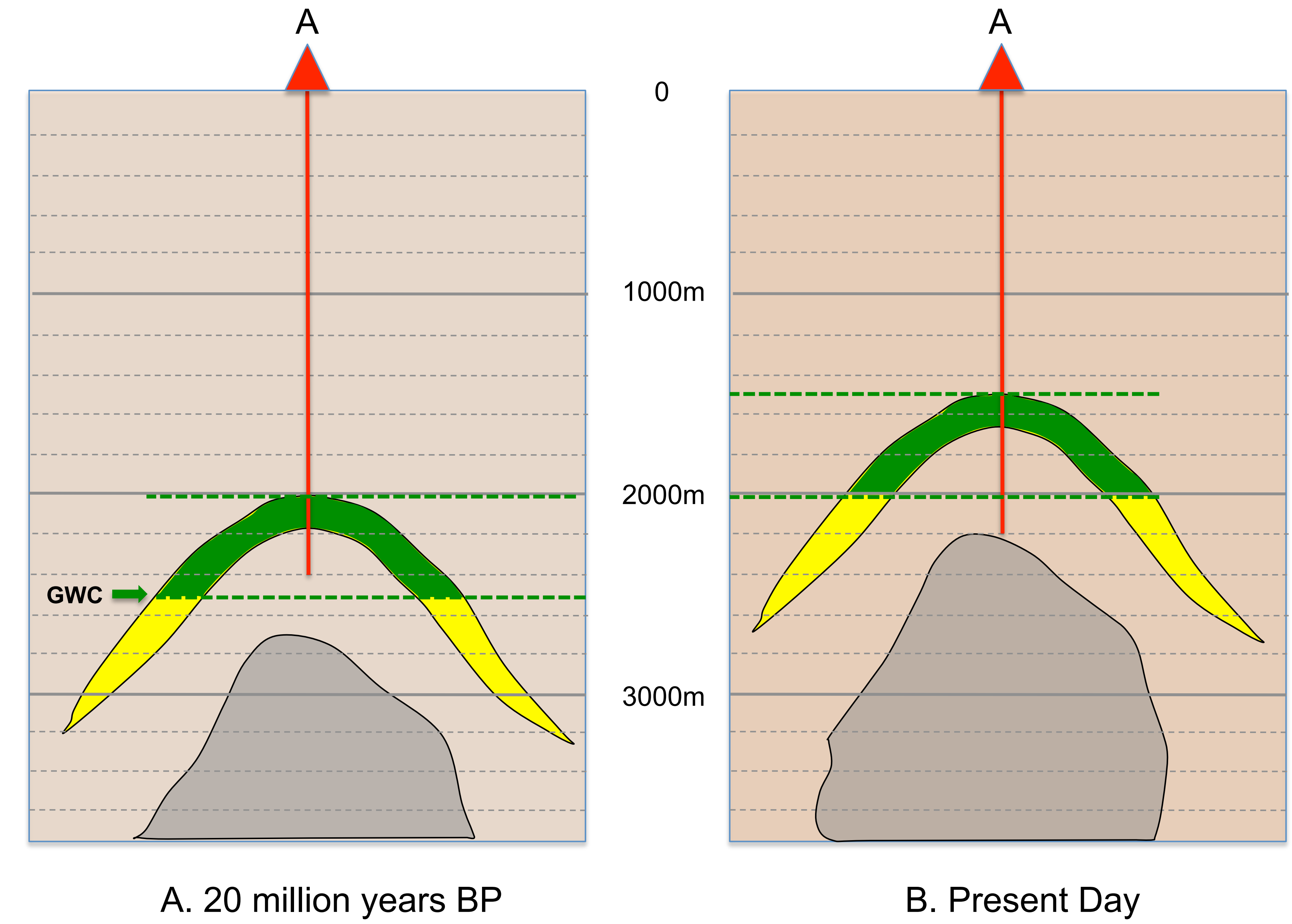
Question 3: what do you conclude for the likelihood that the reservoir is still gas bearing in present day conditions?

To answer this, we need to determine the gas pressure at the top of the structure from the pressure profile we constructed in Question 1 (Fig.4). This pressure is 25 MPa, which is higher than the maximum allowable pore pressure of 22 MPa. Conclusion is that the seal will be breached and gas will leak.

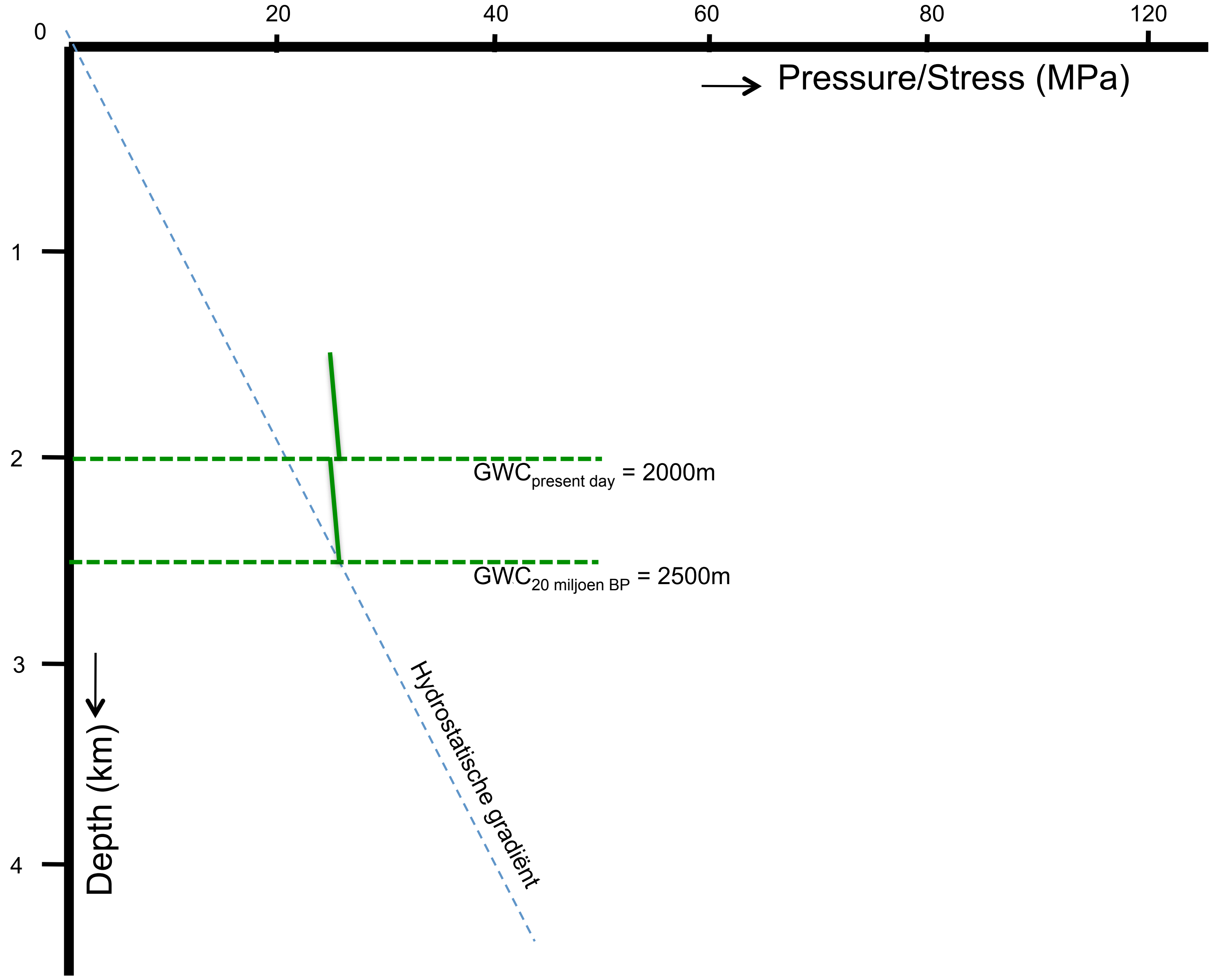
Question 4: consider a case where the reservoir is not completely closed and therefore has been in contact also during the last 20 million year with a hydrostatic pressure system: what can you say in that case about the length of the gas column? Will it be longer/equal/shorter than the column in Question 1?

If the reservoir is not completely closed and in communication with a hydrostatic pressure regime, this means that the pressure in the reservoir will drop during uplift. Hence the gas will expand and the column will be longer

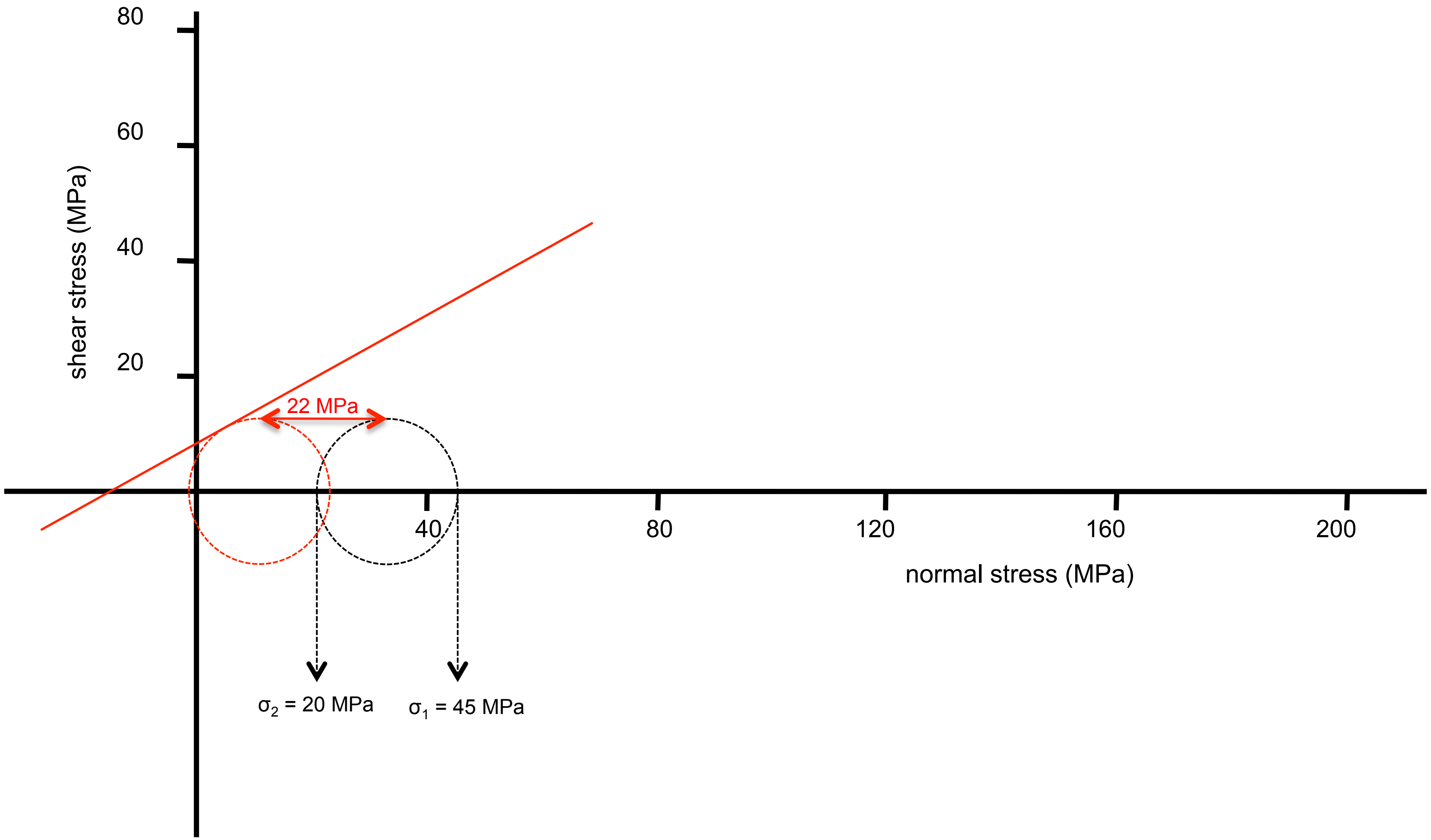
Problem 1 – Figure 1



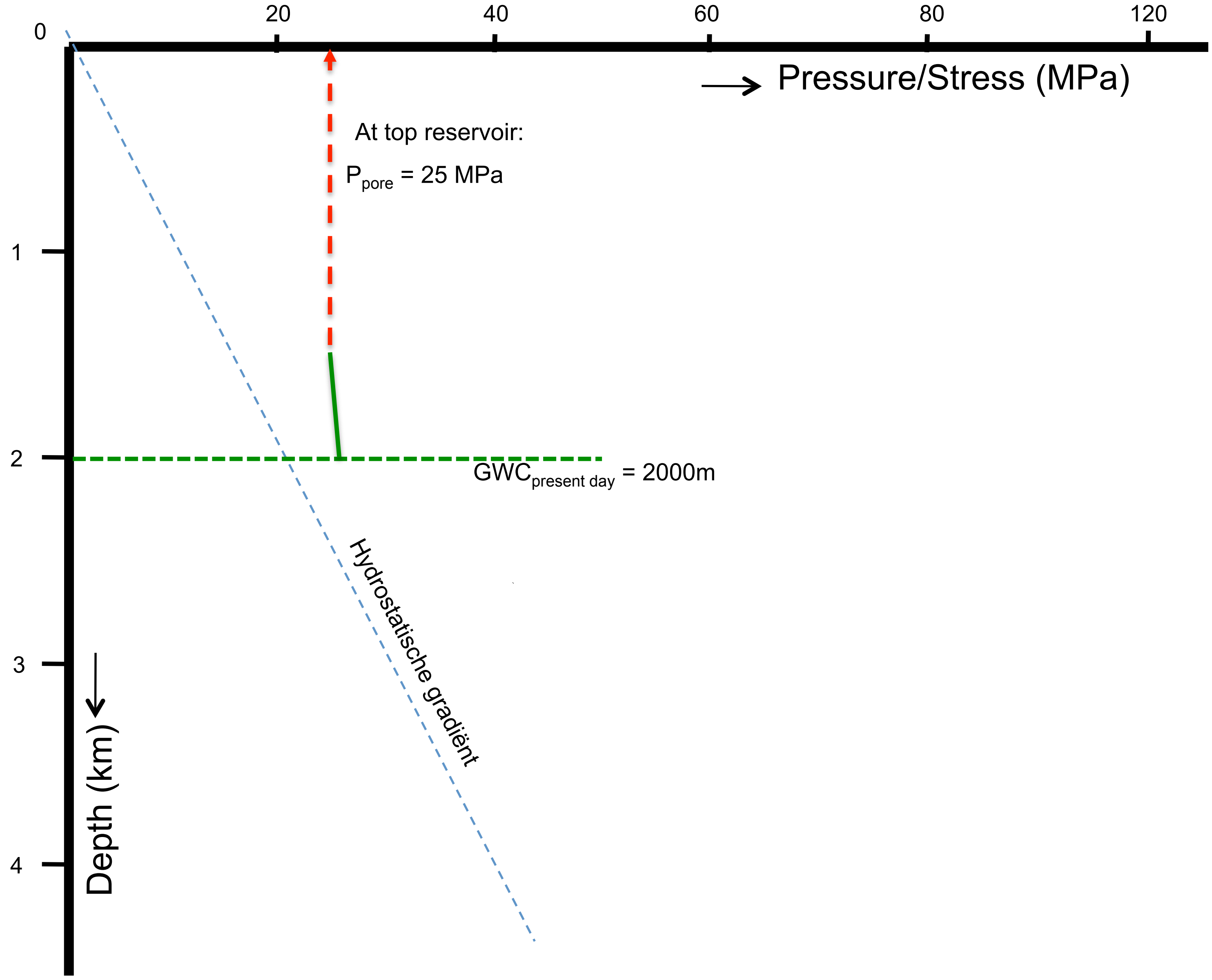
Problem 1 – Figure 2



Problem 1 – Figure 3



Problem 1 – Figure 4



Problem 2

A gas company wants to store its summer production of 20 BCM gas from the offshore in an empty gas field onshore. A field is available in the form of a horizontal sandstone layer with a 150m thickness in a rectangular horst-structure of 5 x 2.5 km with top reservoir at 2500m. This horst is bounded by faults on all sides where salt layers form a lateral seal. The field is hydrostatic and is situated in an area with a geothermal gradient of 3˚C/100m.
The standard conditions at the surface are a temperature of 15˚C and atmospheric pressure of 1.01325 bar. The sandstone reservoir has a Net-to-Gross ratio of 25% and an irreducible water saturation of 10%.

<u>Question 1</u>: What is the minimum porosity the reservoir should have to be able to store this gas volume?

A competing power company has however bought the empty field for CO_2 storage.

<u>Question 2</u>: How many million tonnes of CO_2 can be stored in this field, whilst taking into account a safety margin of 10 bar below the original pressure of the gas field?

<u>Question 3</u>: In Figure 3 you see 2 seismic sections through the reservoir: 3A shows the acoustic impedance before injection and 3B the section at the same location but after 10 years of injection. Indicate on section 3B where the CO_2 is situated.

<u>Question 4</u>: some thin red layers are visible on section 3B (indicated with arrows).
What do these layers represent?
Why does the lower layer get brighter on 3B when comparing with 3A?

<u>Question 5</u>: What causes the “pushdown” on section 3B?

Problem 2

Question 1

Bulk rock volume : 5 x 2.5 x 0.15 km^3 = 1.87 10^9 m^3

Storage space available: Bulk Volume x N/G x S_g x phi = 1.87 x 0.25 x 0.9 10^9 phi = 0.42 10^9 phi (1)

where phi is porosity

Gas available for storage at standard conditions: 20 10^9 m^3

Expansion factor E = $(T_s/p_s) . (p/ZT)$

T_s = 288˚K at surface

P_s = 1.01325 bar at surface

T_{2575m} = 365˚K

P_{2575m} = 258 bar

Z_{2575m} = 0.93 (see fig.1) Hence E = 216

Gas volume at 2575m: 20 10^9 / 216 = 0.0926 10^9 m^3 (2)

Combining expressions (1) and (2) gives: 0.42 phi = 0.0926 --- >   phi = 22% as the minimum porosity

Problem 2

Question 2

Storage space available: 0.42 x 0.22 $10^9 m^3$ = 0.092 10^9 m^3

Density of CO_2 at 2575m and 92˚C and 248 bar (from graph in fig.2): 630 kg/m^3

Mass of CO_2 = 0.092 10^9 x 0.63 Tonnes = 58 Mton

Question 3

See zone indicated on fig.3B

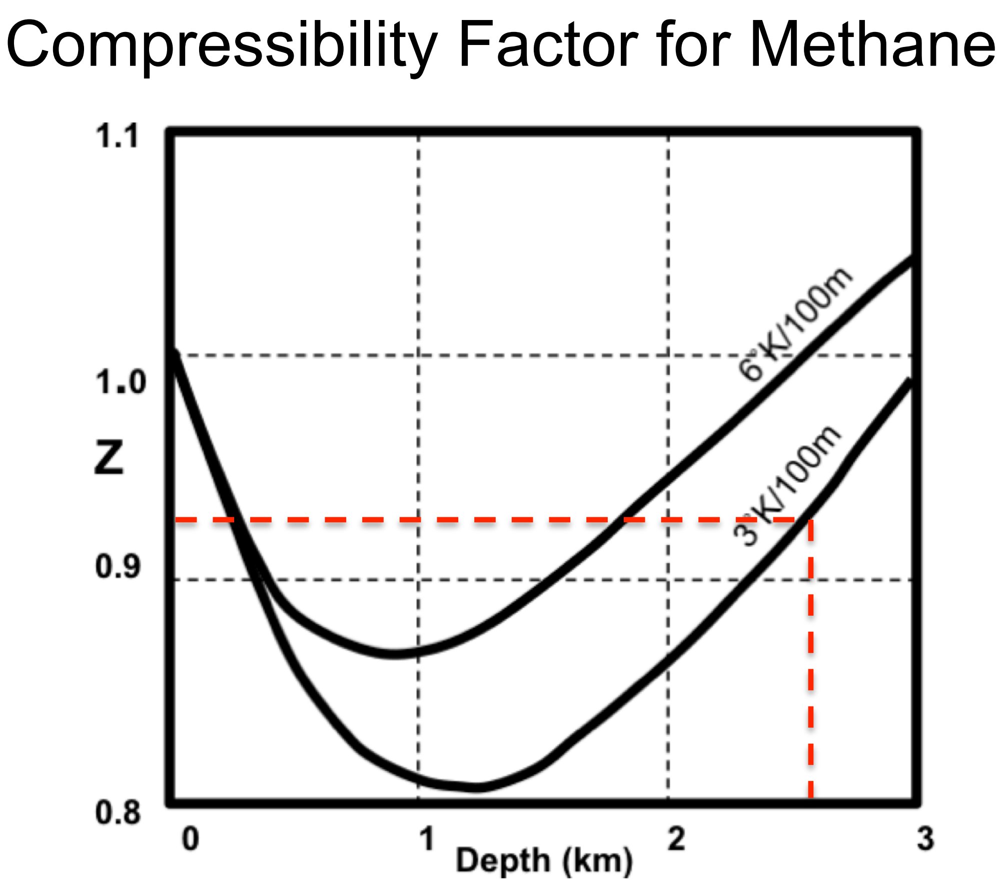
Question 4

The thin red layers indicated with arrows represent acoustically 'hard' layers embedded in the sandstone. These very likely represent shale layers since their acoustic impedance has not become 'softer' due to CO2 injection and thus have likely no porosity. The lower layer is brighter on 3B than on 3A since the acoustic impedance of the surrounding, initially waterbearing sandstone is reduced due to the presence of CO2 gas which yields lower density and velocity.

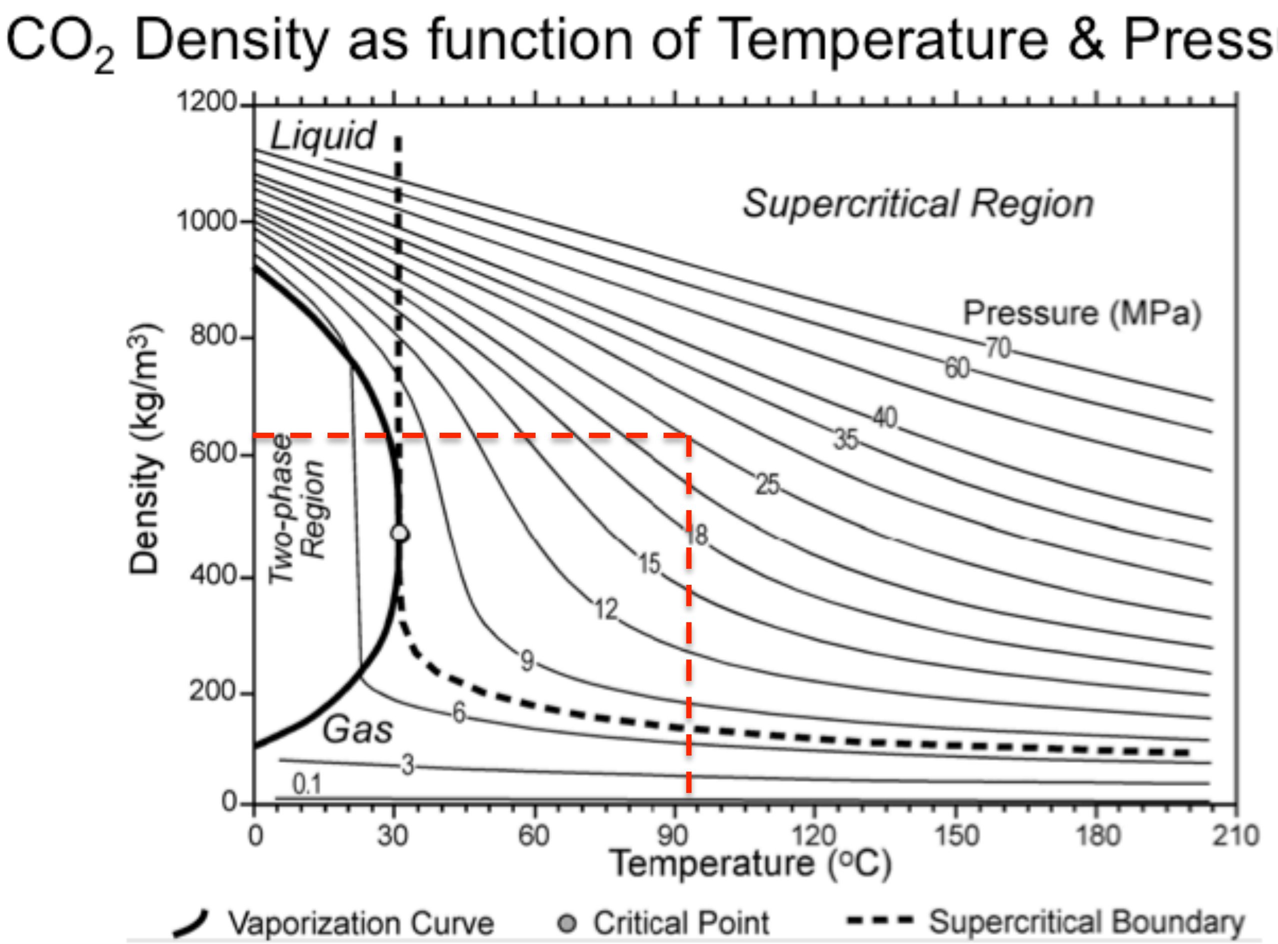
Question 5

The acoustic velocity of the sandstone is locally reduced due to the presence of CO2. This results in a time-delay for the underlying layers on the seismic time section, thus creating a 'pushdown' in time

Problem 2 – Figure 1



Problem 2 - Figure 2

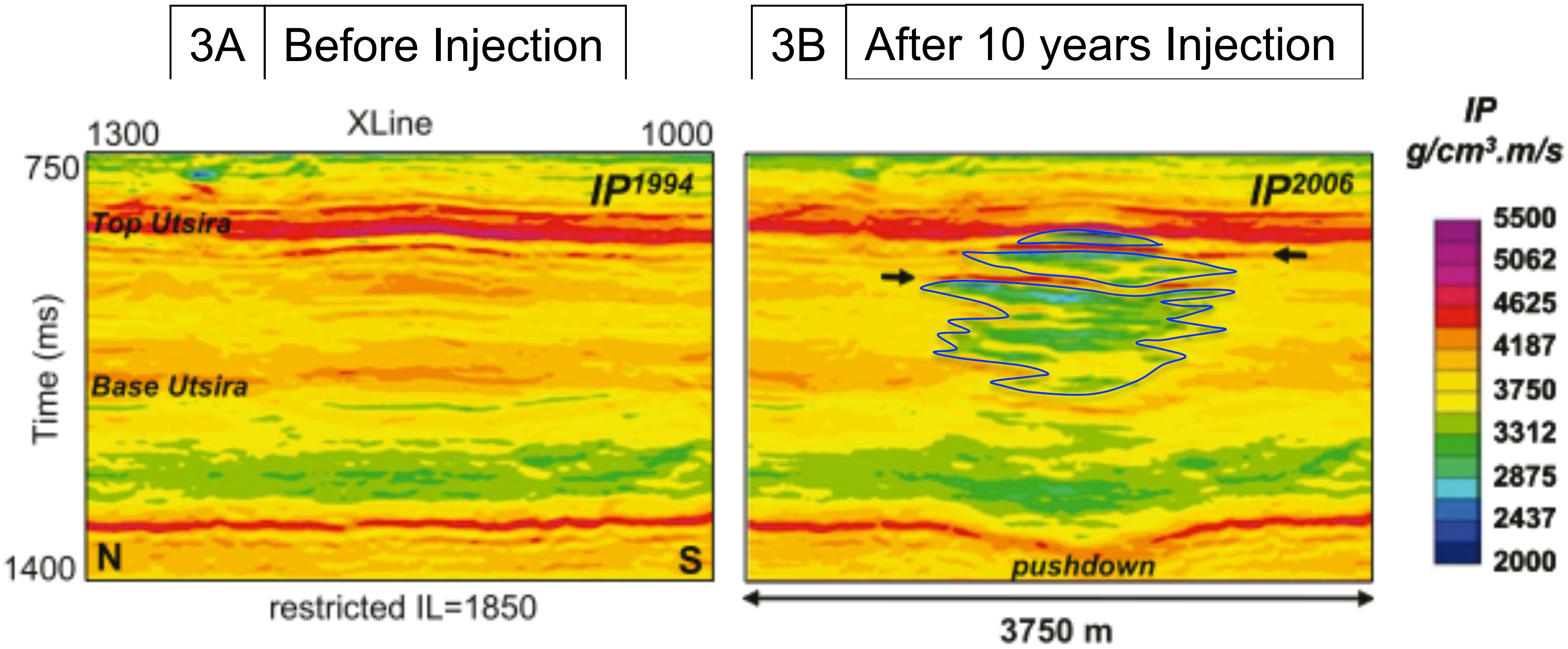


At standard conditions: ρ = 1.87 kg/m^3

NOTE: 1 bar = 0.1 MPa

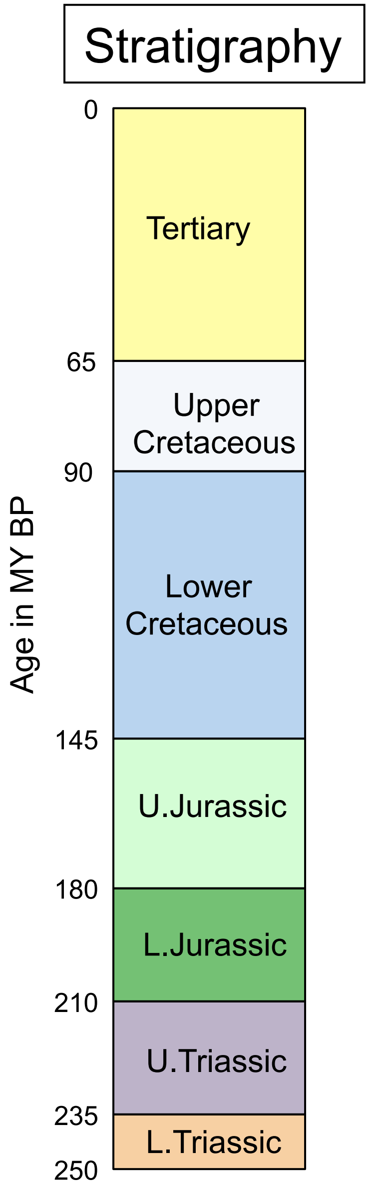
Problem 2 – Figure 3

CO$_2$ Injection – Seismic Monitoring



IP = P-wave acoustic impedance

Problem 3



Consider the seismic depth section (Figure 1) in a geological province which was subjected to several phases of uplift and deposition.
The chrono-stratigraphic column is given to the left.

Questions:

1) The basement rocks in the deeper part of the section mainly consist of basalts. Taking into account the magnetic behaviour of the sedimentary rocks as well, you can sketch the magnetic profile which we would measure along this section (top Figure 1)

2) Assuming that the deformation in the layers in location "A" is caused by movement of the deeper salt layer, at which time did this movement start?

3) There are 2 main unconformities visible; indicate both on the cross section with the symbol 

4) The unconformities at location "B" do not seem to be related to salt movement, since there is no anomalous salt thickness observed in "B". What else could cause these unconformities?

5) The government is asking to be advised about the suitability of well locations "A" and "B" for safe storage of CO_2 in Lower Cretaceous reservoirs. Based on the geological information on the cross section, what would be your advice for each location? Please motivate your answer.

Problem 3

Question 1

The magnetic profile is affected by the depth of the magnetic basement. The overlying sediments have very low susceptibilities and therefore have no effect on the magnetic profile (see Fig.1)

Question 2

We can determine the time of growth of the salt dome by inspecting the thickness variations of the overlying layers. The Lower and Upper Triassic do not show any lateral thickness variation over the dome. This means that they were already deposited when the salt started to move. The Lower Jurassic shows some light thinning over the top of the dome when compared with the flanks. This means that the salt started to move somewhere in the time interval 210-180 MY ago.

Question 3

Unconformities are caused by erosion followed by normal deposition. We therefore need to look for places where the base of a stratigraphic unit shows an angular relationship with the underlying unit, accompanied by a thinning of that lower unit. On the seismic section in fig.1the 2 unconformities occur at the base L.Cretaceous and the base Tertiary

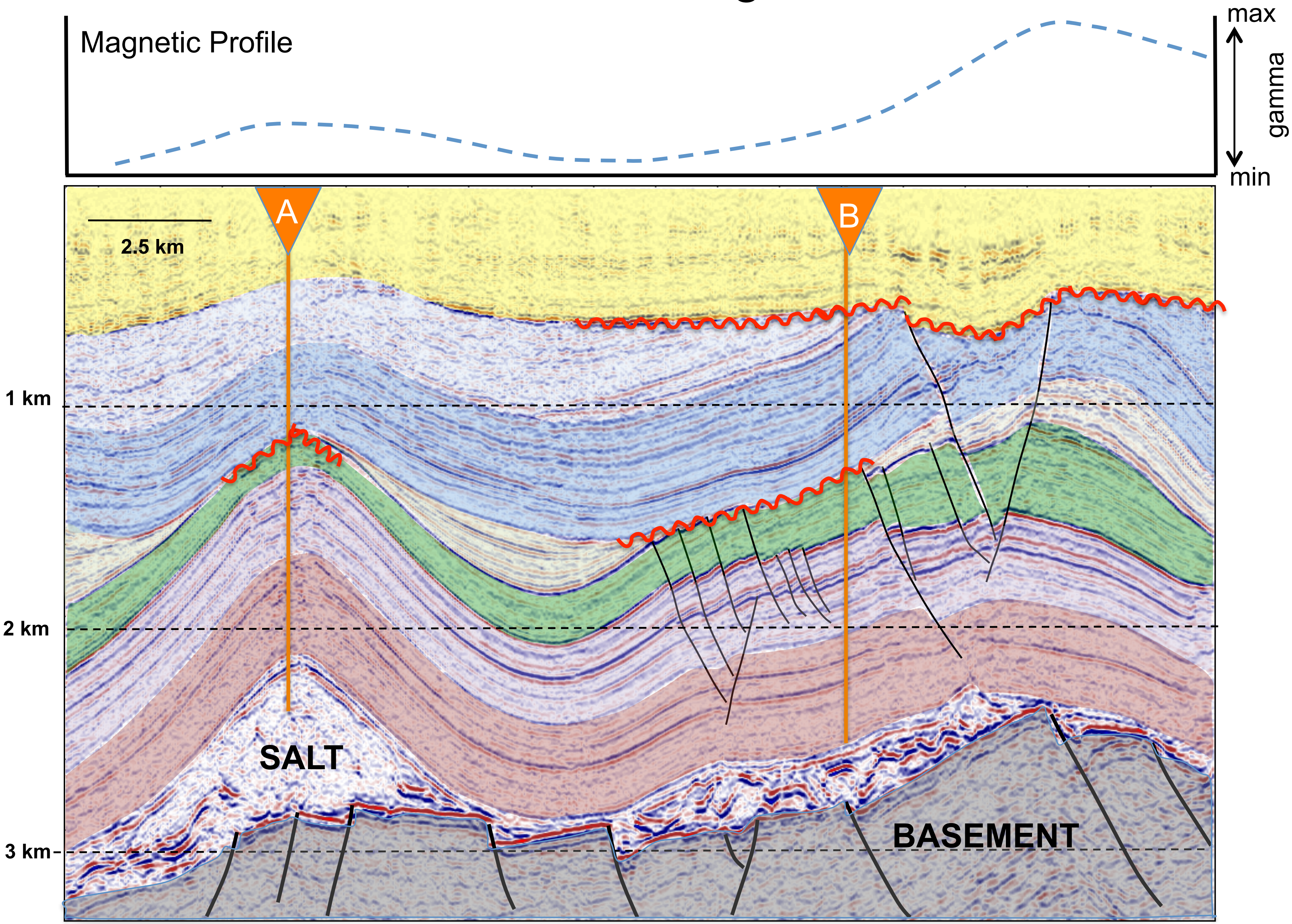
Question 4

The unconformities are caused by an overall uplift (in 2 phases) of the deep seated magnetic basement

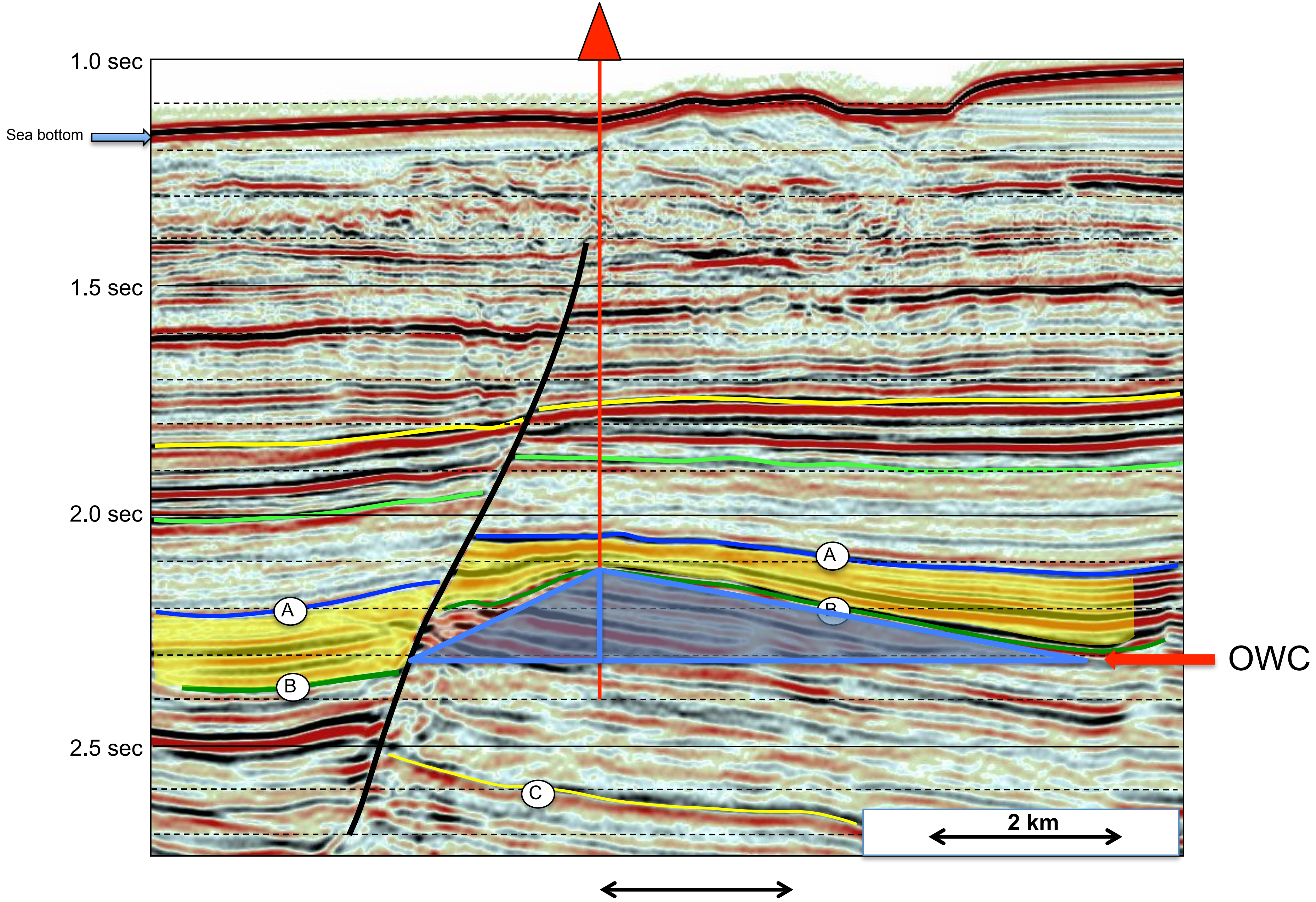
Question 5

In location A the L.Cretaceous layers are forming a structural closure, at least on 2D seismic, and are not affected by faulting. This seems to be a safe location for CO_2 storage, provided the closure is also present in a 3D sense.
To the right hand side of location B the L.Cretaceous is partially eroded and also quite severely faulted. This represents a strong risk of top- and lateral seal leakage. B is not a safe location for injection of CO_2

Problem 3 – Figure 1



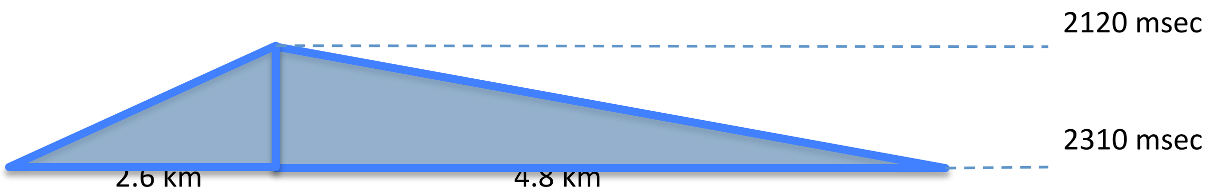
Opgave 4 – Bijlage 1



Problem 4

Question 1:
A seismologst has interpreted the oil-water-contact (OWC) at 2310 msec. At this level we see a number of reflections in the reservoir changing character from “bright” above 2310 msec to “dim” below. This can be caused by the fact that the density of oil is lower than that of water which makes the reflection coefficient at contrasts between porous sands and shale intervals larger in the oil-filled zone. Secondly, it appears that on the right-hand side of this (2D) seismic line the spillpoint of the structure is situated a this level as well. There is however one proviso: the spillpoint can only reliably be determined in a 3D sense and it therefore not sure that this seismic line is representative!

Question 2:
We first calculate the bulk-rock volume, and for this purpose we approximate the cross section of the reservoir above the OWC by 2 adjacent triangles (see also fig.1)



The common height of the triangles is: $0.5\ \Delta t \times v_{reservoir} = 0.5 \times 0.19 \times 3000 = 285$ m
Their area then becomes: $285 \times (2600 + 4800) / 2 = 1.0545\ 10^6\ m^2$
And the bulk rock volume: $V_{bulk} = 10\ 10^3 \times 1.0545\ 10^6 = 1.0545\ 10^{10}\ m^3$

The oil volume is then: $V_{oil} = V_{bulk}\ .\ \varphi\ .\ N/G\ .\ S_{oil} = 1.0545\ 10^{10} \times 0.25 \times 0.2 \times 0.75 = 395\ 10^6\ m^3$

And under standard conditions: $STOIIP = V_{oil} / B_0 = 395\ 10^6 / 1.3 = 304\ 10^6\ m^3$

Opgave 4

Question 3:
In the interval 9150 – 9650 ft the average hydrocarbon yield 20 ‰ (fig 2)

Thus the yield in mass of oil per m^3 sourcerock is: 0.02 x 2300 = 46 kg/m^3

This delivers a volume of 46 / 800 = 0.06 m^3 oil per m^3 sourcerock

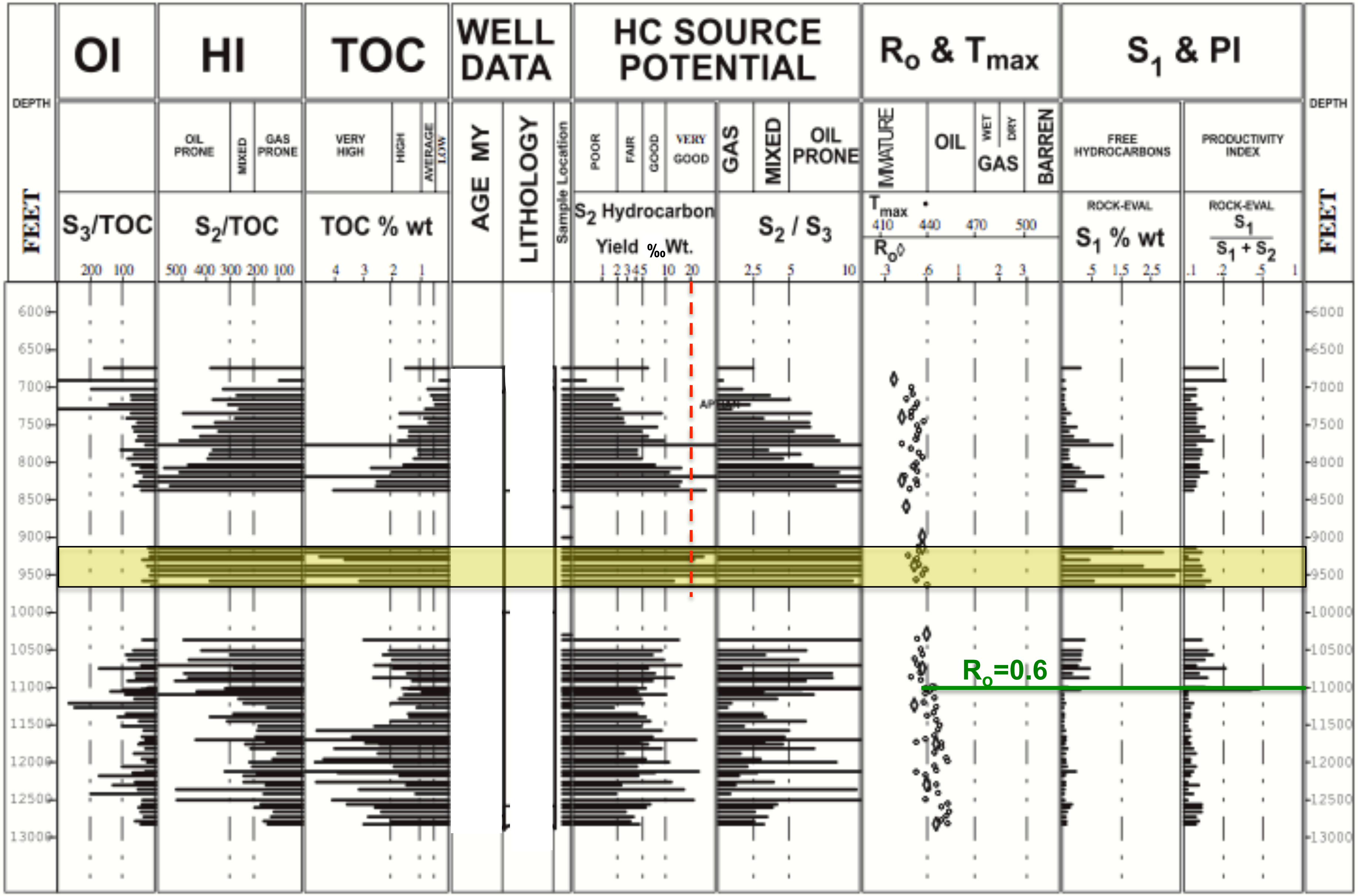
Over a length of 500 ft = 152m this results in 152 x 0.06 = 9 m^3 oil per m^2 sourcerock
And 9 10^6 m^3 oil per km^2 sourcerock of this thickness.

The in situ oil volume in the field is 395 10^6 m^3 (from question 2)

Therefore this requires an area of 395 / 9 = 44 km^2 with sourcerock needed to fill the field

Question 4:
the minimum depth where the source rock is mature (VR>0.6) for oil is 11000 ft = 3300m (fig 2)
On the seismic line the deepest point of horizon "C" is situated at approx. 2650 msec, which is 340 msec below the OWC. With an interval velocity of 3000 m/sec this translates into 0.34 x 3000 / 2 = 510m under the OWC.
The depth of the OWC we determine at the well location:
OWC = waterdepth + thickness interval (seabottom-horizon B) + interval (horizon B – OWC) making use of the arrival times and seismic velocities:
OWC = (1130 msec x 1500 /2) + [(2120 – 1130 msec) x 2500 /2] + 285 (question 2) = 847 + 1237 + 285 = 2370m
Horizon C is thus situated at 2370 + 510 = 2880m where the sourcerock is not yet mature.

Opgave 4 – Bijlage 2



Problem 5

Below you find 9 statements; some are true, some are false.
Please indicate for each statement whether it is true or false.

1. The "spreading rates" of oceanic crust in the Pacific are considerably larger than in the Atlantic Ocean — true

2. Coral reefs cannot be formed at water depths around 4000m due to the fact that carbonate particles dissolve below the "Carbonate Compensation Depth" — false

3. Fluvial point bar reservoirs have a limited lateral continuity — true

4. When during drilling of a well the level of the "drilling mud" in the annulus is rising, it is required to decrease the "mudweight". — false

5. Gypsum is the first mineral which precipitates when a sea or salt lake dries out through evaporation — true

6. In an unconventional "basin centred gas" accumulation in tight sandstone the relative permeability for gas is zero at water saturations of more than 40-50% — true

7. The amount of gas (eg methane or CO_2) which can be absorbed in a coal layer decreases with increasing pressure — true

8. The continental heatflow is larger than the oceanic heatflow — false

9. The compressibility factor Z is independent of the type of gas — false