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It's All a Matter of Space and Time

(Editor's note: The Geophysical Corner is a feature that regularly appears in the EXPLORER. This column is produced by M. Ray Thomasson of the AAPG Geophysical Integration Committee. This new feature will discuss some of the fundamentals of geophysical technologies, integration of the technologies with geology and address the impact of geophysical technology and techniques on exploration.)

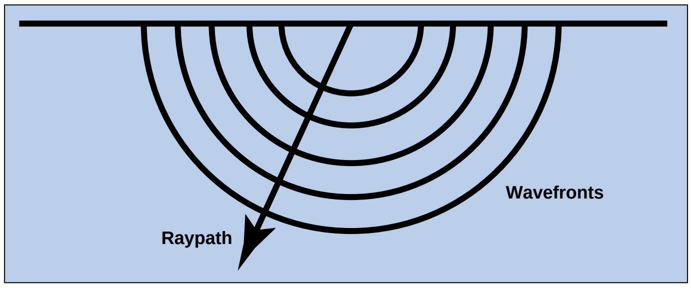

Figure 1: Wavefront and raypath orthogonal to wavefront.

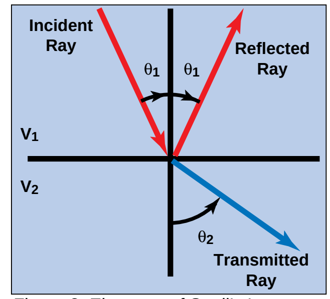

Figure 2: Elements of Snell's Law.

By JEREMY J. ZIMMERMAN

Most geoscientists in the petroleum industry are dealing with the problem that seismic information is usually displayed in some form of a time section, be it a time stack section or a time migrated section.

Drillers, engineers, geologists, geophysicists and earth scientists in general describe the earth in depth, as in "x" number of feet to target, "x" number of feet of oil column, etc.

How do you get easily from time to depth?

The answer depends on the level of complexity that you wish to attain, which is usually dictated by how soon something is needed or how much it will cost.

The overall process is called depth conversion, although some prefer to be more rigorous and call it depth migration. More on that later.

The simplest definition of depth conversion is the conversion of some measurable time quantity into some understandable value in depth.

The old joke of when someone asks how deep is the well and the junior geoscientist responds that "it's about three seconds ..." pops into many people's minds when dealing with representations of well progress with respect to a chosen seismic section. So just how do we convert from time to depth?

The purpose of this month's column is to introduce geoscientists to some basic ideas about depth conversion as well as give examples of when it is appropriate to use a given method.

(This is not meant to be a rigorous dissertation of depth migration.)

The Raypath Concept

The raypath concept is the keystone to seismic exploration.

If we suppose that an expanding wavefront (think about the expanding circle that is produced when you drop a rock in water) can be simulated by a collection of raypaths that are traveling perpendicular to the wavefront, then you have the basis of seismic modeling and travel time simulation.

Most seismic modeling packages, whether they two-dimensional (2-D) or three-dimensional (3-D), simulate the expansion of the wavefront in the subsurface by describing a raypath along which a portion of the wavefront travels (figure 1).

A seismic source imparts energy into the ground, sending waves of energy down into the subsurface, where some of the energy is reflected, some of it is transmitted and some portion is lost as attenuation. That part which is reflected is measured or detected by geophones (land) or hydrophones (marine).

A seismic section is a measure of the amount of energy that is reflected back to the location of the geophone/hydrophone with respect to the time it takes a wavefront, and therefore the assumed model of the wavefront – the ray – to travel along selected paths.

Typically, rays are easily influenced by the medium in which they travel. The characteristic that is of greatest concern to the geoscientist is the velocity of the different layers through which the rays travel.

When seismic energy encounters a medium of different velocity from the one it is traveling in, it is deflected in accordance with the velocity change, as shown in figure 2. If the new medium is higher velocity, the energy – and therefore, the raypath – is bent more away from vertical.

If the new medium is a lower velocity, the seismic energy is deflected to more nearly vertical.

Examples

The first type of section (and most often ignored by much of the petroleum industry) is the time stack section.

It is seen as confusing because it contains segments of events, events that exaggerate the size of structures and even events that cross each other (the ubiquitous "bow-tie" structure).

The time stack image of the depth model is shown in figure 4. Note that the flat portion of the model remains flat, but the dipping events are much more complex.

The second type of section (and the one most often used by the petroleum industry) is the time migrated section. It is seen as less confusing and more of a realistic depiction of the subsurface.

To many geoscientists, this represents a realistic cross-section and therefore can be used to infer structural and tectonic forces at work.

Many of the models regarding interaction between salt and sediment in the Gulf of Mexico are based on these time migrated sections.

As you can see in figure 5, this image is still distorted in comparison to the actual model that produced it.

Seeing a time migrated section, one is apt to describe geologic processes that have produced such a structure. But the problem remains that the section is shown with respect to time.

When dealing with flat or slightly

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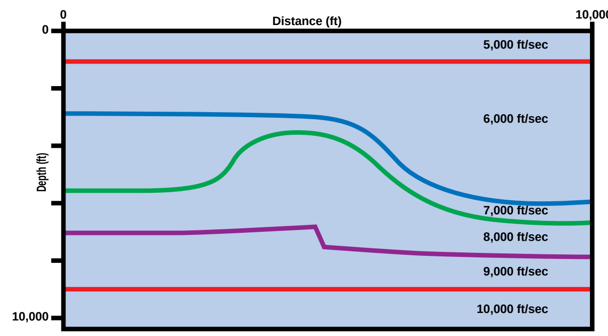

Figure 3: Idealized model.

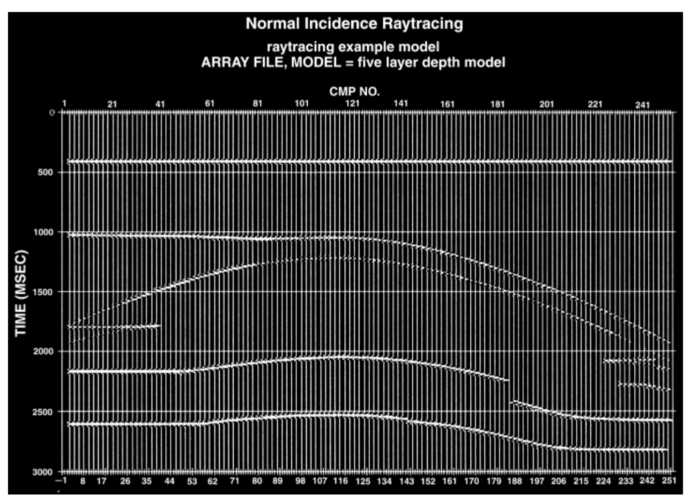

Figure 4: Normal–incidence (time–stack) seismic section.

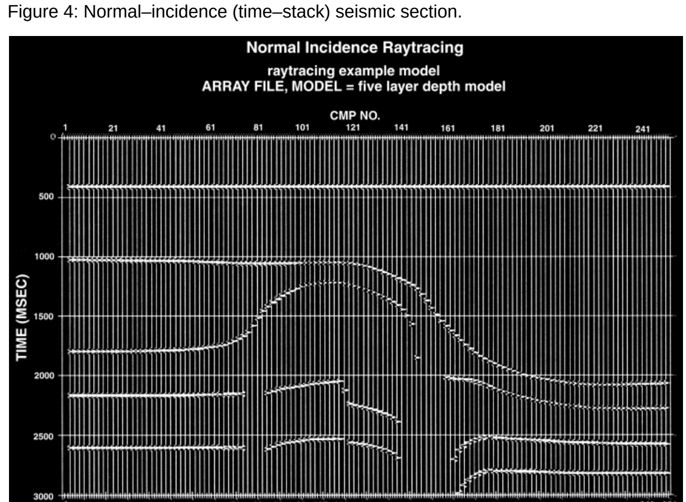

Figure 5: Time–migrated section.

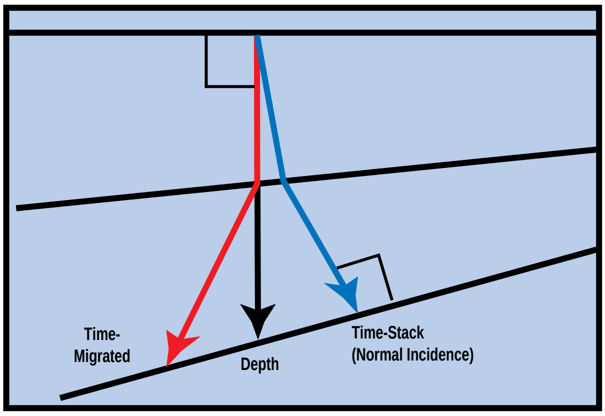

Figure 6: Raypath endpoints for time–stack, time–migrated, and depth rays.

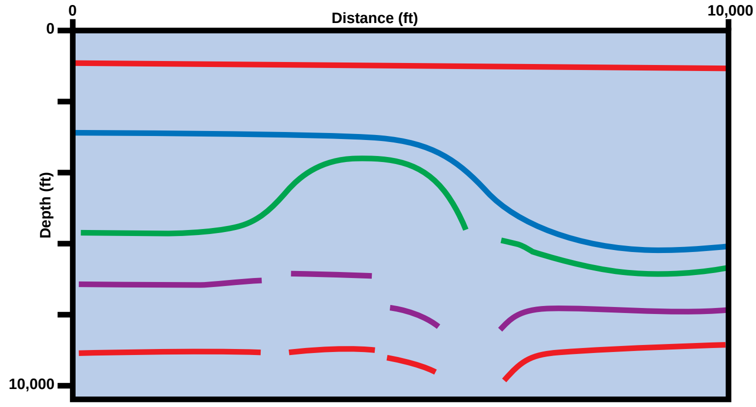

Figure 7: “Depth–stretched” section.

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dipping events (less than 10 degrees), a simple depth conversion using the straight vertical ray assumption can be used. This is done by taking the vertical time difference between events on a time-migrated seismic section and multiplying it by the interval velocity.

This result must be divided in two to account for the two-way travel path (down to the reflector and back up to the shallower reflector). The interval velocity value is often calibrated to available well information in the area.

(A whole different problem exists with respect to deriving interval velocities – a subject best left to another discussion.)

If dips on events exceed 10 degrees and the velocity field is “well-behaved,” then depth conversion becomes a little more complicated. The idea that vertical travel times taken from even a time-migrated section can be used to calculate a depth section using an interval velocity value (be it local, regional, constant or varying) can lead a geoscientist down the primrose path to a dry hole.

What often happens is an interval velocity map is created for selected horizons at sample points taken from wells. This interval velocity map is then multiplied by the isochron map made on the time differences between the two selected horizons, and a depth map that matches at the well is created by this “depth-stretch” method.

Of course, this depth map agrees with the information at the wells; it was derived using that information. The fallacy of this method is the assumption that the raypath generated by the seismic source travels along a purely vertical path.

If the subsurface reflectors exhibit no dip, then this is a valid assumption. Otherwise, the endpoint at depth for the vertical raypath and the actual raypath for the time-migrated sections differ (see figure 6, page 25). The greater the dip, the greater the offset between these two endpoints.

What this means is that the lateral placement of the events is wrong, often leading to misplaced highs or unplanned for lows.

An example of errors inherent in using the “depth-stretch” method is shown in figure 7 (page 25). The time-migrated section generated previously (figure 5, page 24)) was then depth converted using the vertical ray assumption and the interval velocities

See **Depth Conversion**, page 27

Depth Conversion

from page 25

in the original model that was used to generate the time-migrated section.

Compare it to the original depth model in figure 3 (page 24). Note the lateral errors in placement or reflections on the right side of the small mound. This error is carried through the deeper horizons on the section, also. This is due to bending of the raypath at the interface above.

Even though the velocities are gently increasing with each horizon, the dip on the second and the third horizon is such that the resulting reflection is moved horizontally.

Snell's law tells us that small changes in dip and velocity can cause the raypath to refract. To best compensate for this change in raypath direction, depth migration is usually applied.

The term "depth migration" is different from "depth conversion" in that the lateral movement of the endpoint of a raypath is taken into account. The best situation to have is when both the interval velocity model and the depth conversion (read depth migration) takes the refracted raypath into account.

Map Migration

The example shown here is only in two dimensions. A method for creating depth models based on ray displacements in three dimensions is called map migration.

The usual input into map migration is an interpreter's time map created from a series of 2-D time migrated seismic lines or one 3-D time-migrated dataset. The more appropriate method is to use an interpretation made of the time-stack data, but this is prohibitive in that interpretation of time-stack data in a complex structural domain is difficult to do.

Many map migration algorithms take this into account when inverse raytracing the data into the depth domain and calculate a raypath based on the relationship between the time-migrated ray and the depth-migrated ray.

Although not rigorous in execution, this type of result is better than a vertical "depth-stretch" based solely on a time-migrated section and interval velocities.

Conclusion

Depth migration is not a panacea.

Question: ' So, how deep is your well?'

Junior Geoscientist: 'Oh, it's about three seconds.'

Limitations in algorithms, computer power or the failure of the raypath assumption all contribute to lessening one's ability to get the perfect solution to imaging problems.

Moreover, although the mathematics of depth migration have been around since the turn-of-the-century, the concept and practice are still in their infancy.

The hope here is that they will grow slowly, and will find many fans and supporters.

Software packages for depth migration are currently available for use on high-end desktop workstations. If you are interested, consult your local geophysicist. ❑