Seismic Velocities in an Inhomogeneous Earth

In this chapter, we show that as a matter of principal, downward continuation makes it possible to estimate seismic velocities in regions where the earth has no structural continuity. We also derive continuation equations which can be used in velocity estimation. Finally, we investigate the parameters that are relevant to the interpretation of seismic velocity in terms of the physical properties of the rocks.

S.M.D. and J.F.C. 27 September 1974

MIGRATION AS A TOOL IN VELOCITY ESTIMATION

by Steve Doherty

Velocity estimation techniques now in use perform well in most circumstances. However, since they are usually based on a layered earth assumption their performance tends to degrade as the reflectors deviate from horizontal layers. There are two main classes of ways the earth may deviate from the assumed plane layers. See figure 1. One type of deviation occurs when velocity is constant or layered but the reflectors have arbitrary dips and curvature. Another occurs when the reflectors are planar but the velocity structure is arbitrary. The second class of structure tends to have the more drastic effect on velocity estimators. Unfortunately, it is also the harder of the two to compensate for. Accordingly, we will confine our discussion to the first class of structures. Although these structures cause less drastic degradation of velocity estimates than the others, there are situations where accomodation of their effects may be of overriding importance.

It is well known that, when viewed on a common midpoint gather, the arrival times of reflections from dipping planes follow hyperbolic trajectories. It is also common knowledge that RMS velocities, V_{RMS}, obtained from these data are always greater than the true velocities V. Specifically, we have

$$V_{RMS} = V/\mathrm{COS(DIP)} \tag{1}$$

Often, the only correction necessary to obtain true velocities from dipping or curved interfaces is the dip correction implied by (1). In order to make this correction, dip must be estimated directly

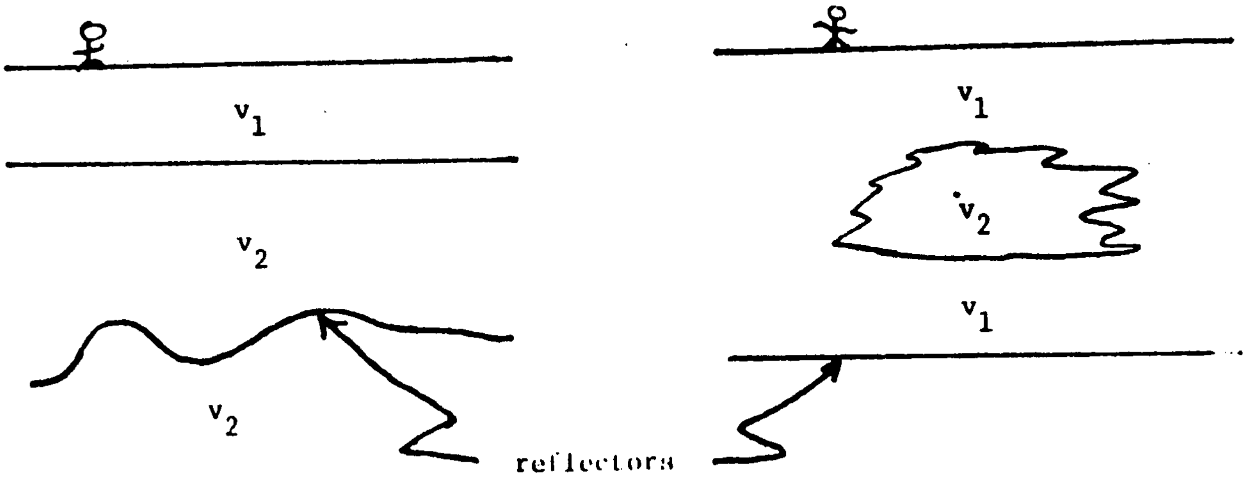

Figure 1. Earth structures for which velocity estimation may be difficult. The left frame shows an earth in which the velocity is layered but the reflectors have arbitrary dip and curvature. The right frame shows an earth in which the reflectors are horizontal planes but the velocity structure is arbitrary. Realistic earth models should contain both types of structures. The methods we describe here are strictly valid for structures like those on the left. However, we hope they will have some applicability to structures like those on the right.

from the data. Usually, this is not difficult. Problems arise when there are conflicting dips or when there are so many dips present that estimation of any single dip is impossible. Figure 2 shows an earth model for which dip estimation may be difficult. Diffracted events are also a problem, since the apparent dip as measured from the data is not the angle needed in equation (1). See figure 3.

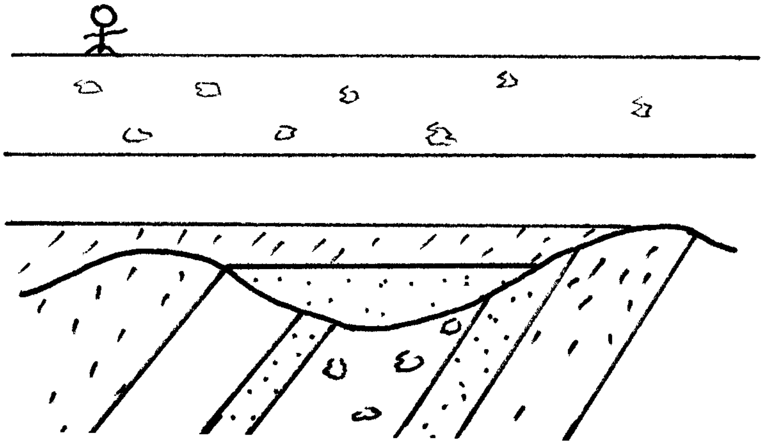

Figure 2. An angular unconformity. Conflicts will make dip estimation from data recorded over this structure difficult.

Reflections from a point scatterer illustrate a second characteristic of non-planar reflectors which can be important to those concerned with estimating velocity. The hyperbolic arrival times of point scatterer reflections tend to diffuse (both in time and space) the velocity information contained in rays propagating between the scatterer and the surface source and receiver. Even if dip corrections are made, erroneous results may be obtained because the location of the velocity estimate does not coincide with the reflection point of the waves on which the

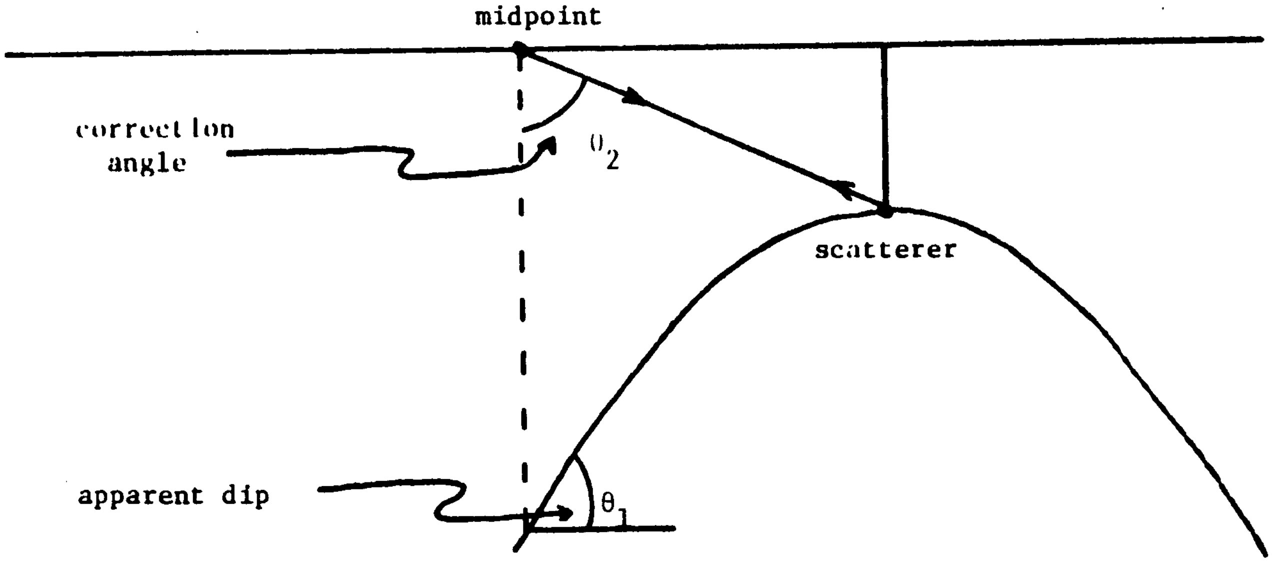

Figure 3. Apparent dip of diffraction events cannot be used to correct moveout velocities for the effects of structure. At midpoints far from the scatterer, the apparent dip of the diffraction is independent of shot and receiver location. The dip is governed solely by the asymptote of the hyperbola. For these midpoints the ray paths for all offsets are nearly horizontal. Because of this, the travel times of the reflections are nearly independent of offset and the moveout velocity is very large. As the midpoint goes to infinity, travel time becomes independent of offset and the moveout velocity becomes infinite. In this case equation 1 requires the correction angle to be 90°. Clearly the apparent dip of the data cannot be 90°, since that would imply that the material velocity was zero. The angle required to correct the moveout velocities is shown in the figure as θ_2 . Note that θ_2 becomes 90° for midpoints far from the scatterer. Since measurement of θ_2 requires knowledge of the scatterer position, we can conclude that dip estimation for diffracted data cannot be a local process.

estimate is based. Since propagation angles used in reflection seismology are generally less than 45°, velocity information tends to diffuse more horizontally than vertically. Thus, the diffusion is most important when velocity is laterally variable. However, even in the layered models we are concerned with, velocity diffusion may result in contamination of deep velocity estimates with estimates based on reflections from shallower non-horizontal interfaces.

Velocity diffusion occurs when the position of a given portion of data on a section does not coincide with the position of its reflection point. Migration can be described as an operation which positions all data on a section at its reflection point. Hence, the effects of velocity diffusion may be greatly reduced by migrating the data before estimating velocity. A problem with this approach is that one needs to know the velocity in order to migrate the data. Fortunately, the migrated data are only moderately sensitive to velocity. Even if the migration velocity is incorrect, the migrated data will be closer to its actual reflection point than the raw data. At worst, several iterations may be required to find good velocities. In most cases, since one can make reasonable estimates of the migration velocity, one iteration should be sufficient.

An additional advantage of estimating velocity from migrated data is that the resulting velocity estimates are independent of reflector dip and curvature. Again consider point scatterer data. Velocity, estimated from correlations of the unmigrated CDP gather data with hyperbolas, must be corrected for dip as indicated in equation 1 and figure 3. Since migration collapses the point scatterer hyperbolics to focuses, dips measured as shown in figure 3 are zero for the migrated data. Thus no correction is implied by equation 1. Since all reflectors can be constructed by superposing point scatterers, we can conclude no dip correction should be necessary for any reflector geometry.

The approach to velocity estimation described here differs somewhat from that advocated in two papers * at the 1973 SEG meeting. It is my understanding that these papers held that velocity can be determined by finding the velocity structure for which two sections, recorded with different offsets over the same reflectors, stacked best. The underlying principle is the same for the approach advocated here. Only the method of determining the velocity structure differs. The papers cited advocated an iterative procedure in which the data are migrated with several trial velocity structures until a velocity distribution for which the sections stacked well is found. Here we also begin by migrating the data with a trial velocity structure. In contrast to the other methods, conventional velocity estimation procedures are then applied to the migrated data as though they were surface data. In many cases the resultant velocity estimates are accurate and no further operations are required. Additional iterations can be performed if required.

The method described here has the possibility of requiring fewer trial migrations of the data. Another advantage is that velocity is estimated with the procedures now in use. No special estimation procedure peculiar to this approach is needed.

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* Elements of Migration and Velocity Analysis, Gardner, French and Matzuk.

Migration Velocity Determination in Two and Three Dimensions, Sattleger.