SEISMIC IMAGING PRINCIPLES

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The migration of seismic data requires two basic ingredients, a downward continuation or wave propagation operator and an imaging principle. The imaging principle is needed to know when to stop the downward continuation process. There are three main imaging principles in reflection seismology of which the most intuitive is based on the downward continuation of the sources and receivers. This is: *a reflector exists where upcoming energy is received after zero travel time from the source to the receiver.* This implies, of course, that the source and receiver have zero-offset and are located at the reflector. Hypothetically, the entire reflecting structure can thus be mapped by placing a source, receiver pair at every point in the subsurface and observing the upcoming energy arriving at $t = 0$.

The other two imaging principles are the time coincidence of up and downgoing waves and the explosive reflectors model. The former is a more general statement of the imaging principle above and the latter is a special application of the one above to zero-offset sections. In the following note, we will make a brief qualitative examination of these three imaging principles showing where and how the imaged or migrated section is obtained in each case.

Downward Continuation of Sources and Receivers

In the most general case, the data for migration are dependent upon seven variables, which are the shot and receiver locations and time ($P = P(x_s,y_s,z_s,x_g,y_g,z_g,t)$). The input data are the wavefield recorded at the surface for different shot-receiver locations and are on the 5-dimensional hyperplane $z_s = z_g = 0$. The desired output is at zero offset and zero travel time at all spatial locations within the earth and is represented by the 3-dimensional hyperplane $P(x_s=x_g,y_s=y_g,z_s=z_g,t=0)$. Hence, migration can thought of as a process which maps a 7-d function into a 3-d function. If the experiment is done across a 2-dimensional structure, as we shall assume in this paper, the mapping becomes one of 5 dimensions to 2 dimensions, where we have eliminated the y dependence.

Figure 1 shows the location of all seismic traces in shot, geophone space. The time coordinate can be considered to be into the paper. We are considering a 2-d experiment so the coordinate along the x_s and x_g axes both refer to locations along the traverse line. The line marked m in Figure 1 is the midpoint, or zero-offset, axis ($x_s=x_g$). The imaging principle tells us that any energy lying along this axis at zero travel time must be from a reflector at the source, receiver depth.

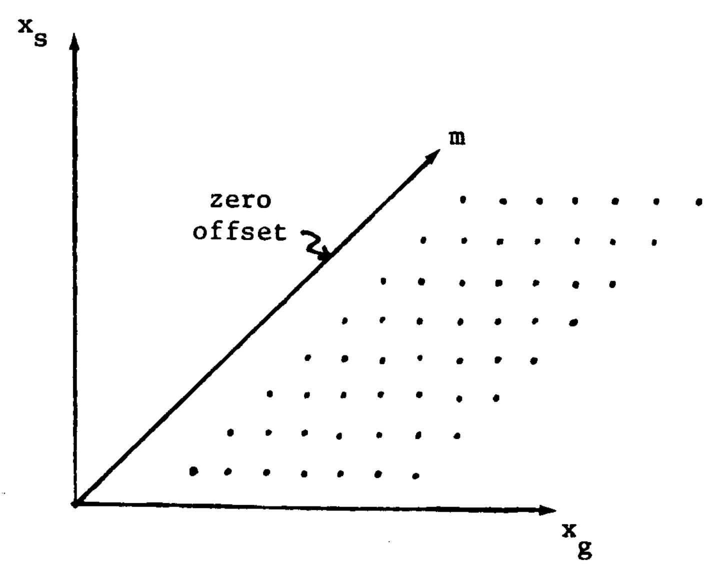


Figure 1

In order to invoke the imaging principle it is necessary to downward continue the sources and receivers into the earth. To do this, we have the equations

$$P_{x_g x_g} + P_{z_g z_g} = (1/v^2(x_g,z_g))\ P_{tt} \qquad (1a)$$

$$P_{x_s x_s} + P_{z_s z_s} = (1/v^2(x_s,z_s))\ P_{tt}\ . \qquad (1b)$$

Rewriting these equations into one-way wave equations in z, we first downward continue the geophones to z_1 using the common shot gathers. Invoking reciprocity to justify the downward continuation of the sources, we next use equation 1b to downward continue the shots to z_1 using the common geophone gathers. At each z level we pick off the energy arriving at zero travel time along the m axis (zero offset) to form the migrated section. The process is then continued down to the next z level and so forth. Neglecting any error induced by approximations to the wave equation and if the correct medium velocities are used in the downward continuation, then theoretically *all* of the *primary* energy will migrate to the zero-offset, zero-travel time plane.

Since the common shot and common geophone gathers are downward continued independent of one another and in alternate steps, the flow of energy during a downward continuation step is *parallel* to either the shot axis *or* the geophone axis. Hence, the primary energy migrates to the zero-offset axis via a jagged route in x_s, x_g space like the one shown in Figure 2.

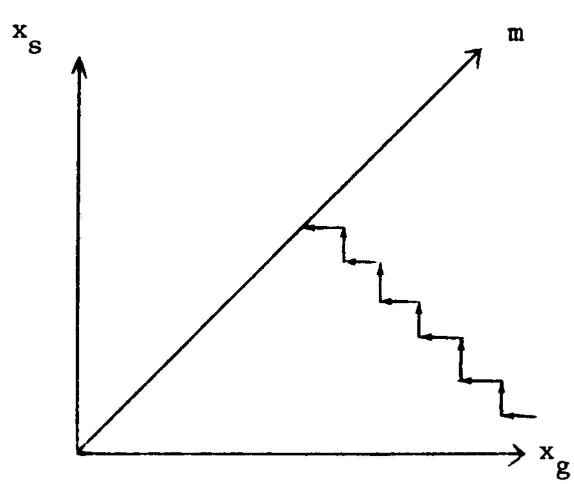


Figure 2

Explosive Reflectors Model

It is readily apparent that downward continuing both the sources and receivers is a major undertaking. Until recently, industry has avoided this bulk of work by migrating common-midpoint stacked sections instead of shots and geophones and by basing the imaging on an explosive reflectors model (also known as the Loewenthal-Sherwood model). In this model, the sources are assumed to lie *on* the reflecting surfaces. Hypothetically, they all go off simultaneously at t=0, each with a strength proportional to the reflection coefficient of their respective reflector. As pointed out by Claerbout (this report), two assumptions are involved with this method. First, this experiment is equivalent to a zero-offset experiment with the velocity of the medium halved. Second, a common-midpoint stack is equivalent, or nearly so, to a zero-offset section. The first of these two assumptions appears valid at least in terms of primary energy. The second assumption is valid only in a stratified earth (see Clayton, this report). Hence, only in this simple case will the migrated section be truly correct.

The process of migration collapses hyperbolas to their tops, as does the process of stacking common-midpoint gathers. Hence, stacking is like a migration along the offset direction which in effect moves the non-zero offset energy directly to the zero-offset axis as shown in Figure 3. Migration or downward continuation is still per-

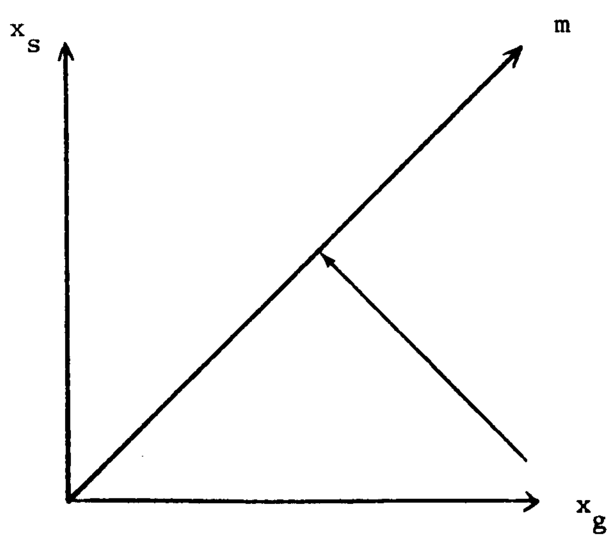


Figure 3

formed along two dimensions (midpoint and offset). Only now, the direction of energy movement in x_s, x_g space is rotated 45 degrees to the correct downward continuation axes as shown in Figure 2.

Time Coincidence of Up and Downgoing Waves

In FGDP (p. 230), Claerbout describes the basic imaging principle as "reflectors exist in the earth where the onset of the downgoing wave is time coincident with the upgoing wave." The imaging principle based on the downward continuation of shots and receivers is a special case of this principle. If the sources and receivers are situated directly above a reflector, then indeed the up and downgoing waves will be time coincident. Moving them away from the reflector only changes the time coincidence from $t = 0$ to some $t > 0$.

This principle is much more general than the downward continuation of shots and geophones in that the migrated section is contained in all offsets. That is, at each depth and for all offsets the downgoing "spherical" wave is compared to the downward continued upgoing wave (recorded at the surface) to see if they are time coincident. If so, then a reflector must exist there.

If we were trying to image the earth with just one shot and many receivers, then this would be the principle we would have to apply. Since we have many shots, using this principle would yield a lot of redundancy in obtaining the migrated section and thus not very useful in this circumstance. It is, however, very useful in multiple suppression and modelling (see FGDP, sec. 11-4).

This imaging principle can also be thought of in terms of holography. That is, for a monochromatic source, the up and downgoing waves will be in phase at the reflector. However, there will also be many other places where the waves will be in phase. To remove this ambiguity, the true image is obtained by superimposing the images produced by many different monochromatic sources. Figure 4, taken from Peterson and Walter (1977) nicely illustrates this concept.

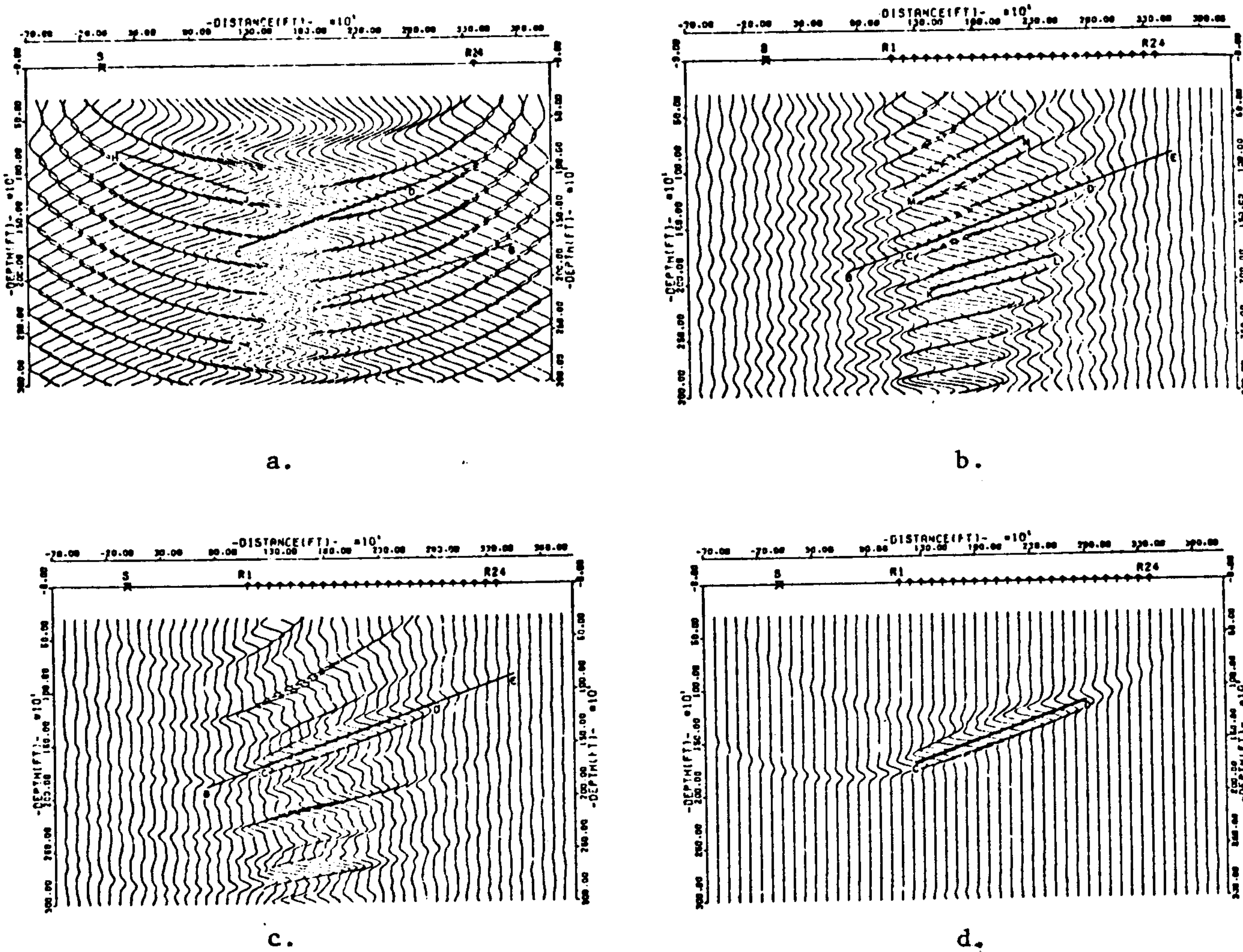
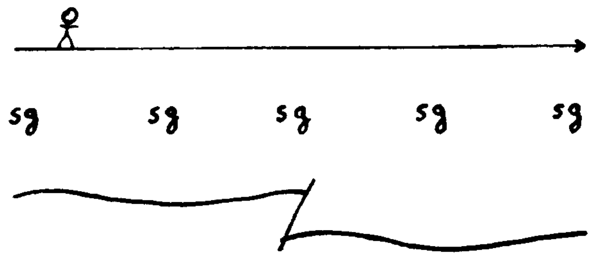
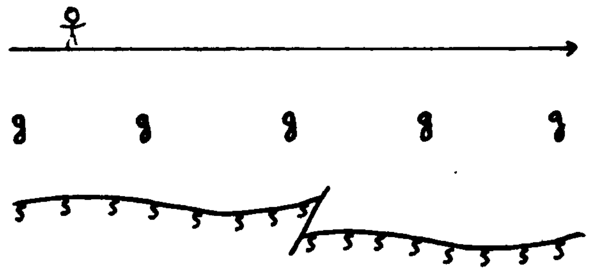


Figure 4. Taken from Peterson and Walter (1977). Holographic imaging of a truncated bed using a single source and 24 receivers. Reflectors exist where the up and downgoing monochromatic waves are in phase. The problem is, they can also be in phase where relectors do not exist. a) Reconstruction of the reflecting subsurface using a single frequency and only one geophone. The location of the reflector is unrecognizable. b) Lateral resolution is increased by superimposing the reconstruction from all 24 geophones. c) Temporal resolution is increased by superimposing 10 different frequency reconstructions like b. d) Superposition of 26 frequencies using all geophones. The location of the bed is now easily recognized.



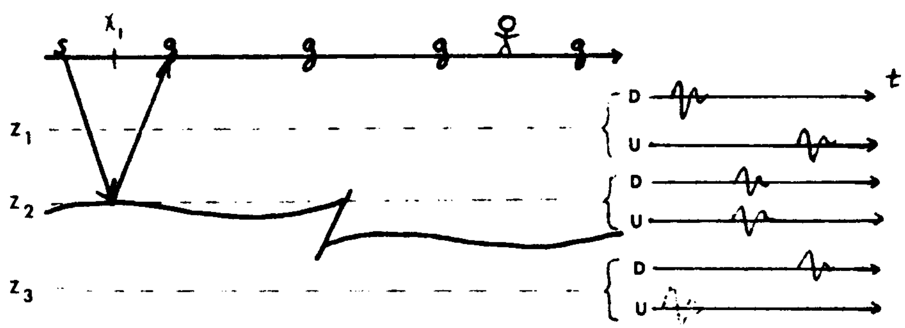
a.

Downward continuation of shots and receivers. The shots and geophones are downward continued into the earth using the wave equation. The migrated section is obtained by taking the upgoing energy arriving after zero travel time from the source to the receiver at each z level.



b.

Explosive reflectors model. The sources are assumed to lie on the reflecting surfaces, each with a strength proportional to the reflection coefficient at its location. They are set off simultaneously at t=0. If the medium velocities are halved in this experiment, then the resulting section is equivalent to a zero offset section recorded at the surface. The migrated section is obtained by downward continuing the geophones and taking the energy arriving at zero travel time at each z level.



c.

Time coincidence of up and downgoing waves. Modified from FGDP, Figure 11-2. Reflectors exist where the onset of the downgoing wave is time coincident with the onset of the upgoing wave. The traces at the right of the figure are the U and D waves recorded by the geophone at x_1 at three different z levels. Only at z_2 are U and D time coincident.

Figure 5

A pictorial summary of the three imaging principles is shown in Figure 5. In the downward continuation of shots and geophones, Figure 5a, the sources and receivers are downward continued to every z level and the migrated section is obtained by observing the upgoing energy arriving after zero travel time. The explosive reflectors model, Figure 5b, is valid for the migration of zero-offset sections and is needed for the migration of common-midpoint stacked sections. The time coincidence of up and downgoing waves, Figure 5c, is the most general of the three but is used mainly for the modelling and suppression of multiples.

References

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[3] Clayton, R., "Common Midpoint Migration," this report.

[4] Peterson, R. A. and Walter, W. C., *Seismic Imaging Atlas*, (1977), v. II, United Geophysical Corp.