What Is This Seismic Stuff?

What's It For?

With some rare exceptions, the petroleum (oil and natural gas) that has been found on planet earth is contained within sedimentary rocks. Sedimentary rocks are formed in topographically low areas called 'basins' in which sediment and organic material have been deposited and preserved. Although a certain amount of organic material is likely to be preserved in all basins, this material can only become an effective source of petroleum ('source rock') if it is preserved in relatively high concentrations in anoxic conditions, and has been subjected to a sufficiently high temperature to convert it to petroleum. As petroleum is produced from source rocks it tends to migrate upwards through pore spaces, fractures and faults and can accumulate in geological features known as 'traps'. Traps occur where a porous and permeable 'reservoir' formation is overlain by an impermeable 'sealing' layer, in a configuration that literally 'traps' the migrating petroleum. A rock's porosity is simply a measure of the amount of pore space within the rock and its permeability is a measure of the degree of connectedness between the pore spaces. Good porosity and permeability allow for higher flow rates and recovery of a greater proportion of the oil and gas from the reservoir.

It is the combined job of the geologist and geophysicist to identify potential traps that have a reasonable chance of containing petroleum in commercial quantities and to thereby recommend drilling locations. Although there is a great deal of overlap between the roles and the skills of the geologist and geophysicist, it can be generally said the geologist is a more hands-on individual, who handles the rocks and studies them directly. By analyzing drill cuttings, cores and other information from previously drilled wells, and studying rock outcrops, the geologist can discern much about the petroleum potential of an area. Having conferred with the geologist in regard to which rock formations have the best potential for petroleum, the geophysicist utilizes remote sensing techniques to 'see' what these formations are doing in the subsurface.

Although there are several remote sensing tools available to the geophysicist, the most useful among current technologies is reflection seismic. We speak of 'reflection' seismic to differentiate it from, the less-commonly used, 'refraction' seismic, which involves recording sound waves that are refracted along the subsurface layers, as opposed to being reflected from them.

How Does It Work?

Seismic reflection is essentially an echo sounding technique. A sound wave (a.k.a. 'seismic wave') is produced at or near the earth's surface by a seismic source.
On land the source is usually a buried dynamite charge or an array of large vibrator trucks. In marine surveys the source is an array of high-pressured 'airguns' that are discharged within the water column a few metres below the surface. The seismic wave travels downward and a portion of the wave's energy is reflected whenever it encounters an interface between two distinctly different kinds of rock. Sedimentary rock is particularly suited to mapping by the seismic method because sedimentary depositional processes tend to create broad and roughly horizontal layers that will reflect downward traveling seismic energy back to the surface. For a detectable amount of energy to be reflected back to the surface from a given layer it must also be thick enough (usually several metres) to interact with a significant proportion of the seismic wavelength. Higher frequency waves have shorter wavelengths and can detect thinner beds, so a great deal of effort goes into maximizing the frequency content of the data. Seismic energy is reflected at

lithologic interfaces because the different kinds of rock present different transmission characteristics (a.k.a. 'acoustic impedance') to the advancing seismic wave.

The acoustic impedance of a rock is obtained by multiplying the rock's density by the speed at which it transmits sound. The strongest seismic reflections are generated where the change in acoustic impedance is both abrupt and substantial (e.g. going from a shale to a limestone), and it is not unusual to be able to image rock formations located tens of kilometers below the surface using standard seismic methods.

Detecting seismic reflections from deep below the surface requires very sensitive listening devices. When operating on land thousands of 'geophones' are laid out on the ground in set patterns for this purpose. In marine operations a buoyant cable or 'streamer' (typically three to ten kilometers in length) containing thousands of acoustically sensitive 'hydrophones' is towed behind the ship. The guns are fired and the streamer 'listens' for about four to seven seconds (longer in deeper water); the data is recorded; after a pause of a few seconds the process is repeated; and this continues until the end of the line is reached. Seismic lines can range from just a few kilometers to hundreds of kilometers in length depending on the specific goals of the survey. Generally, longer and more widely spaced lines are used for reconnaissance work and shorter, more closely spaced lines are used to define actual drilling targets.

Marine Seismic Schematic

Understanding Different Types Of Seismic

Today it is common to acquire what's called '3D' seismic. To understand this type of seismic, we will first take a look at what we mean by '2D'. Consider that when a seismic source is activated the resultant sound wave travels outward from the source in all directions – just as we observe when we throw a stone into a quiet pond.

Although some energy is bound to go upward and can be heard as an air blast, a properly deployed source does in fact focus most of the energy downward. And so the seismic energy propagates into the earth as a kind of expanding hemisphere of sound. If all of the sedimentary layers were perfectly flat and homogeneous the only sound waves that would reflect back to the seismic line would have come from points directly beneath it. But, as completely flat layers seldom exist (and would be unlikely to trap petroleum if they did) the echoes that are recorded on the seismic line do not necessarily come from directly beneath it. Some of the reflections will have come from either side of the line, or even from geologic features located off the ends of the line.

Whereas fifteen years ago, 3D seismic was primarily used to choose development well locations, it is now widely used at the exploration stage. This is particularly true in marine operations where a new generation of purpose built vessels are capable of pulling multiple streamers with multiple energy sources, and on-board computers can do processing on the fly to provide improved quality control and timely delivery to the client.

With only a single line, or with widely spaced lines, there is no means to properly correct for these out-of-the-plane or 'broadside' reflections when processing the seismic data. Raw seismic data, as collected in the field, must go through considerable computer processing before it can provide interpretable images. Seismic processing, for the most part, involves trying to sharpen the acoustic images of the subsurface, and ensure that these images accurately represent the location of subsurface features. A 2D seismic line provides an image of a two dimensional cross-section ('section') of the earth that is, unavoidably, contaminated by broadside reflections that can mislead the interpreter – which increases the ever present risk of drilling in the wrong place!

If, however, the data were to be acquired as a closely spaced grid of lines (say only 25 or 50 meters apart) then it is possible to process it as a 3D cube of data, in which the broadside reflections can be correctly positioned. This requires orders of magnitude, more data storage and computing power, but the resulting data set provides for a much more accurate representation of the subsurface.

Three dimensional seismic has become more economically and technically feasible because of advances in field equipment, the increased speed of computers and the ability to store vast quantities of data quickly and compactly. Whereas fifteen years ago, 3D seismic was primarily used to choose development well locations, it is now widely used at the exploration stage. This is particularly true in marine operations where a new generation of purpose built vessels are capable of pulling multiple streamers with multiple energy sources, and on-board computers can do processing on the fly to provide improved quality control and timely delivery to the client.

Can We See Petroleum Directly On Seismic Data?

For the most part we cannot see petroleum directly on seismic data. One notable exception is that the presence of natural gas in a porous formation can sometimes alter the acoustic impedance enough to affect the reflection amplitude in predictable ways. A famous example of this is the 'bright spot', but depending on the specifics of the geology the presence of gas can also cause a dimming of the reflection amplitude. In very fortunate cases the presence of a gas-oil, gas-water or even oil-water contact can be imaged as a 'flat spot' – but this is not common. What is, in fact, most often mapped by geophysicists is the topography of the most reflective layers, and from this the structure of acoustically invisible layers can be inferred by what is seen to happen above and below them. The geophysicist also searches the data for reflection patterns that are characteristic of known petroleum producing systems. In this manner the geophysicist is able to construct maps that highlight the subsurface structures (buried hills, river deltas, beaches, coral reefs etc.) that are likely to contain producible accumulations of petroleum.

What's Next?

The new buzzwords are '4D', 'AVO' and 'multi-component'. A four dimensional (4D) seismic survey is essentially a 3D survey that is repeated in the same area to track changes in the distribution of oil and gas in the reservoir as the field is produced. Obviously this method can only be effective where production causes acoustically detectable changes in the reservoir. AVO (amplitude vs. offset) is a means of processing seismic data that takes advantage of the fact that changes in reflection amplitude with the angle of incidence of the seismic wave can be used in certain geological circumstances to predict reservoir content and quality.

Multi-component seismic is an area that holds great promise. Conventional seismic utilizes pressure waves (p-waves), which image the rock matrix as well as the fluids contained within that matrix. These waves travel as pressure pulses that oscillate parallel to the direction of propagation. A second type of wave, the shear wave (s-wave), oscillates perpendicular to the direction of propagation and is not directly affected by the fluid content of the reservoir. Shear waves can be generated directly by seismic sources and indirectly by p-waves that convert some of their energy to s-waves at reflection points. They also travel at a slower speed than p-waves, and the ratio of p-wave to s-wave velocity can be used to predict lithology and detect porosity.

Recording shear wave data presents unique challenges because it requires equipment that can separate and record both the horizontal and vertical components of seismic waves. An additional challenge for marine surveys is that as s-waves cannot be transmitted through a liquid, they can only be captured by placing seismic recording devices directly on the seabed. Several companies are working on effective means of multi-component cable deployment, as well as ways to achieve adequate coupling between the seismic cable and the seabed.

Although the physics of seismic exploration has been understood for many years, it is only recently that technology has allowed a more complete utilization of the information contained within the seismic signal. Driven by the need to reduce the risk of dry holes in increasingly expensive drilling ventures, the methods of seismic acquisition, processing and interpretation will continue to push the limits of technology and test the imaginative and deductive powers of geoscientists.

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