Reservoir Geophysics Simulation Instructions

The *ReservoirGeophysics.html* program simulates seismic data obtained over a hydrocarbon-filled anticline. It will allow you to perform reservoir-geophysics analyses to see how you would use such methods to spot hydrocarbons (especially gas). The advantage of a simulation is that we know the right answer and so it is easy to compare what you produce to what should be there. The objective of the following exercise is to train you in these standard approaches and to emphasise their limitations (e.g. by seeing what happens when the data is noisy).

1. **Using the Program**

   Start up the program *ReservoirGeophysics.html* using any HTML5 compatible web-browser (e.g. a recent version of FireFox, Chrome or Edge. NB the program does not work well with Internet Explorer). The program will work on a tablet or smart-phone but it is much easier to use on a larger screen, and with a mouse, so it is probably better to use a desktop computer or a laptop if possible. It should work equally well on Mac, Windows or Linux based operating systems.

   The initial image shows a hydrocarbon-filled anticline and the program simulates amplitude versus offset effects in seismic data shot-over this structure.

   Click on the options in the *Display Options* box to see the different displays that the program produces. Do not worry if you do not understand everything you're looking at; we'll cover all of these displays in the exercise which follows. However, in broad outline, the first row (*Anticline Property*) shows the assumed geophysical properties such as P-wave velocity (*Vp*) and how these change as we go from the cap-rock, into the gas-filled part of the anticline, down through the oil column and into the lower part of the anticline where the porosity is water-filled. The second row (*AVO plot*) shows how the reflected P-wave amplitude changes with offset using three slightly different ways to display the results. The final row (*Seismic Section*) shows how the anticline would appear on various different types of seismic section.

   Now use the slider controls to change the numbers in the *Anticline Properties* box. Look for the effect of these on the various displays. For example, if you change the gas-column height from 50m to 100m, you should see this reflected in the *Anticline Property* and *Seismic Section* displays. Also change the *Seismic Options* and observe the effects on the various seismic displays. Again, don't worry if you don't understand all the changes that occur; we will cover this below.

2. **Cap-rock properties**

   We are now going to look at how we change the cap-rock properties, i.e. the material deposited on top of the anticline.

   Refresh your browser to set the values back to their defaults (in most browsers this involves clicking a ↻ icon somewhere near the address bar). The cap-rock, in this simulation, is assumed to have the typical properties of mud-rocks so that the p-wave (v_p) and s-wave (v_s) velocities are related by Castagna's mudrock line (Castagna, 1985)

$$v_p = 1.16v_s + 1.36, \tag{1}$$

whilst the density (ρ) is related to the p-wave velocity by Gardner's rule (Gardner et al, 1974)

$$\rho = 0.31v_p^{0.25}. \tag{2}$$

Hence, the s-wave velocity, density and impedances of the cap-rock are completely determined by the *Cap rock Vp* supplied in the *Anticline Properties* box. Try changing this value to see what happens to the *Vp, Vs, Density* and *Impedance* displays. You should see that only the properties of the cap rock are changed (i.e. the numbers in the anticline do not change). You should remember that impedance is the product of density and velocity. Hence, there are two impedances – the s-wave impedance (ρv_s) and the p-wave impedance (ρv_p).

3. **Anticline properties**

Now we'll look at how you can control the geophysical properties within the anticline. The anticline is assumed to be a porous sandstone containing different fluids (i.e. gas, oil and water). The key property defining the geophysical properties of the anticline is the *porosity* supplied in the *Anticline Properties* box.   Alter this to see the effect on the *Vp, Vs, Density* and *Impedance* displays.

I'll now describe how the porosity (ϕ) controls these properties. Let's start with density as this is the simplest example. The bulk density of the fluid-filled rock (ρ) is a weighted average of the matrix density (ρ_m) and the fluid density (ρ_f) in the form

$$\rho = \rho_m(1\text{-} \phi) + \rho_f\phi. \tag{3}$$

In the program, I have assumed a quartz matrix of density 2650 kg/m^3 and that the fluid density is 300 kg/m^3 (gas), 900 kg/m^3 (oil) or 1000 kg/m^3 (water). Hence, you should find that the anticline density is 2650 kg/m^3 throughout when the porosity is set to 0% and that the densities change to their respective fluid-values when the porosity is set to 100%. Try it to check. Also verify that the densities are intermediate between these extremes when the porosity is set to a sensible value (e.g. 20%).

Next, we need to look at the influence of porosity (and fluid fill) on the seismic velocities. You should remember, from PGM251, that

$$v_p^2 = (K + (4/3)\mu) / \rho \tag{4}$$

and

$$v_s^2 = \mu / \rho \tag{5}$$

where K is the bulk modulus and μ the shear modulus of the combined matrix plus pore-fluid. The most important factor is that gas has a much lower density and is much more

compressible than either water or oil. Hence, a gas filled rock has a reduced K and ρ. However, the effect on μ is much less as the shear-rigidity of a rock is almost entirely due to the matrix and is therefore largely unaffected by the fluid-fill. Given this background, take a look at the *Vp, Vs* and *Density* displays and check that you understand the variations in these properties. In particular, think about why the s-wave velocity is anomalously high in the gas-filled part of the anticline (compared to the water-filled velocity)? In contrast, the p-wave velocity is anomalously low in the gas; why?

In more detail, the program uses the Gassmann model (see Smith et al, 2003) to calculate the bulk modulus and shear modulus. To do this I have assumed a bulk modulus for the sandstone matrix of 10 GPa and bulk moduli for the fluids of 0.2 GPa (gas), 1.5 GPa (oil) and 2.5 GPa (water). I have also assumed a shear modulus of 5 GPa which is unaffected by the fluid fill. Note that these numbers have been chosen as reasonable estimates that produce sensible results and should not be taken as definitive under all circumstances. For example, the bulk modulus of oil and gas are strongly dependent upon pressure and temperature and could therefore have very different values to those used here.

4. **Amplitude versus Offset (AVO) plots**
    Once the velocities and densities of the cap rock and anticline have been fixed, the p-wave reflection strength can be calculated for the five different reflectors in the model: cap-rock over gas-fill; cap-rock over oil-fill; cap-rock over water-fill; gas-fill/oil-fill; oil-fill over water-fill. Take another look at the *Fluid Fill* display and you should see where each of these 5 reflectors will be found (e.g. identify where you can see cap-rock underlain by gas-filled reservoir and so on).

    For each of these cases, the reflection strength versus angle of incidence can be calculated. This is done using expressions called the Zoperittz equations (see link on the Moodle page for further details) but the important point is that the strength of reflection changes with angle and the way it does so is controlled by the properties of the rock on either side of the reflector. Hence, we can use this behaviour to determine rock-properties; in particular, as we'll see below, whether pores are filled with gas.

    The results are shown in the *AVA* (amplitude versus angle) plot. For the default parameters you should be able to see that the Cap-rock/Gas reflector (the yellow curve) decreases strongly with increasing angle and, in fact, goes from a positive reflection coefficient to a negative one. The other four reflectors show a less dramatic change but, nevertheless, do alter significantly with offset.

    It's worthwhile, at this point, to watch what happens when the model parameters are altered. In particular, change the *cap-rock Vp* and the *porosity* to see what happens. Can you get the Cap-rock/Gas reflection to show an increase, rather than a decrease, in amplitude with offset? You should find that the Cap-rock/Gas reflection always starts off positive and then decreases with angle (although it can sometimes climb back up again at very high angles). This fact is the key to spotting a gas-filled reservoir using amplitude versus

offset (AVO) techniques; we expect to see a swing from positive reflectivity to negative reflectivity as the offset (and hence angle of incidence) increase.

You should have seen, from the above exercises, that the amplitude versus angle behaviour is non-linear (i.e. these curves are not straight lines). The next plot (*Shuey 2-term*) uses the truncated Shuey equation (see Castagna & Swan, 1997)

$$R(\theta) \sim A + B.\sin^2(\theta) \tag{6}$$

where $R(\theta)$ is the reflection coefficient as a function of angle whilst A and B are constants. This expression implies that a plot of reflection strength against $\sin^2(\theta)$ should approximate a straight line with an intercept of A and a gradient of B. You should therefore find that switching from *AVA* to *Shuey 2-term* produces straighter lines. Does it? Note that this plot also shows best-fit straight lines (the dashed lines).

The final plot in this row is the *Seismic Gather* which is our first plot showing something we might actually see in a real data case. This plot shows data that has been through a pre-stack migration process and has then been "gathered" to collect all data corresponding to a particular location. You can change that location by switching back to the *Fluid Fill* display and clicking on the screen to indicate a new *Gather* location. Returning to the *Seismic Gather* display, each vertical trace through the gather corresponds to migrated data with a different angle of incidence. This display is very similar to a CMP-gather in a conventional seismic processing scheme except that, here, the data has been fully migrated (i.e. not just had NMO) and the horizontal axis has been deformed so that it gives incident angle rather than offset.

You can also see that this gather contains a number of different reflection events. If you select a gather location near the centre of the anticline you should see three clear reflections (one each from the cap-rock/gas, gas/oil and oil/water reflectors). By looking at the colours (red is strong positive and blue is strong negative) can you see that the cap-rock/gas reflection amplitudes changes with angle?

Select this reflector by clicking on it with your mouse; the graph to the right of the gather now shows the amplitudes, at this time location, and how they change with $\sin^2(\theta)$. Thus, if equation (6) is accurate, the graph should show a straight line (the red dots are the data from the gather and the blue-dashed line is a best-fit straight line). Note the intercept, gradient and mean values given below the graph. Also note that these values could easily be recalculated for other time-values and for other gather-locations and, in fact, we will do so later in this exercise. For a reflection from the top of gas, should the intercept be positive or negative? What about the gradient?

Finally, in this section, let's look at the check-boxes in the *Seismic Options*. With the display still in *Seismic Gather* click *Noise* and watch what happens to the gather and to the graph as you switch this on and off. This option adds random numbers to the data in the gather to simulate the fact that real-world data is noisy. The gather should therefore now look

"speckled" and, in addition, you should see that the data in the graph is scattered around the best-fit straight line. However, you should find that the intercept, gradient and mean do not change much and, therefore, we can still estimate these even when the data is noisy.

Turn the noise off and look at the effects of *Low-cut filter* and *Hi-cut filter*. These options change the bandwidth of the data. Specifically, they apply a low-cut filter (to remove low frequencies) and a high-cut filter (to remove high frequencies). Real-world data tends to lack these low and high frequencies and so, once again, these are options designed to make the simulated data more realistic. This will be particularly important when we look at seismic inversion later in the exercise but, for now, just observe the effects that these bandwidth changes have on the intercept, gradient and mean.

5. **Seismic Sections**

   The final set of displays show various seismic sections that can be produced from this type of analysis. The *Time Lapse* check-box, at the end of this list, will be looked at below so leave this option "off" for now.

   The first of the section options (*Stack*) is the conventional approach in which each gather is averaged (over offset) to reduce noise and produce a stacked section. NB this data has undergone prestack migration and, therefore, there is no need for post-stack migration; the section is already migrated. If you select this option you should see a section which shows, reasonably clearly, the anticline along with base-gas and base-oil horizontal reflectors (to see this clearly, make sure the noise and the frequency filters are now off).

   Now, as we've already seen, it is possible to not only average over offset but, instead to produce a best-fit to equation (6) at each time and each gather location. If this is done and the resulting gradient plotted at each time and space location, the result is a gradient section. You can see what this look like by selecting the *Gradient* option. The resulting section should look like the stacked section but with a very different pattern of reflectivity. Similarly, we can produce an intercept section. In this program that is done by selecting 0° incidence (in *Seismic Options*) and then selecting the *Constant θ* section. Compare this result to the stack and to the gradient section; they should each highlight different features.

   More generally, the *Constant θ* option allows you to look at sections at angles of incidence other than zero (NB the intercept is, by definition, the value at zero incidence). Try varying this angle, whilst looking at the *Constant θ* display, to see what happens.

   You should find that the gas-cap to the anticline shows up quite differently on these different sections. This, in itself, is often used as an AVO analysis tool, i.e. stacked, gradient and intercept sections are produced and compared to look for "interesting" anomalies. However, there is a more systematic approach - the use of gradient/intercept plots – and we'll look at these now.

6. Gradient-intercept plots

Select any of the section displays and then use the mouse to click on the anticline reflector at a location where it is cap-rock over water (i.e. below the base-oil reflector, see figure 1 below).
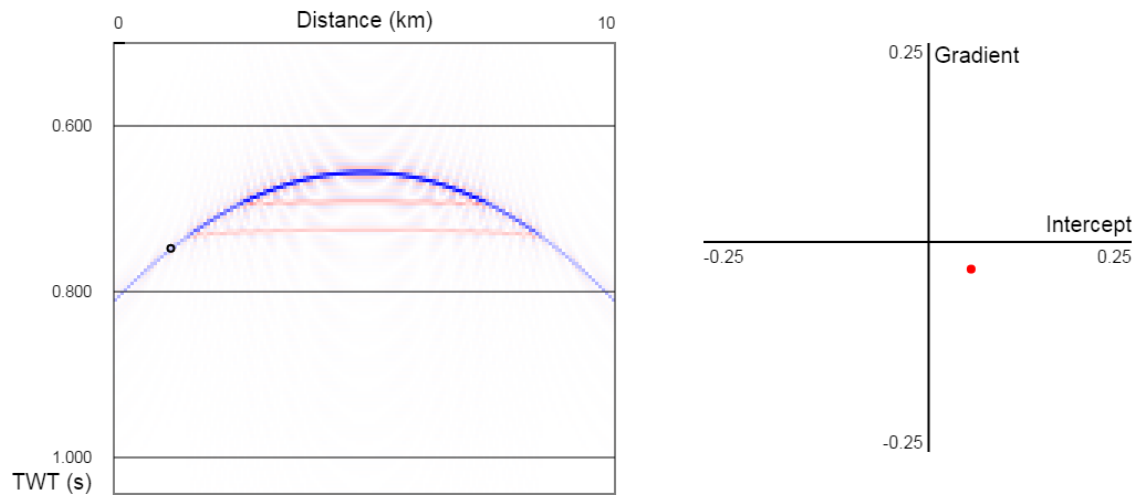

Figure 1. Gradient-intercept analysis of a point on the cap-rock/water reflector.

You should see a circle appear where you clicked and another circle appear in the gradient-intercept graph to the right. This shows the best-fit gradient and intercept from equation (6) at the chosen time and space location. Now click some more-points on the cap-rock/water reflector. You should get something similar to figure 2.
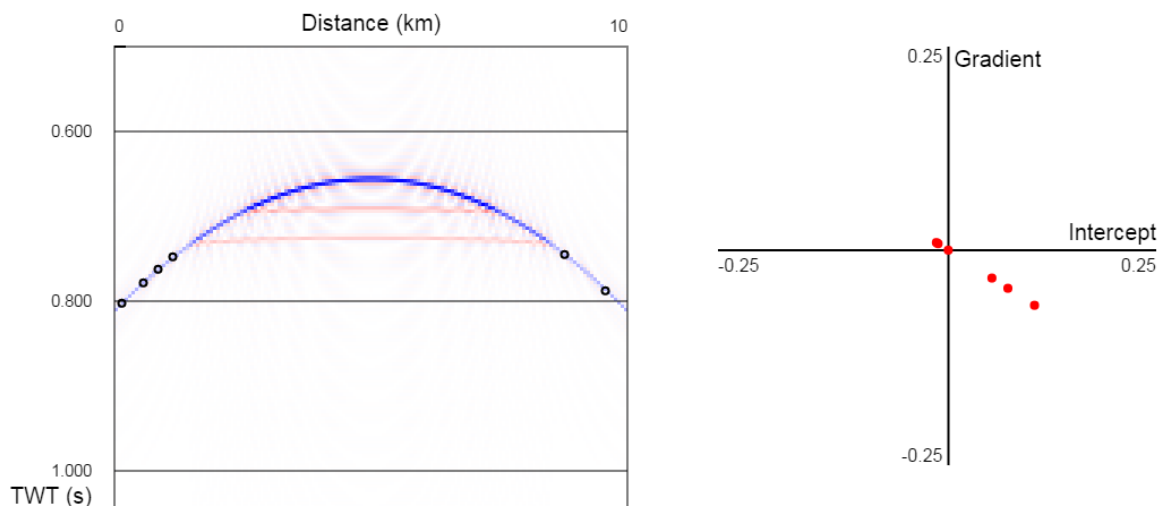

Figure 2. Gradient-intercept analysis of several points from the cap-rock/water reflector.

Note the clear trend on the gradient-intercept plot. This is a baseline trend for comparison to the next step — gradient-intercept analysis of the gas reflection. Try selecting more points on the anticline reflector but, now, chose locations above the base-gas reflector (see Figure 3). These give rise to points, on the gradient-intercept plot, which have a very different trend to the baseline.
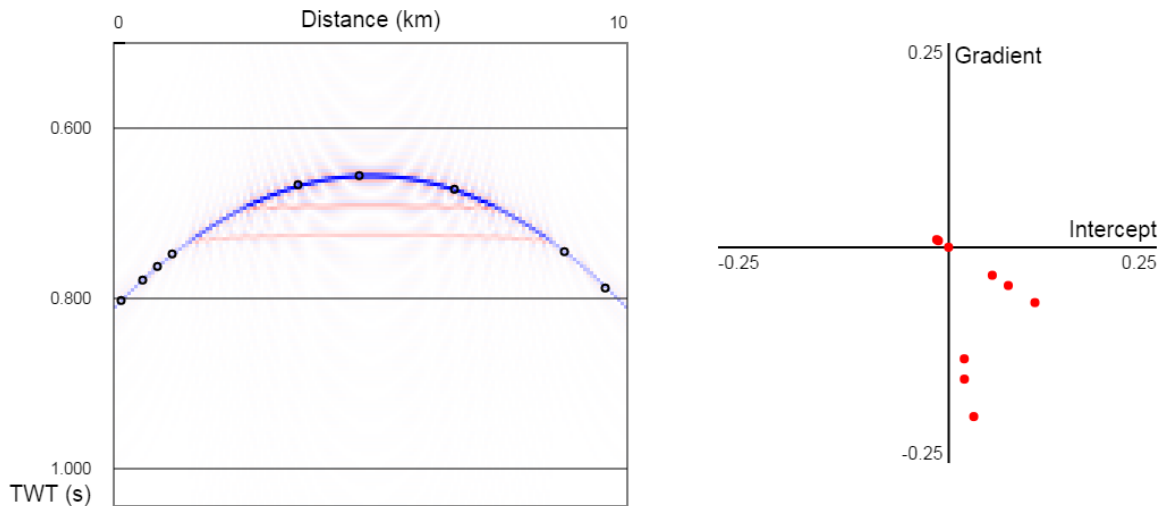
Figure 3. Gradient-intercept analysis after including points from the cap-rock/gas reflector.

This type of analysis is discussed in detail in Castagna & Swan (1997), Castagna et al (1998) and Daniels & Schulte (2015).

To finish this part of the exercise, repeat the gradient-intercept analysis but (for greater realism) with the frequency filters and noise turned on. Does the analysis still work?

7. **Inversion**

The next aspect of this program is its use for illustrating seismic inversion. The principle of inversion stems from the normal-incidence special-case of the Zoeppritz equations i.e.

$$R(0) = (Z_2 - Z_1) / (Z_2 + Z_1) \tag{7}$$

where the acoustic impedance is $Z = \rho v_p$ (with Z_2 the impedance of the lower layer and Z_1 the impedance of the upper layer). This expression was discussed in PGM251.

Equation (7) can be rearranged to give

$$Z_2/Z_1 = (1 + R) / (1 - R). \tag{8}$$

Hence, the size of the impedance below the reflector (relative to the upper impedance) can be calculated from the size of the reflection amplitude. More generally, by starting at the top of a seismic trace and working down it sample by sample, equation (8) can be used to produce an "impedance trace". To see the effect of this, select 0° of incidence and then select the *EI* option from the seismic sections. Does the result resemble the *P-impedance* plot, i.e. do we recover the correct impedance from "inversion" of the intercept-section?

You should have found that this process worked quite well. However, this simulated data is unrealistic as we've already discussed. For a more realistic demonstration, check what

happens when the data is noisy, when the data lacks high frequencies and when the data lacks low frequencies.   Which of these problems is most serious do you think?

Fortunately, more sophisticated processing methods are capable of reducing these problems and so inversion is still a useful technique. In fact, it can be taken a stage further. Turn off the frequency filters and noise so that the inversion method works reasonably well. Now try changing the incidence angle to 30° and then compare the result to the density plot. Has this worked reasonably well as a method to estimate density? If not, try changing the angle of incidence until you do get a reasonable match (it may need to be a different angle if your parameters have changed from the defaults).

What you have just done is to produce a constant-θ section (at an angle other than zero) and then inverted that using equation (8). The result is a generalized impedance $Z(\theta)$ which changes with angle. This generalized impedance is often called the elastic impedance (hence *EI* in the *Display Options*). The remarkable thing is that, at certain angles, this elastic impedance corresponds to certain real geophysical parameters such as density. By adjusting this angle to give the best fit to a known result (e.g. at a well location) the technique can be used to produce all sorts of useful sections (e.g. it has been used to produce a γ-log section!).

As an exercise, try and find an angle which gives an EI-section with a similar appearance to the S-impedance. Hint, try a negative angle!

8. **Time-Lapse (4D) Seismic**
   Your final task with this program is to use it to illustrate time-lapse seismic; plotting of changes over time resulting from extraction of hydrocarbons from a reservoir. You can see the effect of this by clicking the *Time Lapse* check box in the *Display Options* whilst looking at one of the seismic section displays. The program simulates the effects of hydrocarbon extraction (over a period of months to years) by reducing the gas-column thickness by 5m. The program then simply calculates the resulting section before and after this extraction and plots the difference between the two sections. When *Time Lapse* is "on" you will see the base of the gas and oil come through very clearly as these are the reflectors that have been changed (i.e. they've shifted up by 5m).

   Note that any of the seismic sections can be used (stack, gradient, constant θ or EI) but which ones work best? To assess this, you need to look at what happens when there is noise and when the data is band-limited so don't forget to play with the *Seismic Options* whilst you're deciding what works best.