Comments on exam problems 1 and 2, 2015 (Bo Holm Jacobsen, June 26, 2015)

In the following, I will comment on how the exam problems were supposed to be answered, and I will highlight some of the likely mistakes. Hopefully, this may be helpful for you as exam participants, and also for future students who use these exam problems for training.

In the following, the official text is in Times New Roman fontsize 10 and my comments are in Calibri fontsize 11.

General advice:

- **Possibly rip off figures and inspect carefully while reading the problem text.**
- **Remember that often you are supposed to draw results on figures and hand in these figures with your answers.**
- **Be very careful when reading data values from graphs. Use about 30 seconds per point you read, making sure that you get axis values and units right. You have plenty of time for that.**

Problem 1

You have just been employed at the company SeisConQuest on an investigation of a possible oil / gas field near the Somali coast. Only one reflection seismic profile is available at the site. About 50 km from the location a single well has been drilled.

Table 1 shows the three main lithologies with associated depth interval, P-wave velocity and density.

1. *Interval velocity in the first layer:* Fig. 1a and 1b show CMP-sections at the position x = 5 km and x = 20 km along the seismic profile. Two prominent reflections (marked A and B) are supposed to represent the two layer boundaries between chalk and clay (hyperbola A) and clay and sand (hyperbola B).
   Determine the rms velocity of the chalk layer from hyperbola A at the two positions. It's okay to use only two readings on each hyperbola.
   Use the x^2-t^2 method: Read (x,t) at two points along a hyperbola, compute the ratio of differences, and the square-root. This method determines the rms-velocity between the surface and the reflector. Some were confused by the term rms-velocity and tried to make some computations using lecture notes equation (2.55).

2. *Thickness of the first layer:* Fig. 2 shows the time section along the seismic profile. Again, the two main reflectors are marked by A and B. Table 2 row b shows the two-way time to reflector A for every 5 km along the profile. Note that two two-way times are missing: Read two-way times to reflector A at x = 0 km and 15 km and enter them in Table 2 row b.
   Calculate the depth to reflector A, using as interval velocity the average of the two velocities computed in question 1. If you have not solved questions 1, you may use the appropriate P-wave velocity measured in the drilling, see Table 1.
   Draw reflector A in the depth section in Figure 3. Note the vertical exaggeration 1:10.
   Take the two-way times in Table 2 row b and divide by two, and multiply by the velocity of the first layer. You get full points for this also if your velocity computed in question 1 was wrong.

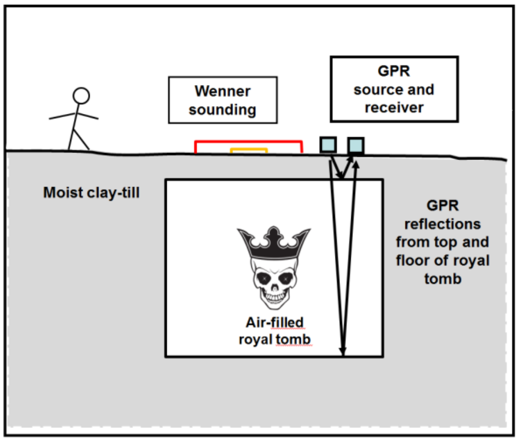
3. *Interval speed in the second layer:* Consider again the CMP-sections in Fig. 1a and b. Determine the rms velocity between the surface and reflector B at both x = 5 km and x = 20 km.
   Then determine an average interval velocity of the clay layer between reflector A and reflector B at both positions.
   Same procedure as question 1. The resulting rms velocity for reflection B is clearly different at the two locations because the thicknesses vary a lot along the profile.
   Then engage Dix' equation (2.58) in order to get the estimate of the interval velocity between A and B. The resulting interval velocities are very similar (~2000 m/s) at both locations.
   Some take the average of the two rms-velocity estimates, which is wrong. You only get the same interval velocity from Dix' equation if you use the different rms-velocities estimated from the hyperbolas.

4. *Geometry of the second layer:* Fill in the rows e, f and g in Table 2 and plot reflector B in the depth section in Fig. 3.

Subtract row b from row a to get row e. Then use this time difference and the interval velocity from question 3 (~2000 m/s) in equation (2.59) to get the thickness of the second interval (row f). Add the two layer thicknesses (row d and row f) in order to get the full depth to the base of the interval which is also the depth to reflector B.
It is not completely correct to use the rms-velocity from hyperbola B to depth-convert the full two-way time to reflection B. I would, however, give some credit for such a computation. But you cannot use it at the points (0 km, 10 km, 15 km, 25 km) because you cannot observe the reflection hyperbola from B at these locations. It is entirely wrong to use an average of the B-reflection rms-velocities at the two locations.

5. *Reflection coefficients:* The waveforms of the reflections show that reflection A swings to the negative side (left) along the entire profile, while reflection B swings to the positive side (right), except for the interval between x = 10 km and x = 15km. Explain why this is to be expected from the speeds and densities found in the well, see Table 1. Explain also why the change of sign in the reflectance of reflector B in the range between x = 10 km and x = 15 km may indicate a gas accumulation, i.e. a layer of sand where gas has replaced water as the pore fluid.
Compute reflection coefficients using equation (2.11), either directly from the densities and velocities in Table 1, or by first computing the acoustic impedances. Still, these two reflection coefficients (-0.18 and +0.07) are only estimates, because the interval velocities along the profile differ somewhat from the values in the well (Table 1).
Several of you give qualitative arguments, focusing on either the velocities or the densities. I was generous with points also for such arguments.
Concerning the possible occurrence of gas, I was happy with arguments emphasizing that both sound velocity and density of gas is very low, hence making it likely that gas-sand can have a lower impedance than the clay, thus explaining the flip of sign in reflection B.

Problem 2



The company iArcheo wants to win an EU contract for the geophysical investigation of a number of large royal tombs in the Caucasus region. You have just been hired by iArcheo to make interpretation of some basic example data that iArcheo gathered at one of these royal tombs.
An earlier excavation of another royal tomb revealed an almost cubic air-filled chamber with an edge length of approximately 4 meters.
The left picture illustrates the target as well as two of the involved measuring methods.

1. Using a highly accurate gravimeter a gravity profile was measured with points every metre along a 25 m long profile over the royal tomb. You may assume that the gravimeter sensor was located at a height of 0.2 m above ground level, defining z = 0 m.
Fig. 4 shows the residual anomaly after removal of the regional level. Determine the location (x_{tp},z_{tp}) of the center of the burial chamber (i.e. center of gravity) using the assumption that it can be modeled as a homogeneous sphere.
Most of you had no difficulty determining the center coordinates of the mass. I was generous also if the readings were a bit sketchy. Thus, the smallest reading is at x=12, but the anomaly is clearly displaced, so a value like 12.3 m is more correct.
Depth from the measurement level to center of gravity also came out well for most of you.
But only very few realized that you had to correct for the height of the gravity sensor. So the depth coordinate, z_{tp}, of the mass is 0.2 m less than the depth below the measurement level. Note that we

trained this aspect again and again when modelling magnetic data in the field course.

2. Determine the excess mass below the anomaly. Determine the volume of a tomb, if it is assumed to be air filled. Finally, determine the edge length, assuming that the chamber is cubic. It may be assumed that the burial chamber is surrounded by moist clayey till with a density of 1800 kg/m^3.
   Most of you used the correct equation (3.81). Note that because g_{ampl} is read from the data measured at a height of 0.2 meter above ground, you need to insert $h_{tyngdepunkt} = z_{tp}$+0.2 m. I did not deduct if you used $h_{tyngdepunkt} = z_{tp}$.
   Some forgot to multiply mGal by 10^{-5} to get to m/s^2, and therefor got much larger mass and volume.
   Some used g_{ampl} = +3.1 mGal. This is a very sad choice because it must be taken from some other exercise. I had to rate this as a serious lack of uncertanding of gravity interpretation.
   The volume is simply the excess mass divided by the density contrast. Some use equation (3.84) to get the radius of the approximating sphere and then compute the volume of the body from this. This is ok too.
   The density contrast is the density of the cavity (air ~1 kg/m^3,) minus the density of the till (1800 kg/m^3). I did not deduct if you used -1800 instead of -1799. But I had to deduct in those cases where you used a density of 1000 kg/m^3. Water is so much heavier than air, and it really makes a difference here.
   The edge length of the cubic chamber is clearly the third root of the volume, resulting in a value of ~3 m. So, it seems to be the tomb of a slightly smaller king.
   Some gave the diameter, 2*b, as the edge length. I did give almost full points for that, although the volume of a cube surrounding a sphere has about twice the volume of the sphere.
   Some gave the radius b as the edge length. I did not accept that.

3. The tomb has an almost flat upper surface, which is convenient for geoelectrical sounding. Table 3 contains data measured by the Wenner configuration with electrode spacings, a, between 0.1 and 2 meters. Calculate the lacking apparent resistivity at a = 1 meter. Draw the missing data point in the loglog-plot in Fig. 5. Determine the resistivity of the first layer (moist clayey till in Caucasus) and the depth to the interface where the resistivity increases (the ceiling of the burial chamber).
   Table 3 gives voltage and current values which you divide to get R, and then multiply by the geometrical factor to get the apparent resistivity (in this case 99 Ohmm). Almost all of you got this right, and you also plotted the data in the Schlumberger graph, Figure 5, taking into account that L/2 = 1½ a.
   The transparent rising curves are fitted, and you get a first layer resistivity of between 50 and 55 Ohmm, and a layer thickness of about 0.8 m. I was generous as long as the depth was between 0.6 and 1 m, although the fit is rather poor at these extremes.
   None of you mixed up these resistivity values determined in this exercise and the density values determined in the previous gravity question ☺

4. iArcheo plans to use also GPR (georadar) to map the interiors of the royal tombs. As part of the preparations, you must answer the following:
   What is the skin depth in the rock (moist clayey till) covering the burial chamber?
   Is it realistic to reach the burial chamber with GPR?
   Calculate two-way time for a GPR reflection from the top-side of the burial chamber as determined in question 3 (if you did not find a value for the layer thickness, you may assume the layer thickness to be 1.2 meters).
   Calculate also the expected two-way time for reflections from the bottom of the chamber, assuming that the burial chamber is 4 meters high.
   You may assume that the dielectricity number, K, of the clayey till is 30.
   Use equation (6.13). In question 3 the resistivity of the moist clayey till was determined. The dielectric constant, K, is given in the last sentence above. The result comes out as about 1.5 m. This is clearly larger than the layer thickness determined by the Wenner data, so iArcheo may feel confident that GPR can penetrate to the chamber, at least at this location.
   Some give the d_{limit} from equation (6.21). I give good credit for this.

Some grabbed the density from problem 1 and inserted in the skin depth equation (6.13). Not good, what more can I say ☹.
The calculation of two-way time for the GPR reflections from the top of the chamber follows the same reasoning as used a lot in Problem 1. The GPR velocity is given in equation (6.15), with some examples in Table 6.1.3.
The last and supposedly most challenging question regarded the two-way time of the reflection from the bottom of the chamber. Several of you did correctly take into account that the GPR-velocity in the chamber is equal to c, the speed of light, which is $K^{1/2}$ times faster than the velocity in the till.
Some of you grabbed some seismic velocities for these calculations. I could not give credit for that.

```
%Opg 1
%sp 1
%Aflæsninger på hyperbel A ved x = 5 km:
offset1=100; twt1 = 0.53;
offset2 = 2000; twt2 = 0.91;
VrmsA = 1/sqrt((twt2^2-twt1^2)/(offset2^2-offset1^2)),
VrmsA =   2.7003e+03
%sp2
twt_0km = 0.57,
twt_15km = 0.22,
zA_0km = VrmsA*twt_0km/2,
zA_0km =  770
zA_15km = VrmsA*twt_15km/2,
zA_15km =  297
twtA_obs =     [0.57  0.53  0.22  0.22  0.22  0.22];
zA_obs = VrmsA*twtA_obs/2, %skrives i række d i tabel 2
zA_obs =  769.5880  715.5818  297.0339  297.0339  297.0339  297.0339
%sp3
%CMP x = 5
twtB1 = 0.719; twtB2 = 1.068;
VrmsB = 1/sqrt((twtB2^2-twtB1^2)/(offset2^2-offset1^2)),
VrmsB =   2.5294e+03
twtA = 0.53;
twtB = 0.72, %næsten, da offset=100m
V2_CMP5km = sqrt((VrmsB^2*twtB - VrmsA^2*twtA)/(twtB-twtA)),
V2_CMP5km =   1.9758e+03
%CMP x = 20 km
twtA1 = 0.22, offset1 = 100;
twtA2 = 0.77, offset2 = 2000;
VrmsA = 1/sqrt((twtA2^2-twtA1^2)/(offset2^2-offset1^2)),
VrmsA =   2.7070e+03
twtB1 = 0.82; twtB2 = 1.22;
VrmsB = 1/sqrt((twtB2^2-twtB1^2)/(offset2^2-offset1^2)),
VrmsB =   2.2113e+03
twtA = twtA1;
twtB = twtB1; %næsten, da offset=100m
V2_CMP20km = sqrt((VrmsB^2*twtB - VrmsA^2*twtA)/(twtB-twtA)),
```

V2_CMP20km =   **1.998**9e+03
%Den faktiske værdi er 2000 m/s i lag 2.
%Vi får en mere stabil værdi ved CPM x=20 km, da der lag 2 her er tykkere.
%Den vise studerende vælger den værdi ved den følgende dybdekonvertering
%sp 4
twtB_obs = [0.72 0.72   0.72 0.72 0.82 0.82];
twt_lag2 = twtB_obs - twtA_obs, %række e i Tabel 2
twt_lag2 =   0.1500   0.1900   0.5000   0.5000   0.6000   0.6000
Tykkelse_ler = V2_CMP20km * twt_lag2/2, %række f i Tabel 2
Tykkelse_ler = 149.9199 189.8985 499.7330 499.7330 599.6796 599.6796
(150 190 500 500 600 600)
Dybde_B = zA_obs + Tykkelse_ler, %række f i Tabel 2
Dybde_B = 919.5079 905.4803 796.7670 796.7670 896.7136 896.7136
(920 900 800 800 900 900)
%sp5
Z_kalk = 2450*2350,
Z_kalk =   5757500 **(5.8 x 10^6)**
Z_ler = 1960*2040,
Z_ler =   3998400 **(4.0 x 10^6)**
Z_sand = 2210*2090,
Z_sand =   4618900 **(4.6 x 10^6)**
%Vi ser, at impedansen falder fra kalk til ler, hvilket giver negativ
%refleksionskoefficient.
%Omvendt vokser impedansen fra ler til sand, så R>0
R_A = (Z_ler-Z_kalk)/(Z_ler+Z_kalk),
R_A =   **-0.1803**
R_B = (Z_sand-Z_ler)/(Z_sand+Z_ler),
R_B =   **0.0720**
%Ved gas i porerne falder densiteten, og hastigheden falder endnu mere
%Vi har Wylies lov fra Logging-kapitlet, som giver endog meget lave
%hastigheder ved gas i porerne.
%Dermed vil det gasfyldte sand kunne få meget lav impedans og dermed
%negativ refleksionskoefficient.

%Opg 2
%Sp 1
%Vi aflæser
g_ampl = **-0.55**;
xtp = **12.2**,
x_halv = **3.8**/2;
z_raw = 1.305*x_halv,
z_raw =   2.4795 **(2.5 m)**
z_tp = z_raw - 0.2, %korrektion for gravimeter-højden
z_tp =   2.2795 **(2.3 m)**
%sp2
dM = -0.055*1e-5*z_raw^2/6.67e-11,
dM = **-5.0695e+04**
Vol = dM/(-1799),
Vol =   **28.2**
kant = Vol^(1/3),

kant = **3.04**
%Sp3
R_1m = 0.0584/0.0037,
R_1m = **15.7838**
K_1m = 2*pi*1,
K_1m = **6.28**
rhoa_1m = R_1m * K_1m,
rhoa_1m = **99.17**
Lhalv_1m = 1.5;
tykkelse_moraene = **0.8**;
rho_moraene = **51**;

%Sp 4
K = 30; rho = 51;
delta_GPR = 5.31e-3*sqrt(K)*rho,
delta_GPR = **1.48**33
%Vi ser, at skindybden er klart større end både tykkelsen bestemt ud fra
%data og den angivne nød-værdi på 1.2 meter, så det går lige akkurat an at
%prøve GPR.
%Bølgehastigheden i moræmen beregnes ud fra K,
%Bølgehastighed i kammeret SKAL være den i vacuum. Det er udfordringen i
%dette sidste spørgsmål at være opmærksom på dette.
c = 0.3; %m/ns
v_moraene = c/sqrt(K)
v_moraene = **0.0548**
twt_top = 2*0.8/v_moraene, %ns
twt_top = **29**.2119; %ns
twt_bund = twt_top + 2*4/c,
twt_bund = **55.9** %ns

Tabel 1 / Table 1:

	Interval [m]	P-bølgehastighed [m/s] P-wave velocity [m/s]	Massefylde [kg/m^3] Density [kg/m^3]
Kalklag / Chalk layer	0-300	2450	2350
Lerede lag / Clayey layer	300-600	1960	2040
Sandede lag /Sandy layer	600-620	2210	2090

Tabel 2 / Table 2:

a	x	0 km	5 km	10 km	15 km	20 km	25 km
b	Tovejstid til A [s] / Two-way time to A [s]	0.57	0.53	0.22	0.22	0.22	0.22
c	Tovejstid til B [s] / Two-way time to B [s]	0.72	0.72	0.72	0.72	0.82	0.82
d	Tykkelse af lag 1 (kalk) Thickness of layer 1 (chalk) [km]	0.77	0.72	0.30	0.30	0.30	0.30
e	Tovejs-tidstykkelse for lag 2 [s] / Two-way thickness of layer 2 [s]	0.15	0.19	0.50	0.50	0.60	0.60
f	Tykkelse af lag 2 (ler) / Thickness of layer 2 (clayey layer) [km]	0.15	0.19	0.50	0.50	0.60	0.60
g	Dybde til laggrænse B/ Depth to boundary B [km]	0.92	0.90	0.80	0.80	0.90	0.90

Tabel 3 / Table 3.

a [m]	I [A]	U [V]	R [Ohm]	ρ_a [Ohmm]
0.10	0.0033	0.2902	87.9	55
0.15	0.0036	0.1867	51.9	49
0.20	0.0052	0.2198	42.3	53
0.30	0.0033	0.0912	27.6	52
0.50	0.0029	0.0570	19.7	62
0.70	0.0044	0.0692	15.7	69
1.0	0.0037	0.0584	15.8	99
1.5	0.0021	0.0309	14.7	139
2.0	0.0069	0.1011	14.7	184

Fig. 1a: CMP section at x = 5 km

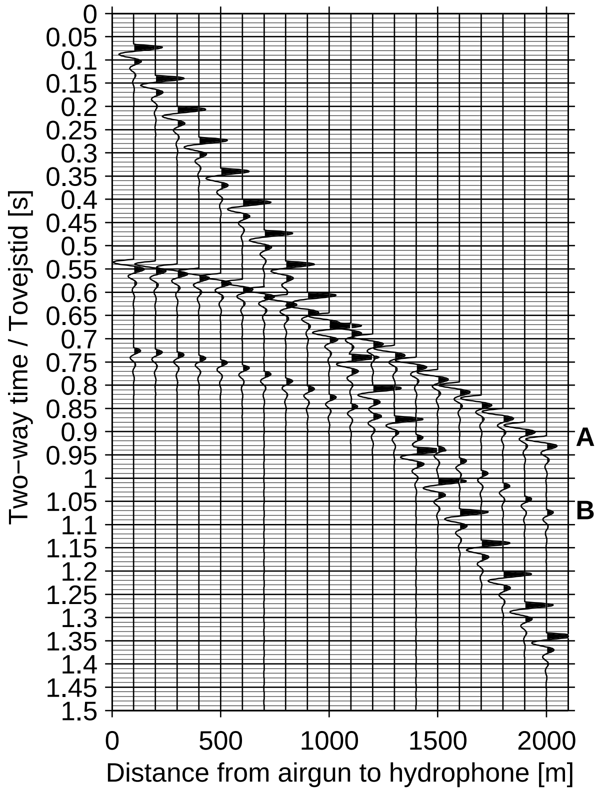


Fig. 1b: CMP section at x = 20 km

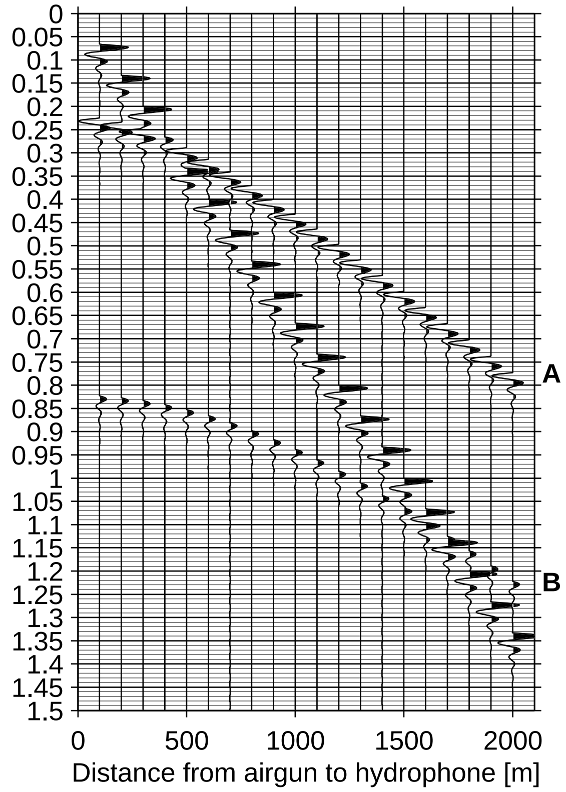
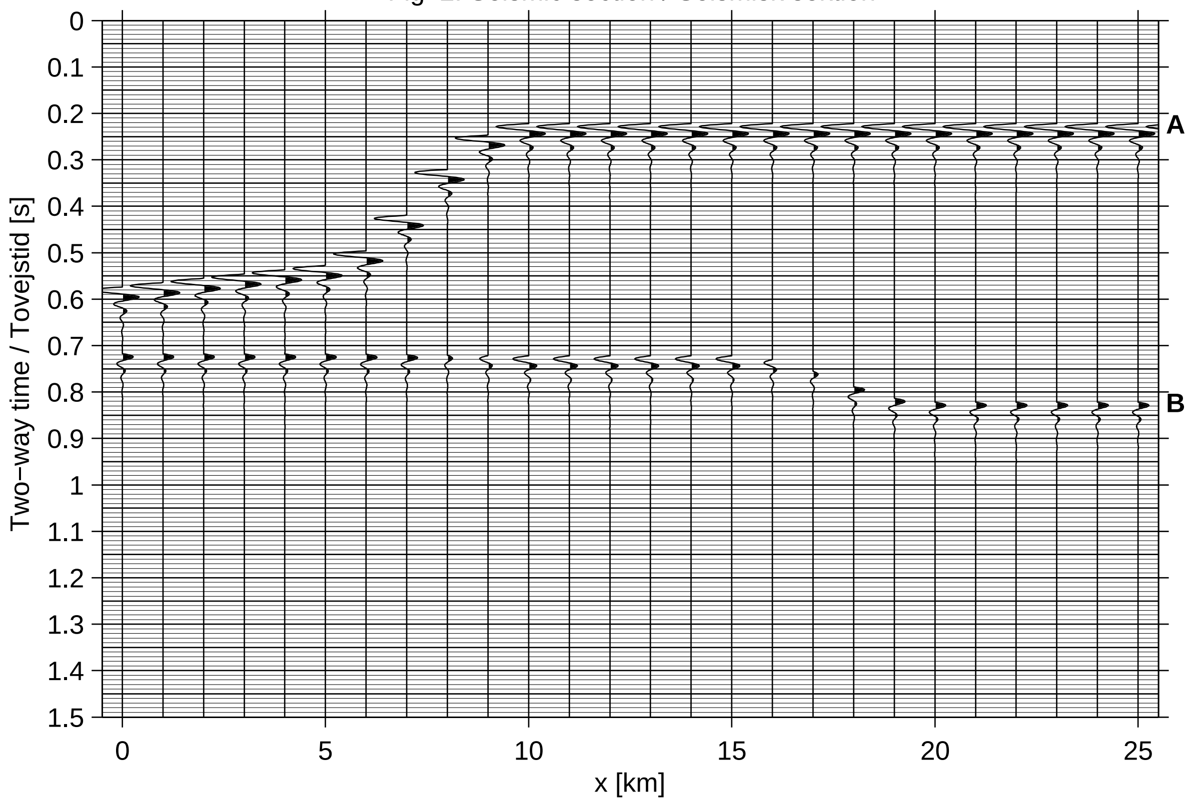


Fig. 2: Seismic section / Seismisk sektion



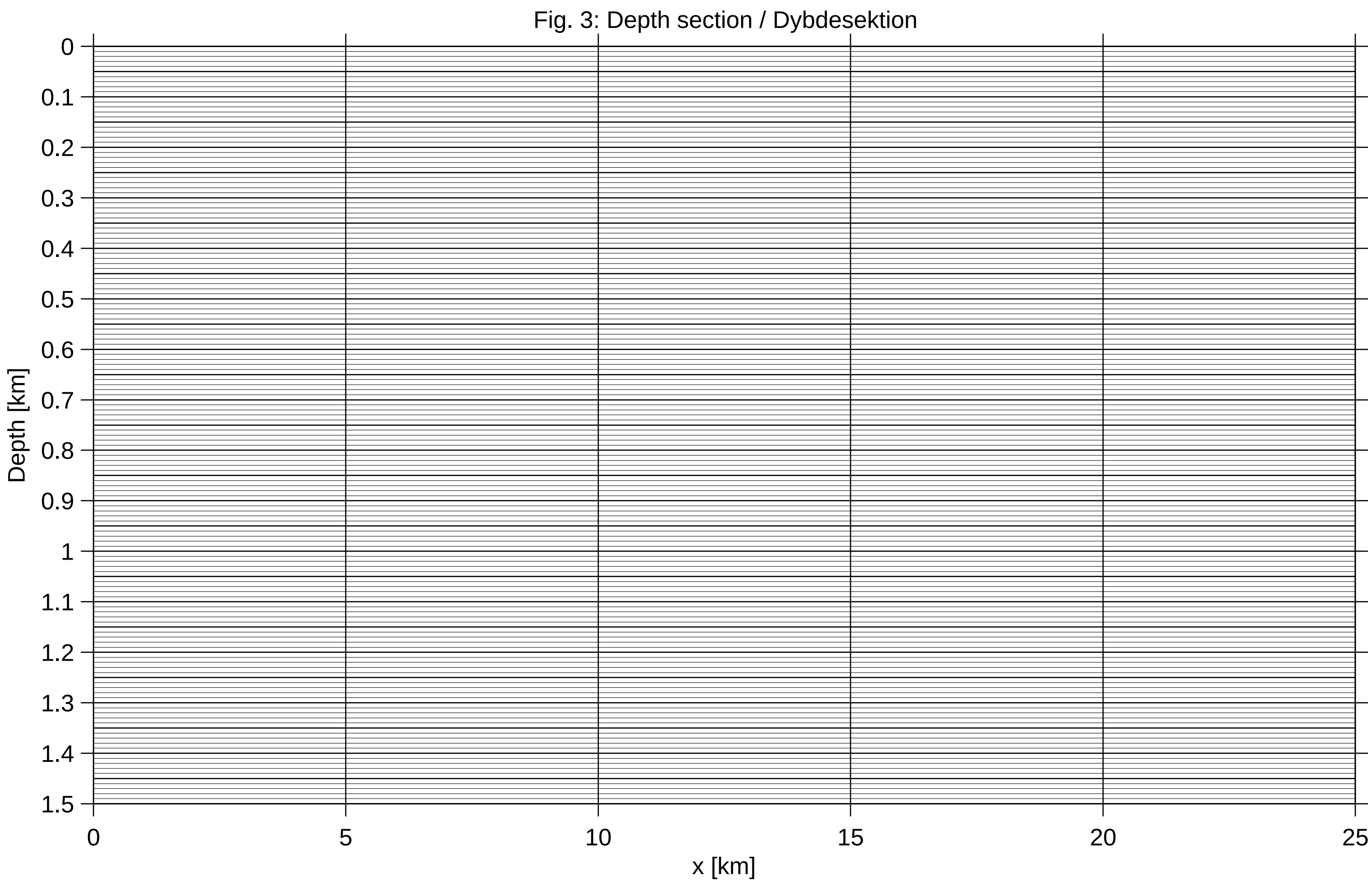


Fig. 3: Depth section / Dybdesektion
Depth [km]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
0
5
10
15
20
25
x [km]

Fig. 4: Residual Bouguer anomaly /Residual Bouguer−anomali

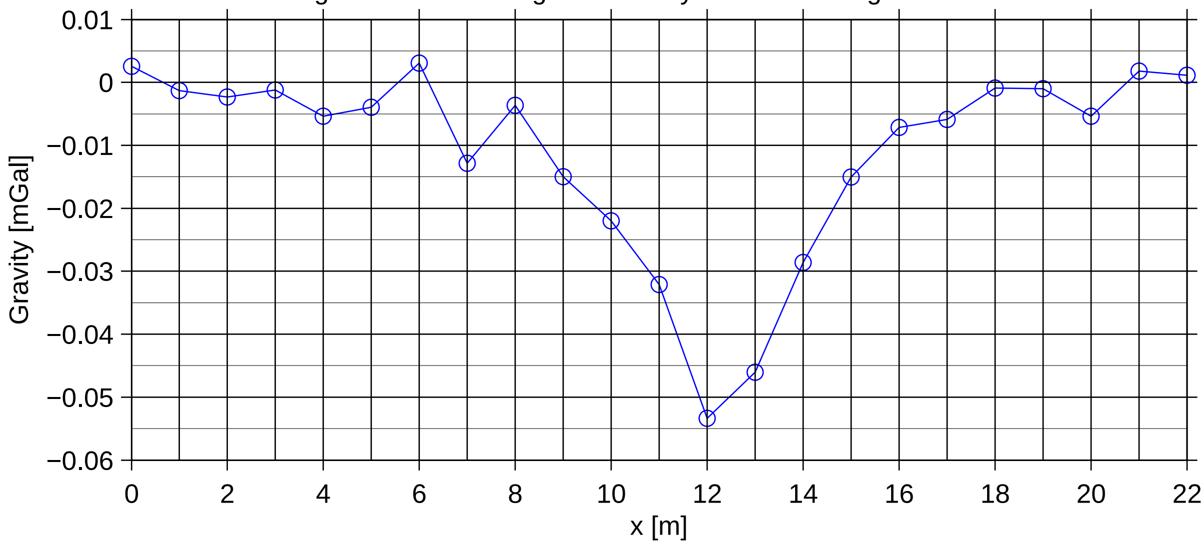


Fig. 5: Geoelectrical sounding data