5.3 Multiple Reflection, Experience

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 often 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.

Multiple reflections are a continuing challenge to geophysicists. When they occur, they cover up the primary reflections which we would like to see. Ideally we would use multiples to add confidence to our interpretation of the primary model. This ideal is hardly ever met. Usually we are just applying two old processes, ***stacking*** and *deconvolution*. The philosophical bases of the two processes are quite unrelated. It is almost accidental that they do remove multiples.

Here we will review experience with multiple reflections. In the next section we will look at future prospects.

Stacking in Routine Data Processing

Conventional stacking is summation along a hyperbolic trajectory on a common midpoint gather. A family of stacking hyperbolas is charactorized by a velocity parameter. As has been shown in the previous section, the best fitting velocity parameter is one which matches the root-mean-square velocity of the ray. This velocity is almost always lower for multiples than for primaries. So, given a data set with both primaries and multiples, stacking at primary velocity will enhance the primaries, and accidentally attenuate the multiples somewhat.

The ratio of enhancement to attenuation can be improved, much as a filter can be designed to be large at one frequency and small at another. To bring out the analogy of stacking to filtration (which is imperfect) consider data after NMO, and look at a portion of the cable far from the origin. The primary reflections lie horizontally and the multiples have stepout. Stacking, *i.e.* summation along a horizontal line, is like a low-pass filter in the space of k_h. Imagining data within a limited range of ω, other velocities will be found at other values of k_h. Why not completely kill the multiples by setting to zero the filter response at the water velocity? The cable has finite length, so filter sidelobes must be considered. Thus some k_h-spectral bandwidth is associated with both the primaries and the multiples. The limited ability of stacking to suppress multiples arises from the overlapping spectral windows. There are two physical situations which aggravate the overlap.

First, stacking works well when the RMS velocities of the multiple and primary raypaths are well separated. This is most often the case for water bottom multiples since water velocity is usually somewhat lower than acoustic velocities in sediments. It doesn't work nearly so well for pegleg reflections. Not only are the velocities more similar, but at late time, the effective cable length may be rather short. A further aggravation is the presence of sea floor dip which raises the apparent velocities.

A second stacking problem is near-surface lateral variations within the cable. Imagine that each geophone has a slightly different local time delay or variation in its ω response. This broadens all the windows in velocity space and causes more overlap between multiples and primaries.

In summary, stacking to suppress multiple reflections is more effective if we have a reliable model for them. On the other hand, the stacking operation is basically a multiplication in the k_h-domain, and since we deal with fairly broad windows, we are not terribly sensitive to the multiple model. It is intrinsically difficult to remove pegleg multiples by stacking because their velocity is very near to that of the primaries.

Deconvolution in Routine Data Processing

Among statisticians there is a rich literature on deconvolution. For them the problem is really that of estimation of a source waveform, not the problem of removing multiple reflections. There is a certain mathematical limit in which the source waveform problem becomes equivalent to the multiple reflection problem. This limit is when the reverberation is confined to a small physical volume surrounding the shot or geophone, such as the soil layer. The reason is that the downgoing wave from a shot is not only intrinsic to the shot itself but also includes the local soil ghosts and resonances.

There is also a rich literature on the vertical incidence model of multiple reflections. Among wave propagation theorists, the removal of multiples is called *inversion*. It seems that for inversion theory to work, it should incorporate an analysis to deal with a spectrally deficient, unknown shot waveform.

Conventional industrial deconvolution has many derivations and interpretations. I will state in simple language what I believe to be the essence of the thing. Every seismogram has a spectrum. The spectrum is a product of many causes. Some causes have fundamental interest. Others are extraneous. It is quite annoying when a seismogram is resonant just because of some near surface phenomena. It is also annoying when the spectrum varies from trace to trace as the near surface varies from place to place. A variable spectrum makes it hard to measure stepouts. The solution is to design a short filter for each trace which tries to give the trace a pleasing spectrum. To the extent that a short filter can do this job, the output spectra will not vary a lot from one trace to another.

The above interpretation of deconvolution and why it works is quite different from what is found in much of the geophysical literature. Often the deconvolution filter is described as one which whitens a trace. After whitening, data is recolored with a bandpass filter. So the result is the same as in the previous paragraph. Alternately, deconvolution is sometimes interpreted in terms of the predictability of multiple reflections, and non-predictability of primary reflections. The reader is cautioned to remember that deconvolution predicts and removes multiples only in the sense that a shot waveform looks like very limited class of multiples.

Deep Marine Multiples, a Phenomenon of Polar Latitudes

It has frequently been noted that sea-floor, multiple reflection seems to be a problem of the polar latitudes. It is rarely a problem of equatorial regions. This observation could be dismissed as being based on the statistics of small numbers. Alternately, two reasons may be given, each of interest whether or not the statistics are adequate.

It happens that natural gas is soluable in water, and it raises the temperature of freezing, particularly at high pressure. Such ice is called *gas hydrate*. Thus it can happen that under the liquid ocean, trapped in the sediments there can be solid gas hydrate. It stiffens the sediment and enhances the multiple reflection.

A second reason for high multiple reflections at polar latitudes has to do with glacial erosion. Ordinarily we think of ocean bottoms as places of slow deposition of fine grained material. Such freshly deposited rocks are soft, generating weak multiple reflections. But in polar latitudes the scouring of glaciers is actively removing sediment. Where erosion is taking place we may expect that the freshly exposed rock will be stronger and stiffer than newly forming sediments. Thus the stronger reflections.

Continents erode and deposit at all latitudes. However, one might speculate that on balance, continents are created by deposition in low and mid latitudes, then they drift to high latitudes where they erode. While highly speculative, this does provide an explanation for the association of multiple reflections with polar latitudes.

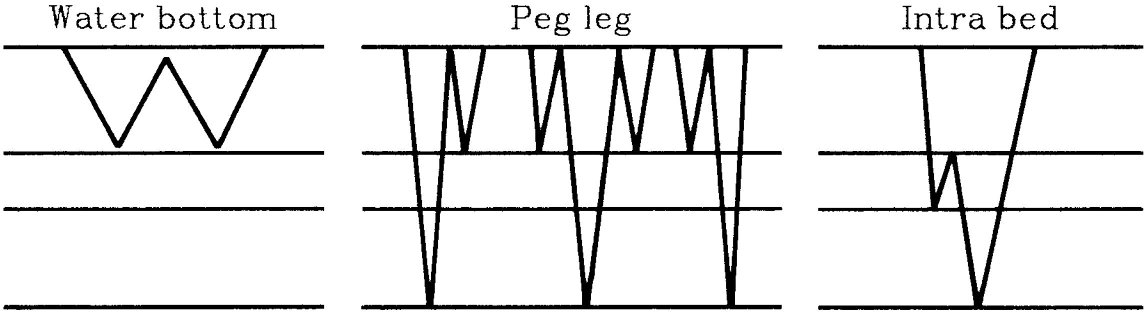

FIG. 1. Raypaths are displayed for (a) water-bottom multiple, (b) pegleg multiple, and (c) short-path multiple.

Examples of Deep Water Multiple Reflections

Multiple reflections fall into one of three basic categories. See figure 1. *Water-bottom* multiples are those multiples whose raypaths lie entirely within the water layer (Fig 1a.). They often have strong amplitudes since the seafloor usually has a higher reflectivity than deeper geological horizons. In deep water these multiples can be very clear and distinct. A textbook quality example is shown in figure 2.

Pegleg multiple reflections are variously defined by different authors. Here we will define pegleg multiples (Fig 1b) to be those which undergo one reflection in the sedimentary sequence and

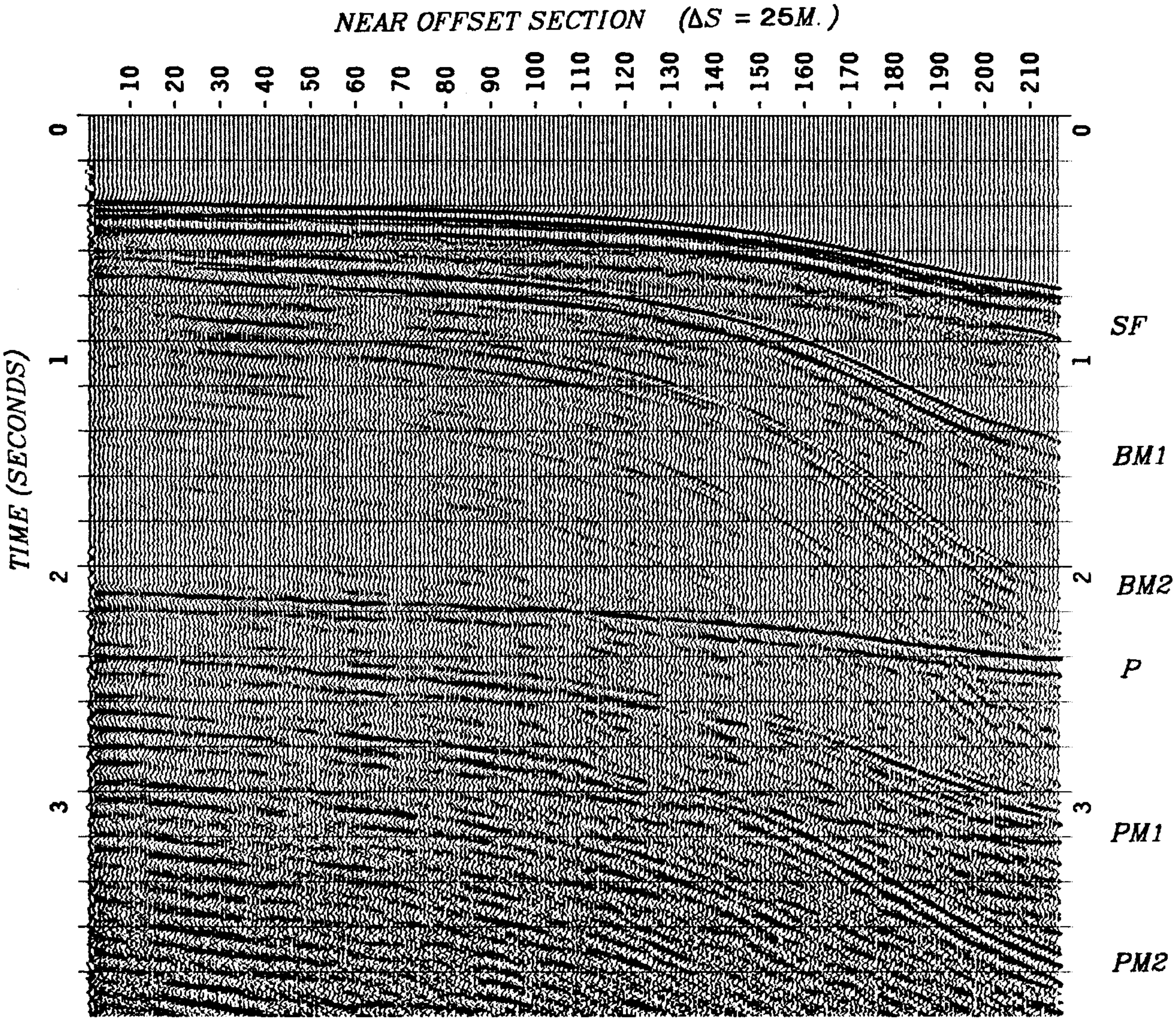

FIG. 2. (AMOCO-Canada, Morley) Near Offset Section — offshore Labrador (Flemish Cap). Offset distance is about 9 shotpoints. Labeled events are SF-seafloor, BM1-first bottom multiple, BM2-second bottom multiple, P-primary, PM1-first pegleg multiple, and PM2-second pegleg multiple.

other reflections in the near surface.

To facilitate interpretation of seismic data, let us consider the timing and amplitude relations of vertical-incidence multiple reflections in layered media. Take the sea floor two-way travel-time to be t_1 with reflection coefficient c_1. Then the n-th multiple reflection comes at time $n\, t_1$ with reflection strength c_1^n. Suppose we have also a deeper primary reflection at travel-time depth t_2 with reflection coefficient c_2. Then we expect seafloor peglegs at times $t_2 + n\, t_1$. Note that peg-legs come in families. For example, the time $t_2 + 2t_1$ could arise from three paths, $t_2 + 2t_1$, $t_1 + t_2 + t_1$, and $2t_1 + t_2$. So the n-th order pegleg multiple echo is actually a summation of $n + 1$ rays, thus its strength is proportional to $(n+1)\, c_2 c_1^n$. The seafloor reverberation is c_1^n which is not the same as the reverberation on sediments which is $(n+1)\, c_1^n$. So if you don't have to worry about the seafloor reverberation at the same time as the pegleg reverberation, you can just think of $(n+1)\, c_1^n$ as a shot waveform.

Every multiple must have a "turn around" where an upcoming wave becomes a downgoing wave. Almost all readily recognized multiples are *surface* multiples, that is, they have their turn-arounds at the earth surface. Figure 2 shows some very clear examples. Land data can have the turn-around at the base of the soil layer, which is almost the same thing.

A ray path representative of yet another class of multiples called "short-path" or "intra-bed" multiples is shown in figure 1c. Their turn-around is *not* at or near the earth surface. These multiples are rarely self evident in field data, although figure 3 shows a clear case. When they are identified, it is often because the seismic data is being interpreted with some accompanying well logs. The reason that observation of these is so rare compared to that of peglegs is that the reflection coefficients within the sedimentary sequence are so much less than the free surface. Compensating for the weakness of any such multiple is the fact that *very many* multiples of this type are possible. Any time the seismic section becomes incomprehensible, we can hypothesize that the data has become overwhelmed by multiples of this type.

Need to Distinguish Between Types of Sections

By 1974, wave equation methods had established themselves as a successful way to migrate CDP stacked sections. Bolstered by this success, Don Riley and I set out to apply the wave equation to the problem of predictive suppression of deep water multiple reflections. Hypothesizing that diffraction effects were the reason for so much difficulty with deep water multiple reflection, we developed a method for modeling and predictive removal of diffracted multiple reflections (see FGDP). We didn't realize that

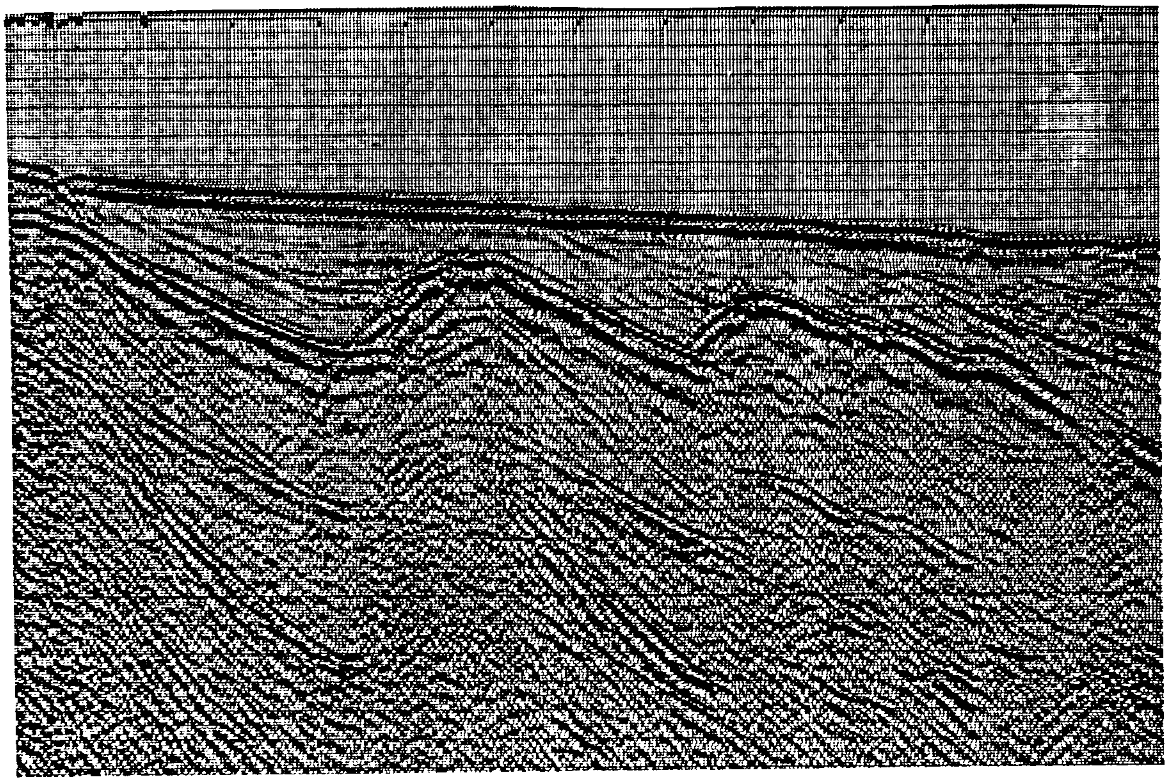

FIG. 3. (Western Geophysical) A rare case of unambiguous intra bed multiple reflections. The data was recorded near Puerto Rico. The inner bed multiple is between the sea floor and the basement. Thus its travel time is $t_{base} + (t_{base} - t_{floor})$. Do you see it?

the practical problem would be so much more difficult than the primary reflection problem. For primaries, the same basic method works regardless whether you are looking at a zero offset section, a CDP stacked section, or a vertical incidence plane wave section. Our multiple suppression method turned out to be applicable only to vertical plane wave stacks. Don Riley prepared figure 4 which shows some comparisons.

One thing to be born in mind while studying these comparisons is that on the field data there is quite certain to be unrecognized aspects of propagation in three dimensions. The third dimension is always a "skeleton in the closet". It usually doesn't seem to spoil two dimensional migration, but that doesn't guarantee that it wouldn't spoil 2-D wave equation multiple suppression.

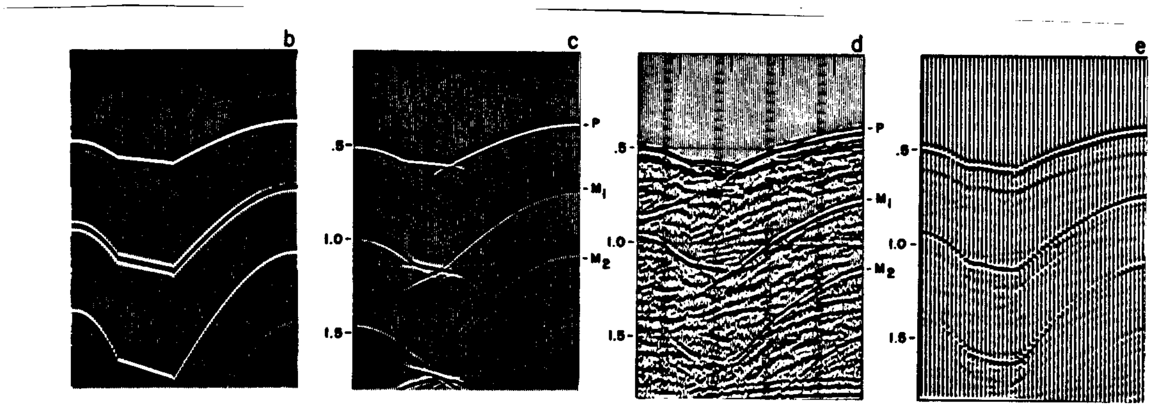

FIG. 4. (Riley) Diffracted multiple reflection examples. (b) 1-D Synthetic, (c) 2-D Synthetic, vertical plane wave source, (d) 27-fold CDP data section (GSI) (e) Near trace section

Examples of Shallow Water Multiples with Focusing

In shallow water it may be impossible to discern individual seafloor reflections. With land data the base of the weathered zone is usually so shallow and 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.

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. Thus, 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 up 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 5 shows such a simulation. A striking feature of the high order multiple reflections in figure 5 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 5 must lead to semicircles. Such semicircles are a most unlikely geological model, which is all too often predicted by industry's best migration programs.

The most important thing to learn from the synthetic multiple reflections of figure 5 is that multiples need not resemble primaries. Occurrence of semicircles on migrated stacks could be due to residual multiple reflections. Unfortunately, there is no simple theory to say whether focused multiples on vertical wave stacks should resemble those on zero offset sections or CDP stacks. Luckily the answer is found on some data. Figure 6 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 6 clearly displays the focusing phenomena in the synthetic calculations of figure 5. 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. There are several reasons why this would not be easy. First, the theory applies to vertical wave stacks. These are quantitatively different 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 6 is so shallow that there is no distinguishing individual bounces.

Why Deconvolution Fails in Deep Water

It has been widely observed that deconvolution generally fails in deep water. We have already seen a possible reason for this, namely, in deep water we are not at the mathematical limit for which the multiple reflection problem is equivalent to the shot

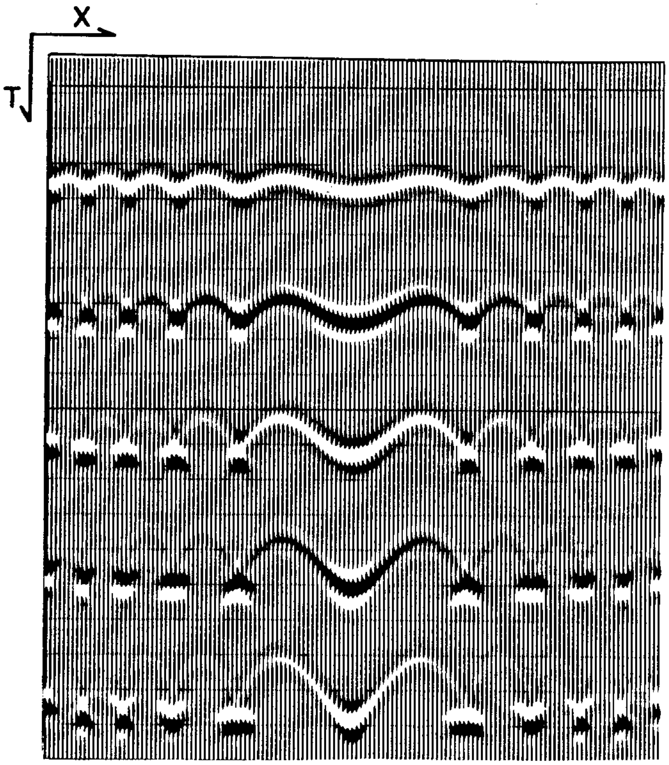

FIG. 5. Simulated sea floor multiple reflections. The vertical exaggeration is 5. Little focusing is evident on gentle sea floor topography, but much focusing is evident on high order multiple reflections. At late times there is a lack of lateral continuity, quite unlike most primary reflection data.

waveform problem. But that is not all.

Theory predicts that under ordinary circumstances multiples should alternate in polarity. You may have noticed that this can be difficult to observe. Actually, it is easy to observe under the right circumstances. Despite the small plot size, you might be able to see it on figure 2. In shallow water the pulses may come too close together to be distinct. Or else the offset may be such that you are looking at grazing angles. Beyond critical angle, theory predicts a shift different from π, so then you shouldn't see simple alternation of polarity. In deep water the pulses are distinct. At the nearest offset the alternation in polarity should be quite clear. But you will have trouble if you look for alternating polarity on CDP stacks. There is a reason for this, and it is another reason why deconvolution tends to fail to remove deep multiples from CDP stacks.

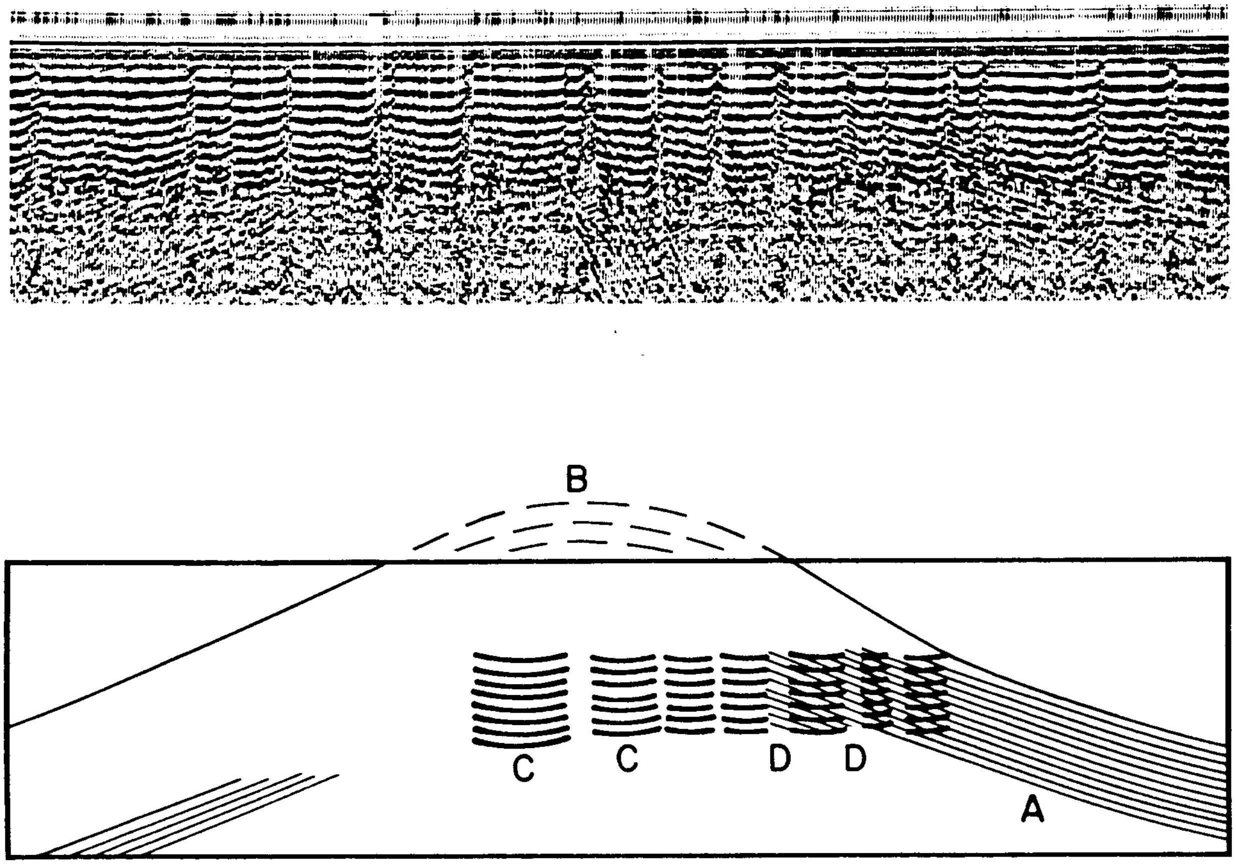

FIG. 6. (U.S. Geological Survey) Example of focusing effects on multiple reflections in near trace section at Chukchi Sea. These effects are obscured by stacking.

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.)

Recall the timing relationships for multiples at zero offset. The ***reverberation period*** is said to be constant. Because of moveout, this is not the case at any other offset. Normal moveout correction would succeed in restoring zero-offset timing relationships in a constant velocity earth. But when the velocity increases with depth, the multiples will have a slower RMS velocity than primaries. So the question is what velocity to use, and whether in typical land and marine survey situations, the residual time shifts are greater than a half-wavelength. No equations are needed to get the answer. It is generally observed that conventional common-midpoint stacking suppresses multiples because they have lower velocities than primaries. This observation alone implies that normal moveout does indeed routinely time shift multiples a half-wavelength or more out of the natural zero-offset relationships.

To make matters worse, the amplitude relationships which we expect at zero offset are also messed up. Reflection coefficient is a function of angle. But if you take a seismogram from some particular offset, each multiple reflection on it will have reflected at a different angle.

Vertical incidence timing relationships are *approximately* displayed on CDP stacks such as that displayed in figures 2,3 or 4. The practical difficulty is that the CDP stack does not mimic the vertical incidence situation well enough to enable satisfactory prediction of multiples from primaries.

Before stack, on marine data, the moveout could be done with water velocity, but then peglegs would not fit the normal-incident timing relationship. Since the peglegs are often the worst part of the multiple-reflection problem, perhaps you should move-out to pegleg velocity. Basically, no matter how you look at it, all the timing relations for deep multiple reflections cannot be properly adjusted by moveout correction.