5.0 THE U:D IMAGING CONCEPT

Regretably, the logic of nature seems to force the analysis of multiple reflections (this chapter) to depart rapidly from the analysis of stacking and velocity (chapter 4). Current industrial practice is based on midpoint-offset analysis, which is largely unsuitable for understanding multiple reflections. Consequently multiples are generally treated as unsystematic noise, although from a human view, multiples are often the most systematic thing seen on the data. With this chapter I hope to provide the reader with the most important *physical* information on multiples. The *statistical* aspects, which dominate analysis of land multiples, are described but not documented. The bulk of the chapter is many physical data processing algorithms which, for various reasons, have not yet established themselves in the industrial world.

Even the basic concept of "experiment sinking" seems to have little utility with multiple reflections.[1] Before we start work on multiples, we need to review an older imaging concept which is based on comparison of upgoing and downgoing waves. It will be called the $U:D$ imaging concept.

The $U:D$ imaging concept says that *reflectors exist in the earth at places where the onset of the downgoing wave is time coincident with an upcoming wave.* Figure 1 illustrates the concept. The $U:D$ concept is used extensively in FGDP for the three problems of migration, velocity analysis, and multiple suppression. Later, for the single application of zero offset migration, $U:D$ was superceded by Sherwood's approach of using the exploding reflector concept. Still later, the experiment sinking concept emerged from work with Doherty, Muir, and Clayton. The sinking concept is simultaneously useful for both migration and velocity analysis. Mathematically it seems to include the exploding reflector concept as a special case.

[1] Note added Sept 29,1980. This tutorial paper was written before research done with Morley in SEP-25 (this report). This new research is a substantially different approach to multiple reflections. If successful, chapters 5.2, 5.3, and 5.4 may become largely outmoded.

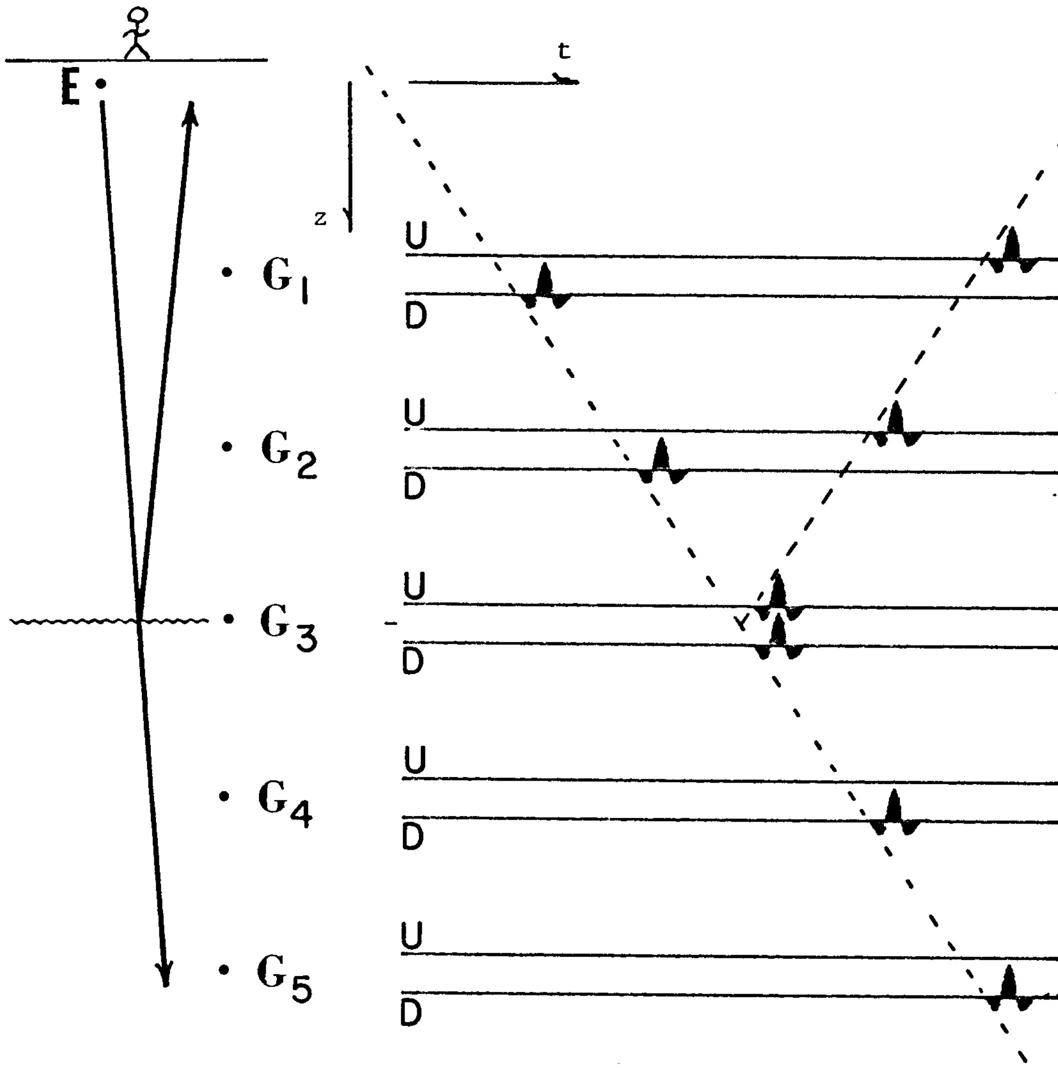

FIG. 1. (Riley) Up and downgoing waves observed with buried receivers. A disturbance exits the surface at $t=0$ and is observed passing the buried receivers $G_1 \ldots G_5$ at progressively later times. At the depth z_3 of a reflector, G_3 receiver records, in time coincidence, both the upcoming and downgoing waves. Shallower receivers also record both waves. Deeper receivers record only D. The fundamental principle of reflector mapping states that reflectors exist where U and $D(t''=0)$ are time coincident. A second principle is that the upcoming waves must vanish for all time prior to the first arrival of the downgoing wave.

It is easy to confuse the *sinking* and the $U:D$ concepts because of the similarity of the phrase "downward continue the shots" and the phrase "downward continue the downgoing wave". The first situation refers to computations involving only an upcoming wavefield $U(s,g,z,t)$ whereas the second situation refers to computations involving both upcoming $U(x,z,t)$ and downgoing $D(x,z,t)$ waves.

The sinking concept seems to be the preferred approach for migration and velocity analysis but the sinking concept seems to be unable to cope with two important situations which $U:D$ does handle. These are (1) shot space aliasing, and (2) multiple reflections.

The sinking concept might incorporate multiple reflections, but I know of no embodiment of the concept - even in one dimension - which actually does it. Riley rephased the $U:D$ concept, thus: "At any given point in the earth, upcoming waves must vanish for all time prior to the first arrival of the downgoing wave."

Some interesting tutorial examples of $U:D$ calculations are found in FGDP (p. 218 and p. 232-233). These concepts will not be reviewed here except to the extent that they are included in analysis of multiples.

5.1 SHALLOW MULTIPLES

Near the earth's surface are a variety of unconsolidated materials such as water, soil, and the so called "weathered zone". The contrast between these near surface materials and the petroleum reservoir rocks of interest is usually severe enough to produce a bewildering variety of near surface resonances. These resonance phenomena are not predicted or explained by the methods of previous chapters. The effective depth of these near-surface resonators varies over a wide numerical range. So wide is the range that our approach to multiple reflection will not be just quantitatively variable, but also qualitatively variable. Statistical and filtration techniques will be favored for shallow reverberation and physical techniques for deep multiple reflections.

Near Surface Inhomogenity

Soils have some very strange acoustic behavior. Their seismic velocities are usually less than or equal to the speed of sound in water (1500 meters/sec). It is not uncommon for the velocity to be five times slower, namely, as slow as the speed of sound in air (300 meters/sec). Where practical, seismic sources are buried under this weathered zone. But for all but the most abnormal environments, the receivers are stuck above the weathered zone.

A source of much difficulty is the fact that soils are severely laterally inhomogeneous. There is probably no such thing as a "typical" situation, so instead I will describe the local California situation. The California central valley is a flat plain, near sea level, and about 150 by 1000 kilometers in extent. A theoretical seismologist would have to be forgiven for making the erroneous assumption that the extreme flatness at the surface implies a flatness in the immediate subsurface. Anywhere on this plain it is not unusual for two geophones separated by 10 meters to see quite different seismograms. In particular, the uphole transit time (seismic traveltime from the bottom of a deep hole to the surface near the top of the hole) can easily exhibit time anomalies of a full wavelength.

How can we understand such severe, unpredictable, traveltime anomalies in the weathered zone? It is important to realize that in recent geological time the rivers in such a valley have been meandering all over the valley floor.

The Stanford University Geophysics Department field trips have always been able to get good geophysical measurements of gravity, magnetism, and electrical conductivity, but reflection seismology has never been successful. It is because a training operation with modest funds can't afford the deep shot holes, large charges and multichannel surface receiver arrays necessary to penetrate the weathered zone. Maybe this explains why so few academic seismologists specialize in reflection seismology!

The shallow marine situation is somewhat better. There are still ample opportunities for lateral variations. There are buried submarine channels as well as buried fossil river channels. But for shallow marine data the dominant aspect of the problem becomes the resonance in the water layer. The power spectrum of the observed data will be controlled by this resonance.

Likewise, with land data it is commonly observed that the power spectrum varies rapidly from one recording station to the next. These changes in spectrum can be interpreted as changes in the multiple reflections due to changes in the effective depth or character or the weathered zone.

When the water is shallow it may be impossible to discern individual seafloor reflections. With land data the base of the weathered zone is usually so shallow or indistinct that it is impossible to discern individual reflections. The word "shallow" as applied to multiple reflections is *defined* to mean that the reflections re-occur with such rapidity or irregularity that they cannot be distinguished from one another.

Focusing Effects on Shallow Multiples

The exploding reflector concept does not apply to multiple reflections, so we have no simple wave theoretic means of predicting the focusing behavior of multiples on a zero offset section. Luckily we can get some idea about the theoretical focusing behavior of multiple reflections on seismic sections by considering a vertical incidence plane wave stack. That is, all shots could be fired at the same time thus generating a downgoing plane wave. Alternately, the plane wave could be simulated by a common geophone vertical stack. This isn't the same as the familiar *CDP* stack but we can easily begin to analyze it with techniques of Chapters 1 and 2. Perhaps it will be indicative of behavior of multiples on *CDP* stacks.

Consider a multiple reflection which has undergone several surface bounces. It began life as a downgoing plane wave. It was unchanged until its first reflection from the sea floor. The sea floor bounce imposes the sea floor topography onto the plane wave. In a computer simulation this is done with a lens equation stage. Then the wave diffracts its way along to the surface and back down to the sea floor for another application of the topographic lens shift. The process of alternating diffraction and lensing repeats as often as you care to keep track of things. Figure 1 shows such a simulation. A striking feature of the high order multiple reflections in figure 1 is the concentration of energy into localized regions. It is easy to see how bounces from concave portions of the sea floor can overcome the tendency for acoustic energy to spread out. These regions of highly concentrated energy which occur late on the time axis do not resemble primaries at all. With primaries a localized disturbance tends to be spread out into a broad hyperbola. Primary migration of the highly concentrated bursts of energy seen on figure 1 must lead to semicircles. Such semicircles are a most unlikely geological model, which is all too often predicted by industry's best migration programs. Primary migration is shown in figure 2.

The most important thing to learn from the synthetic multiple reflections of figure 1 is that multiples need not resemble primaries. Occurrence of semicircles on migrated stacks could often be due to residual multiple reflections. But there is no simple theory to say whether focused multiples on vertical wave stacks should resemble those on zero offset sections. Luckily the answer is found on some data. Figure 3 is a zero offset section which establishes that the focusing phenomena we have been discussing are indeed found in qualitative, if not quantitative, form on reflection survey data.

The marine data exhibited in figure 3 clearly displays the focusing phenomena in the synthetic calculations of figure 1. This suggests that we should utilize our understanding in a quantitative way to predict and suppress the multiple reflections leaving a clearer picture of the earth's subsurface. It has not been done for this data. It has not been successfully done for shallow multiples anywhere. It may not be done soon. The reasons are many. First, the theory of figure 2 applies to vertical wave stacks. From a practical view, these are a drastic departure from common midpoint stacks. Second, the effective seismic sea floor depth is not a known input for the process, it must somehow be determined from the data itself. Third, the water depth in figure 3 is so shallow that there is no distinguishing individual bounces. I do not consider the above reasons to warrant continued avoidance of the physical approach in favor of statistical treatment. But the reasons do explain our status today. Even in the long view we must accept a place for the statistical approach. We must be prepared to accept the possibility that the deterministic, seismic world in which we live has a bigger space of unknown parameters (particularly in the heterogeneous near surface) than any

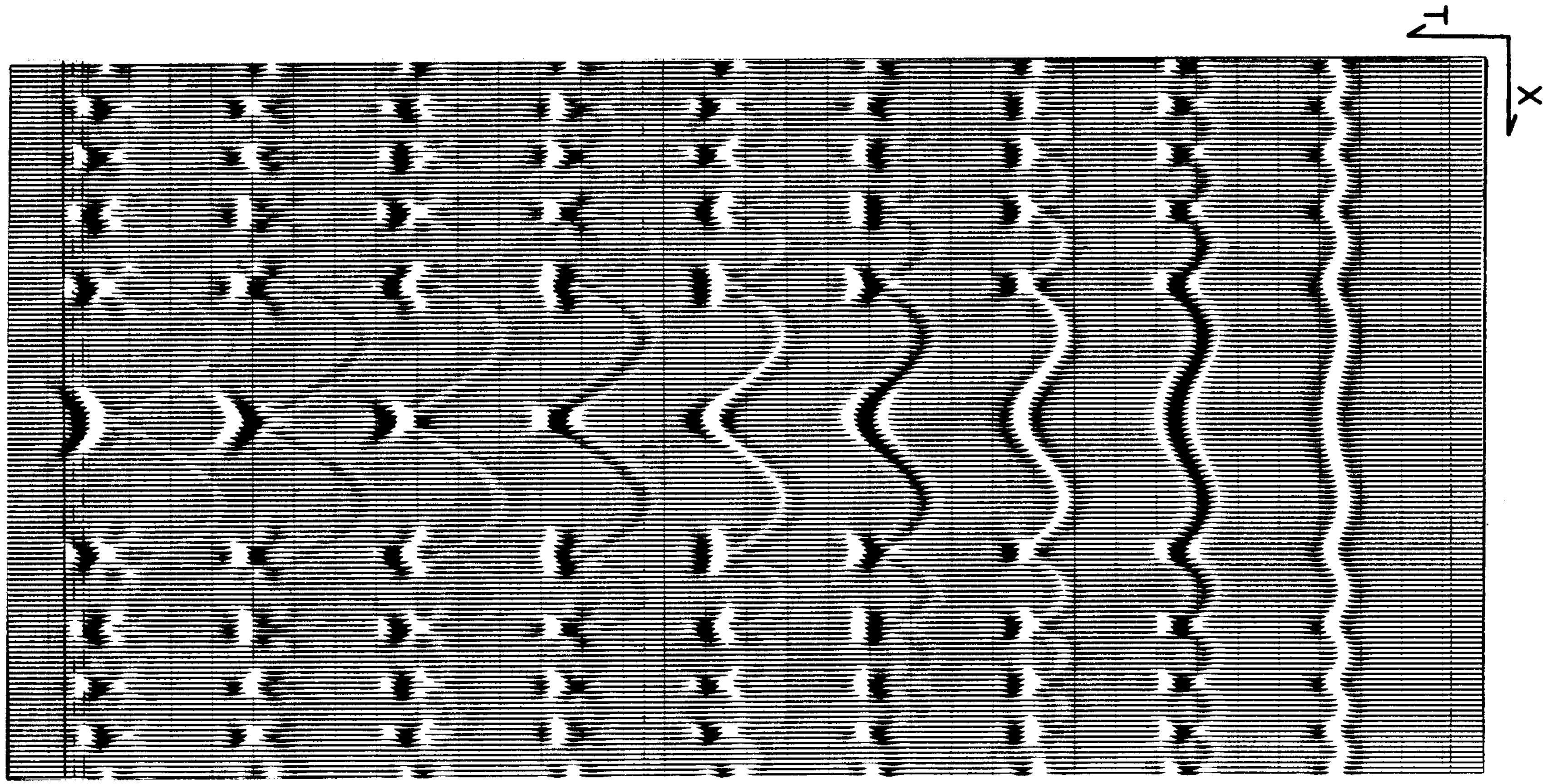

FIG. 1. Simulated sea floor multiple reflections. The vertical exaggeration is 5. Little focusing is evident on gentle sea floor topography, but much focusing is evident on high order multiple reflections.

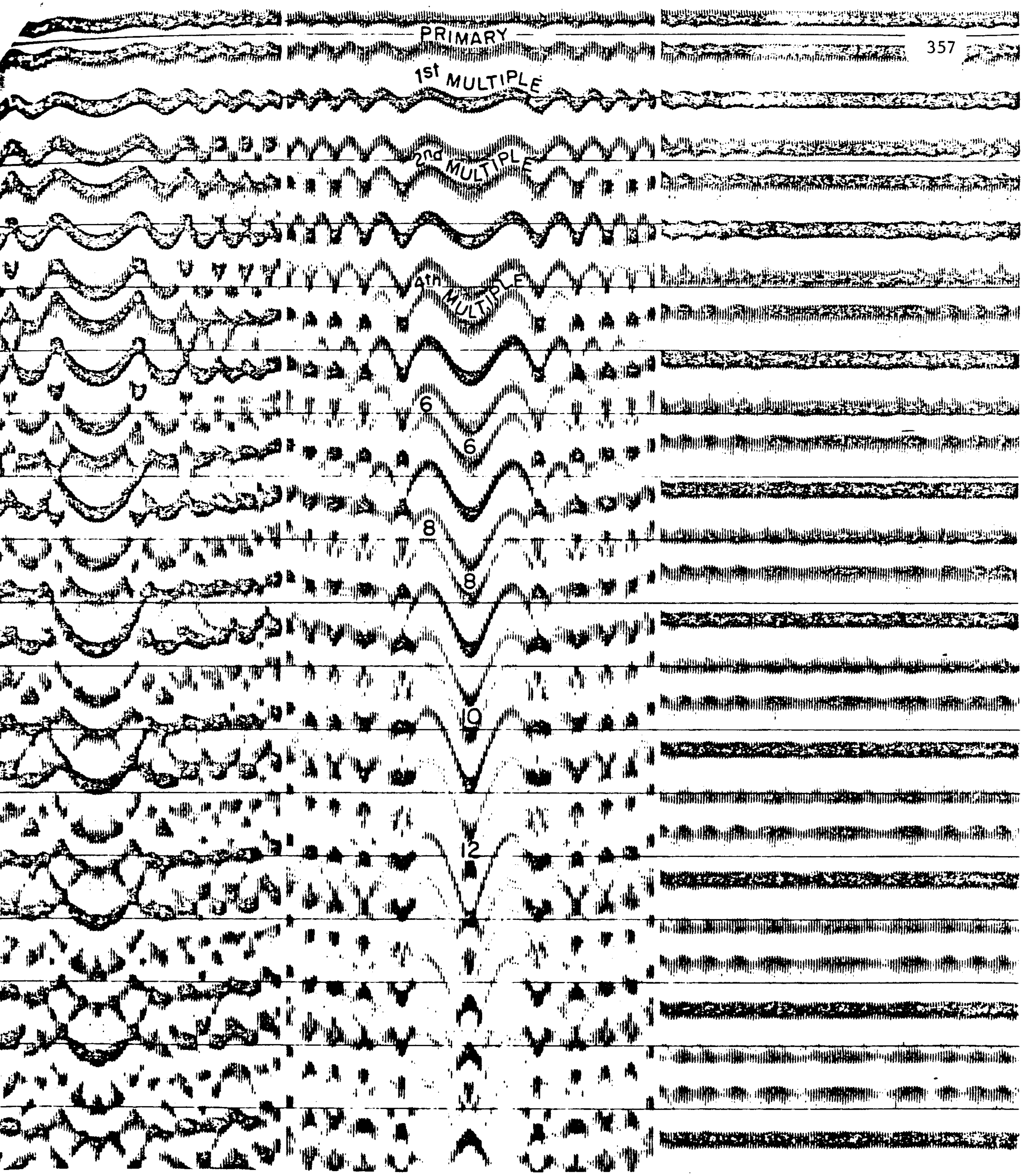

FIG. 2. Center shows the focused multiples of figure 1. Left shows a migration of the multiples assuming they are primaries, hence the overlapping semicircles. Right is the reverse of the original shifting and diffracting process, which produced the original synthetic multiples. Presumably the right frame is ready for conventional deconvolution.

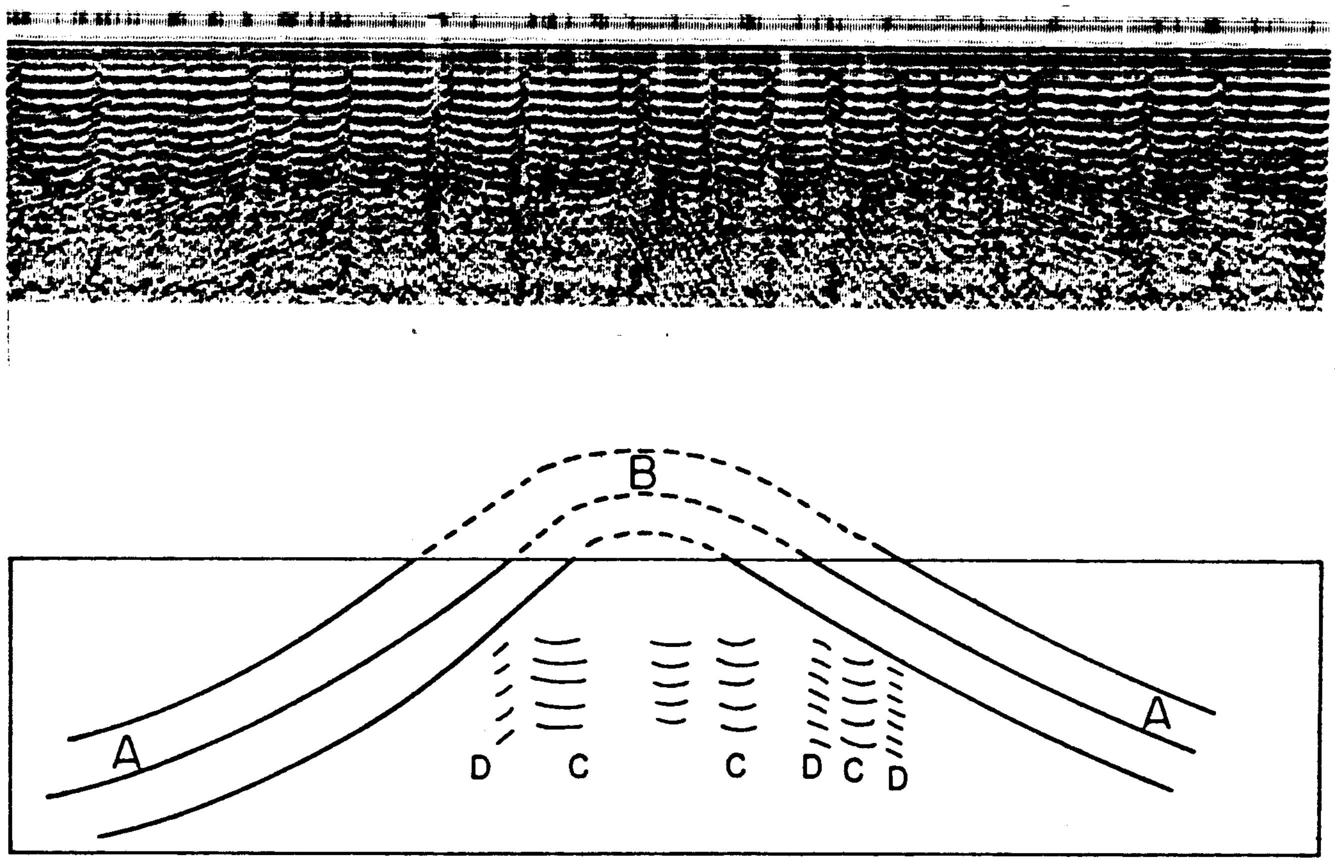

FIG. 3. Example of focusing effects on multiple reflections in near trace section at Chukchi Sea. These effects are obscured by stacking.

A. Existing structure

B. Former structure unevenly eroded away leaving localities of sea floor convex or concave.

C. High order multiple reflections focusing where the sea floor is concave.

D. Existing structural dip exposed in windows where the multiples are weak (i.e., where convex sea floor causes multiple to spread rapidly.)

reasonable seismic data base.

Statistical Rejection

It may be said that "seismic data varies in quality from poor to excellent". This statement says nothing at all about the quality of seismic data which is usually very repeatable. A reference to "poor data" should be interpreted as a statement that the theoretical assumptions of the first part of Chapter 4 are not being satisfied. Proper understanding of the data then involves some important missing ingredients. It may not be easy to tell if the problem is near surface irregularities causing phantom diffractions, multiples, surface waves, the third dimension, shear waves, or something else altogether. You need to try to figure out where the problem lies. Perhaps it can be resolved by a change in recording procedures or a change in the processing. Perhaps you can't figure it out. Perhaps the volume of relevant unknown parameters in the earth exceeds that in your data. Then you resort to statistical techniques.

Believing that strong lateral changes in seismic amplitudes are due to resonance and focusing the near surface and believing that these changes are too rapid and irregular to be systematically determined and compensated, we have some justification for "trace equalization" or "automatic gain control". A more extreme view, somewhat justified by the examples of figures 1 and 3, is that signal amplitude is inversely correlated with signal quality. This view suggests "diversity stack" in which each seismogram is weighted inversely according to its local power.

The rapidity of lateral changes can also be used to improve the quality of seismic data. Seismic theory predicts that surface phenomena such as ground roll or shallow layer resonance can have very high spatial frequencies k_s and k_g. These frequencies can be rejected by spatial averaging in the field. Theoretically, even better is low-velocity rejection filtration during processing.

Deconvolution

Having accepted the idea that the amplitude or envelope of seismic traces should somehow be "equalized", "balanced", or made to vary slowly from trace to trace we are prepared for the next balancing operation. The Fourier dual of the envelope of a seismogram is its power spectrum. As long as we are falsifying the field data by balancing the trace envelopes, why not also balance the power spectra? It turns out that this, too, is a time-honored process. Seismic data is usually "deconvolved", a term defined in

FGDP as well as various other books. Deconvolution gives each trace a white power spectrum. Pure deconvolution is always followed by some kind of filtering operation, which recolors the data with an appropriate spectrum.

Deconvolution has an interpretation in terms of non-predictability of primary reflections. Deconvolution theory is closely related to inverse theory where reflection coefficients are determined from the data. This often misleads casual workers into believing that deconvolution is a process whose output should theoretically be reflection coefficients. A careful look at the theory shows that it does not, but it is closer to being true for earthquake data (seismic source beneath the reservoir) than for reflection data! I believe the reason deconvolution "works" is that it spectrally balances the data. Mostly what we do with seismic data is to look for stepouts. It makes more sense to do this on traces with similar spectra than with dissimilar spectra. Furthermore, the view that each piece of the earth's surface has its own local resonance character provides justification to the trace balancing idea.

My objection to the currently popular means of deconvolution and filtering as a method of spectral balancing is this. The power spectrum given to the traces by the filter after deconvolution is chosen *a priori*. But the downgoing wave has its signal spectrum determined by the local resonance of the weathered zone near the source. It is reasonable to expect the information content to be small where this spectrum is small. Spectral balancing, like trace envelope balancing should not attempt to obliterate all traces of thc original spectrum.

Backus Filter

An attractive dereverberation filter is the Backus filter. It is a double application of the filter $1 + cZ^N$ in which N is the depth of the sea floor in units of two-way travel time discretization intervals and c is the sea floor reflection coefficient. The first application is for the shot resonance and the second application is for the geophone resonance. The Backus filter is a special form of the ordinary deconvolution filter in which certain coefficients should turn out to be zero have been set to zero. As with other deconvolution filters, it does not incorporate the idea that the bandwidth of information content is limited by the bandwidth of the downgoing wave.

Unfortunately, the best practical feature of the Backus filter is obliterated by many theoretical discussions and attempted implementations in which the most important fact is ignored. This fact is that the near surface response at the shot will be different from the near surface response at the receiver.

Most present processing ignores the Backus filter altogether and solves for an independent deconvolution filter for each seismic trace. This loses an important idea. We would do well to try to decompose the matrix (function of s and g) of potential deconvolution filters into the sum of two vectors, one for the shot location and one for the geophone location. Perhaps some offset effects could be incorporated into a third vector.