CANADIAN JOURNAL OF EXPLORATION GEOPHYSICS
VOL. 31, NOS. 1 & 2 (DECEMBER 1995), P 18-24

MIGRATION FROM TOPOGRAPHY: IMPROVING THE NEAR-SURFACE IMAGE

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ABSTRACT

In mountainous areas, such as the foothills of the Canadian Rockies, careful processing of near-surface seismic data is essential, for without an accurate interpretation of the near surface, a reliable map of the deeper reflectors is unlikely. Although statics corrections are the primary focus of attention for near-surface imaging in mountainous areas, other factors can also affect the quality of the image near the earth's surface. In this paper, we investigate the effects of migration amplitudes on imaging quality. We use a synthetic seismic data set that models the geology of northeastern British Columbia to test the application of Kirchhoff depth migration directly from an irregular surface. We show that the near-surface image obtained using migration weights referenced to the recording surface is significantly better than one obtained using migration weights referenced to a flat datum above the surface. In addition, prestack migration velocity analysis, used to estimate velocities for accurate imaging, is more interpretable when the migration weights are referenced to the recording surface.

INTRODUCTION

Poststack seismic migration has two major uses: to image structure and to delineate stratigraphy. Prestack migration commonly has a third use: to estimate migration velocities. Less frequently, prestack migration is used to estimate reflection amplitude versus offset in the presence of complex overburden. For all these applications, poststack and prestack migration must preserve the integrity of the bandpass-filtered seismic wavelet. Some migration methods, such as finite-difference and Stolt migration, automatically preserve the character of the input wavelet. In order to accomplish the same goal, Kirchhoff migration requires the explicit application of a phase rotation to the data, as well as amplitude factors ("weights") to the summation along diffraction curves. The phase rotation occurs in differentiating the traces before or after migration, and is very straightforward to apply. The weights correct for geometrical spreading loss and obliquity factors, and are not so easy to apply. Schneider (1978) presented the simplest expression for these weights in a constant-velocity medium; this expression is often satisfactory in poststack migration even when the migration velocity varies significantly. For prestack migration, the weights account for nonzero source-receiver separation and domain (common shot, common midpoint, or common offset) and are consequently more complicated than the poststack migration weights. Several authors (e.g., Hanitzsch et al., 1994) have presented expressions for "true-amplitude" prestack migration weights. Whether one chooses a simplified, constant-velocity weight function appropriate for poststack migration or the more complicated weights appropriate for prestack migration, it is imperative to use a weight that tapers to zero at the farthest offsets of the migration impulse response operator (Figure 1). For poststack migration, this weight will approximate Schneider's obliquity factor cos θ, where θ is the angle between the normal to the earth's surface and the ray from the image point to the location of the input trace at the earth's surface. For prestack migration, the weight involves both cos θ_S and cos θ_R, where θ_S (θ_R) is the angle between the normal to the earth's surface and the ray from the image point to the source (receiver) location (Hanitzsch et al., 1994). When migration weights are carefully applied in combination with the necessary phase rotation, the migration will preserve the character of the input wavelet, even if the seismic energy has propagated through one or more caustics. On the other hand, careless application of the migration weights can cause the migration operator to alias, or image high-frequency data improperly at steep dips. Migration operator aliasing, at its most benign, causes the output wavelet to be distorted and, when it is severe, can cause irreparable damage to an otherwise correctly migrated section.

Although the importance of migration weights is well appreciated for marine data and for land data acquired over

Manuscript received by the Editor June 22, 1995; revised manuscript received June 22, 1995.
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We thank Gary MacLean for generating the synthetic data set used in this study.

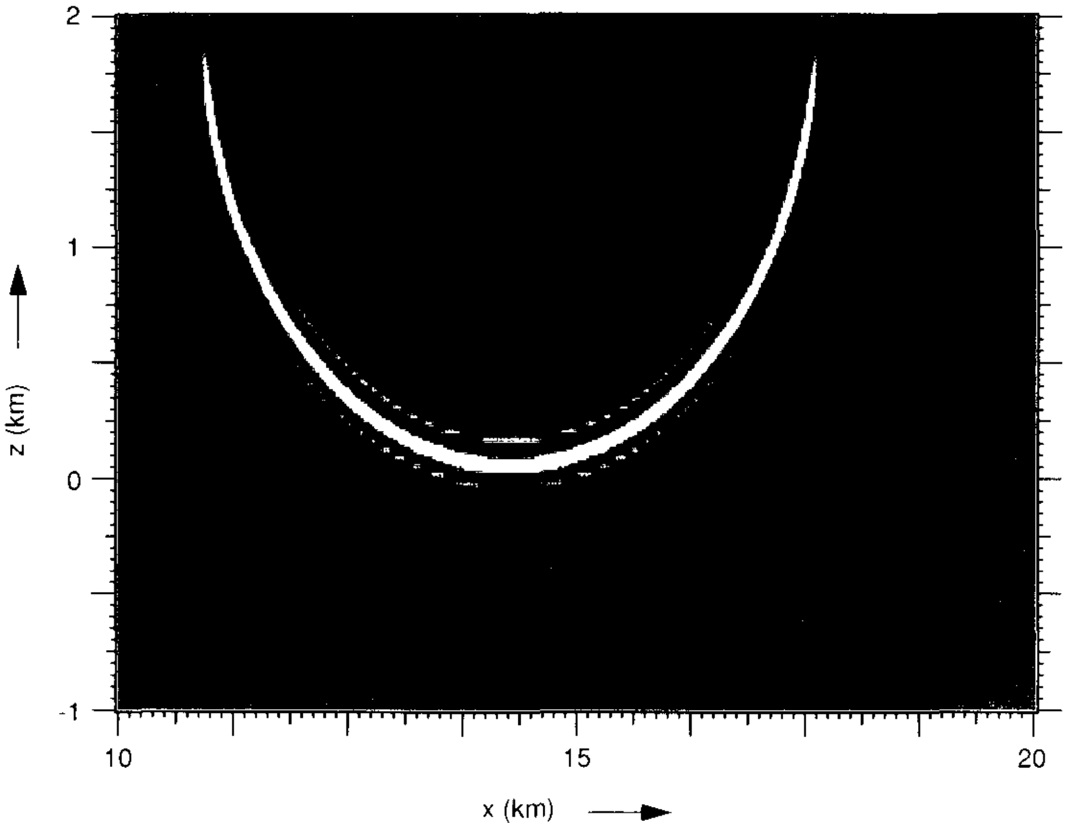


Fig. 1. Migration impulse response for a source/receiver pair located at $x = 14$ km along a flat, constant-velocity recording surface whose elevation is 2 km.

fairly flat terrain, it is perhaps not so well appreciated for data acquired over a surface with significant topographic variations. In this note, we examine the effects of two choices of weights, one simple but inappropriate and the other more appropriate, for Kirchhoff migration of seismic data acquired along an irregular surface and migrated directly from that surface (Wiggins, 1984). When the acquisition surface is irregular, there are considerable advantages to processing seismic data directly from topography, without shifting them to a flat or floating datum. For example, irregular topography is usually associated with highly contorted near-surface formations. Imaging these formations is crucial to tying geologic (e.g., outcrop) control to the seismic data. On the other hand, imaging these beds requires a level of precision in processing the near-surface data that datuming usually does not allow; thus, our preference for processing, including migration, directly from topography whenever possible. However, we shall show that, even when the data are migrated directly from topography, the migration weights must be computed from topography and not from an arbitrarily chosen flat datum to avoid operator aliasing and its consequences for prestack migration. Fortunately, computing the weights from topography can be accomplished as efficiently as computing the weights from a flat datum and, therefore, need not add to the cost of the migration.

The Effect of Migration Weights on the Migrated Images

Figure 2 shows a geologic cross-section, consisting of a number of faulted and folded layers typical of mountainous thrust regions. The top layer is air, with the surface of the earth indicated by the irregular white curve near the top of the model. The model is 25 000 m long; the top of the model in 2000 m above sea level and the bottom of the model is 8000 m below sea level. The total relief of the earth's surface along this cross-section is approximately 1600 m. This figure also indicates velocities, which range from 3500 m/sec (the darkest areas near the top) to 5900 m/sec (the lightest areas near the bottom). The horizontal bands indicate a vertical velocity gradient. This velocity model was used to generate 278 two-dimensional (2-D) acoustic synthetic shot records from the earth's surface. The data were recorded by a split spread of 480 receivers with offsets ranging from 15 m to 3600 m on both sides of the shotpoints. The shot spacing was 90 m. The 2-D wave equation used to generate the data set caused cylindrical spreading loss (roughly proportional to $1/\sqrt{t}$), while the Kirchhoff migration used to migrate the data assumed that energy from the sources underwent spherical spreading loss (roughly proportional to $1/t$) while propagating in the earth. To accommodate this difference in spreading loss, the traces were multiplied by $1/\sqrt{t}$ before migration.

Figure 3 shows the migration of a single, near-offset trace.

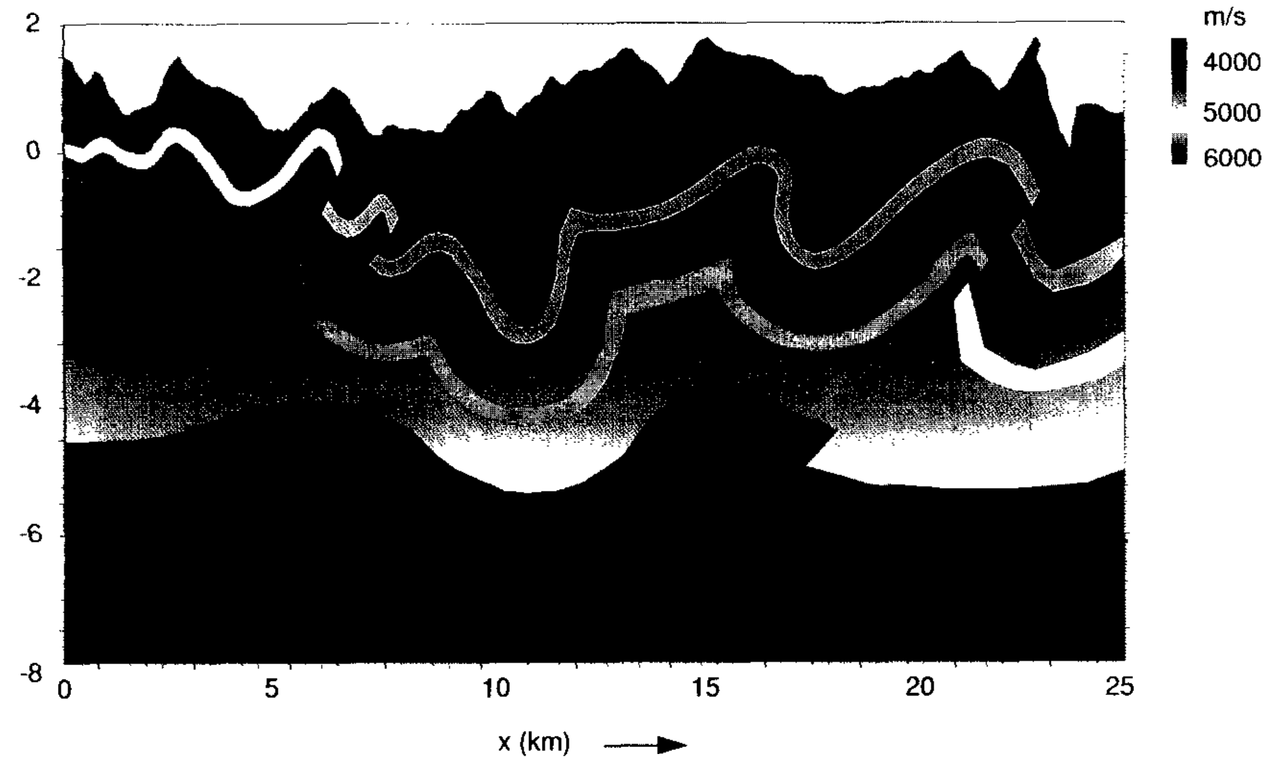


Fig. 2. A velocity/depth model representative of northeastern British Columbia. There is roughly 1600 m of elevation relief along the seismic cross-section.

The correct source and receiver elevations were used in generating traveltime curves to migrate this trace. In Figure 3a, the migration weights, modified from the constant-velocity common offset migration expression found in Bleistein et al. (1987), were computed from the flat datum above the earth's surface. That is, the depth z of an image point, which appears as a factor in the migration weight, was measured from the flat datum at the top of the model (2000 m elevation), well above the source and receiver locations. In Figure 3b, the migration weights were calculated using the same formula, except that the depth of an image point was measured from the lesser of the source and receiver elevations. Thus, the quantity $z-z_{topo}$, where z is again the depth of an image point below the flat datum and z_{topo} is the greater of the source and receiver depths below the flat datum, replaced z when the weight was applied. For the shallow part of the section, $z-z_{topo}$ is nearly zero, resulting in much weaker amplitudes near the earth's surface for the shallow elliptical event in Figure 3b. Because the migrated amplitudes shown in Figure 3a do not decay to zero along the acquisition surface, we can expect some problems when these migration weights are used in migrating the entire data set. Of course, migrating a single trace gives no visual indication of the problems that will arise when inappropriate migration weights are used; it is only through the interference of many migrated traces, as shown in the next figure, that the effects of migration operator aliasing become apparent.

Figure 4 shows the result of a prestack depth migration: all the traces were migrated from topography and accumulated into a final stacked section. In Figure 4a, as in Figure 3a, the migration weights were calculated with depth measured from the flat datum. This section, accurate though it is at depths well below the topography, is excessively blurred out near the earth's surface (which is precisely where we would want to tie to any available outcrop control!). This is the manifestation of migration operator aliasing: the blurring occurred because the migration weights were incorrect. In turn, the migration weights were incorrect because the depth was measured from the wrong elevation. By contrast, Figure 4b shows a very clear image near the earth's surface. [A very small amount of operator aliasing is evident in Figure 4b. This is due to a cause entirely different from the use of incorrect migration weights, namely, the application of common offset migration to seismic data whose source spacing is very different from the receiver spacing. The common offset migration formula, due to Bleistein et al. (1987), combines the common shot and common receiver migration expressions and, thus, depends on the source spacing as well as the receiver spacing. These spacings, and the maximum frequency present in the data, determine the maximum well-sampled apparent dip (Vermeer, 1990), which is transformed by migration into the maximum well-imaged near-surface dip. The effects of this type of operator aliasing can be eliminated, but only with the loss of steep dips near the earth's surface.] As noted in the previous paragraph, the depths used in the migration weights were only approximately correct, being most incorrect for large offset traces with substantially different source and receiver elevations. However, the effects of this approximation on the image are minimal.

Figure 5 shows a detail of Figure 4, chosen from the left side

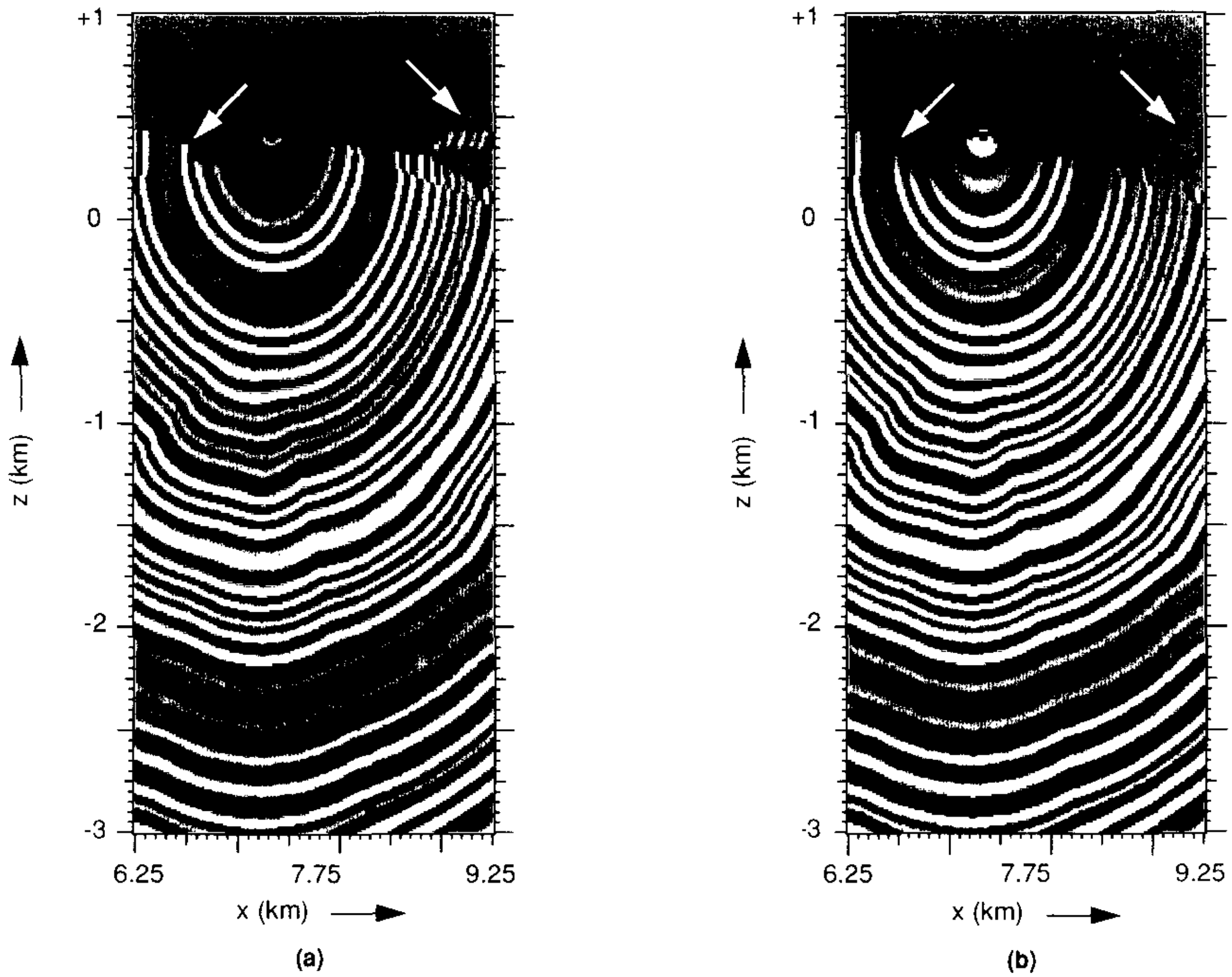


Fig. 3. Prestack Kirchhoff depth migration of a single trace corresponding to a source at 7755 m and receiver at 7770 m. Migration weights are calculated from **(a)** a flat datum at $z = 2000$ m and **(b)** topography, or $z = 375$ m. Note the variation in shallow amplitudes indicated by the arrows.

of the section, where the elevation changes are the most rapid. Although the anticlinal reflector clearly evident in Figure 5b is also evident in Figure 5a, the high-amplitude migration smile and the coherent noise created by the aliased migration operator have degraded the character of the wavelet in Figure 5a as well as our confidence in the event's interpretability.

It might be tempting to simplify our strategy of using the local source and receiver elevations in computing the migration weights; we might, for example, choose to compute the weights from a flat datum z lying between the minimum and maximum elevations. As long as elevation changes along the line are not too severe such an approach will be accurate, but drastic elevation changes will give rise to large differences $z-z_{topo}$, leading to poor images such as those in Figures 4a and 5a. Also, it is as efficient to compute weights from $z-z_{topo}$ as from any datum z.

In addition to compromising the imaging capabilities of a migration, using incorrect migration weights can have an unexpected negative effect on prestack migration velocity analysis. One of the objectives of prestack depth migration is to allow the estimation of seismic velocities by inspection of common-reflection point (CRP) gathers. A CRP gather displays traces at a particular earth location taken from each migrated common-offset section. By comparing the depths of a migrated event on all the traces in a gather, one can determine whether the velocities used in the migration are correct. If a particular event appears to be flat on a gather, then all the common-offset migrations have imaged that reflector at the same depth, indicating that the velocity used is correct, at least in an average sense. If an event shows residual curvature up or down, then the event has been imaged at different depths from different offsets, indicating that the migration velocity is, on the average, too low or too high. Figure 6 shows the effects of the two choices of migration weight calculations on the CRP gathers. The same (correct) velocity function was used for both migrations. In Figure 6a (using migration weights with depths computed from the flat datum), the near-surface amplitudes are skewed significantly towards the mid and far offsets. This has resulted in a high noise level on the shallow events relative to Figure 6b, where the weights were computed from topography. The extra noise in Figure 6a makes the difficult task

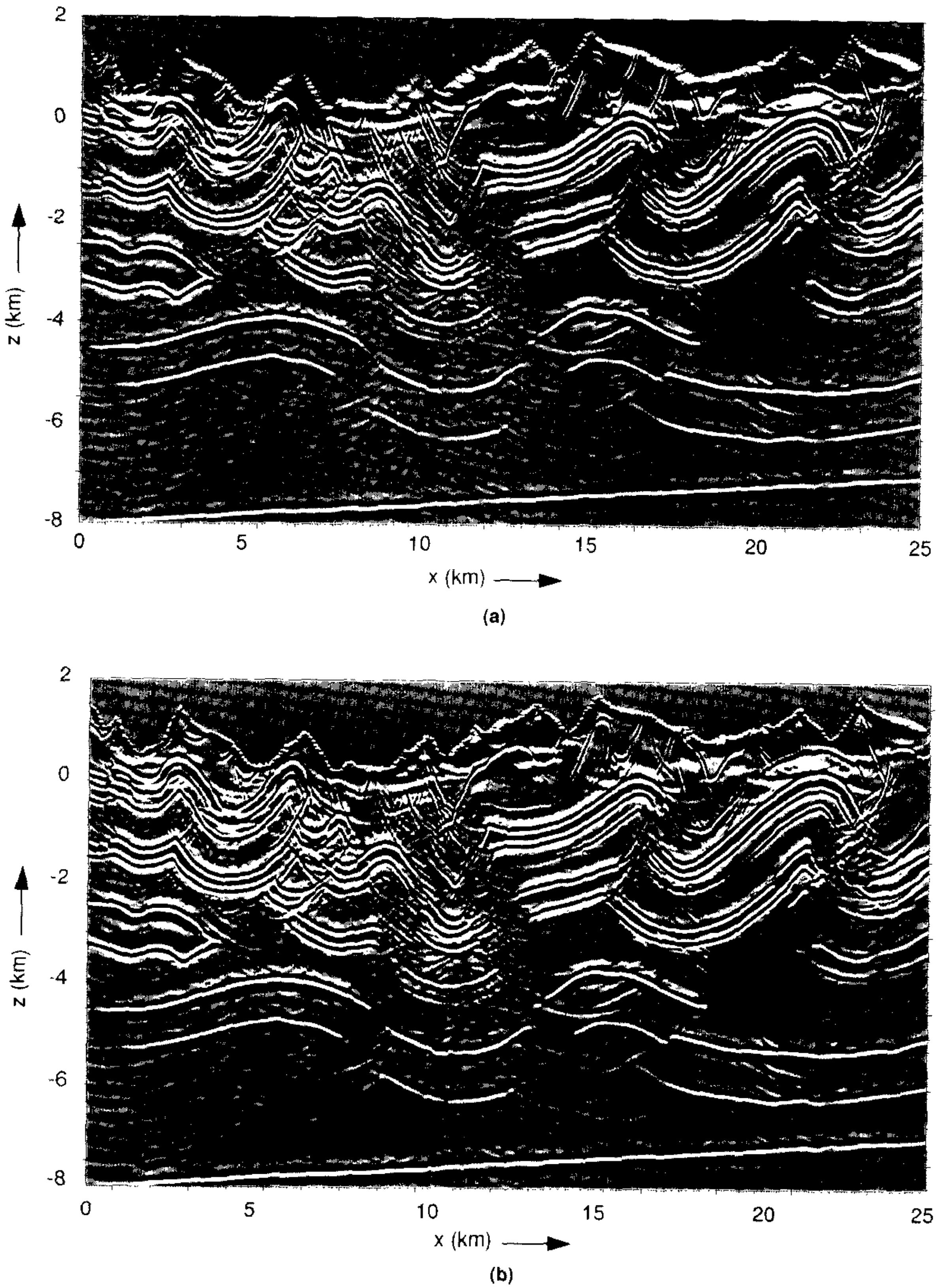
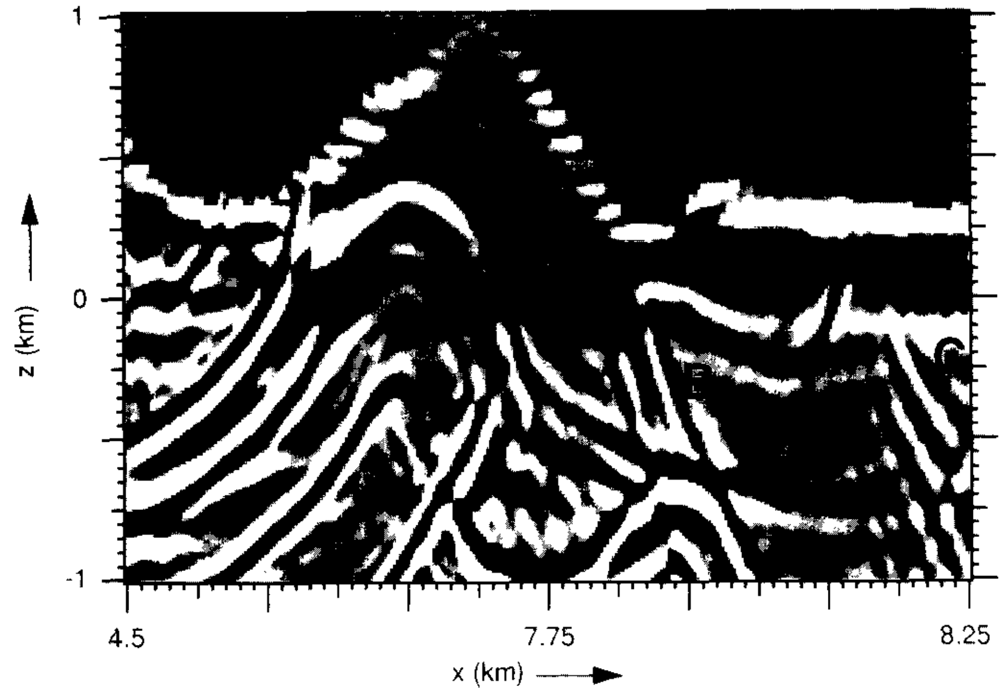
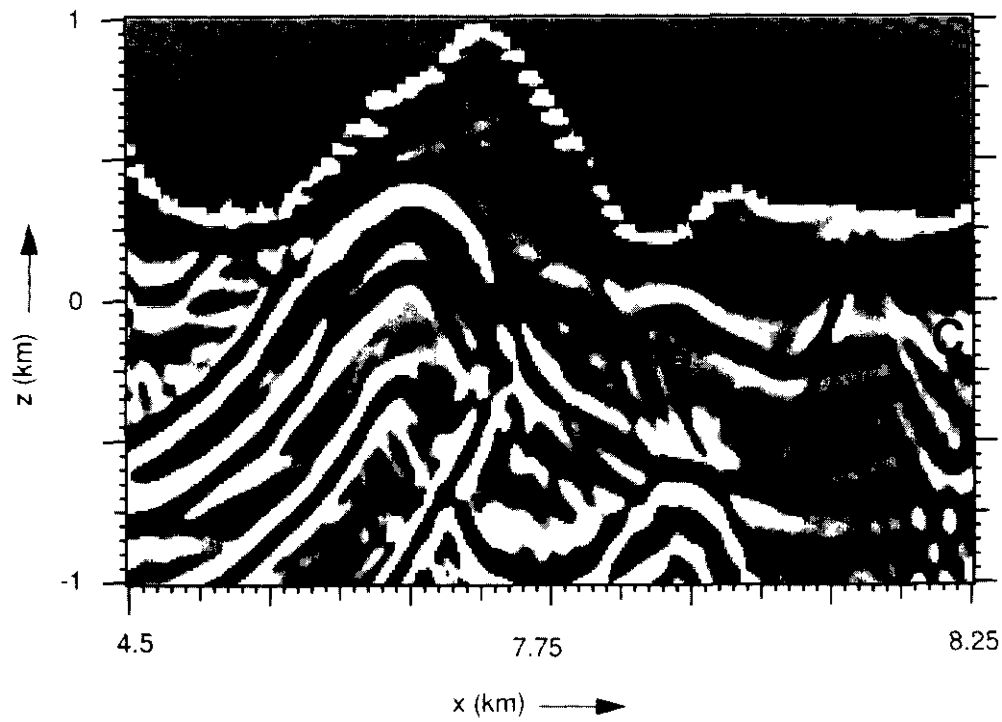


Fig. 4. Prestack Kirchhoff depth migration of 278 common-shot gathers, each with 480 traces. Migration weights are calculated from **(a)** a flat datum at $z = 2000$ m and **(b)** topography.



(a)



(b)

Fig. 5. Enlarged details of images shown in Figure 4. Surface "ties" corresponding to formation A are less ambiguous in Figure 5b. Smiles (event B) due to migration aperture limitations are diminished. Migration operator aliasing of steep events (C) due to the coarse shot spacing of 90 m remains but is attenuated.

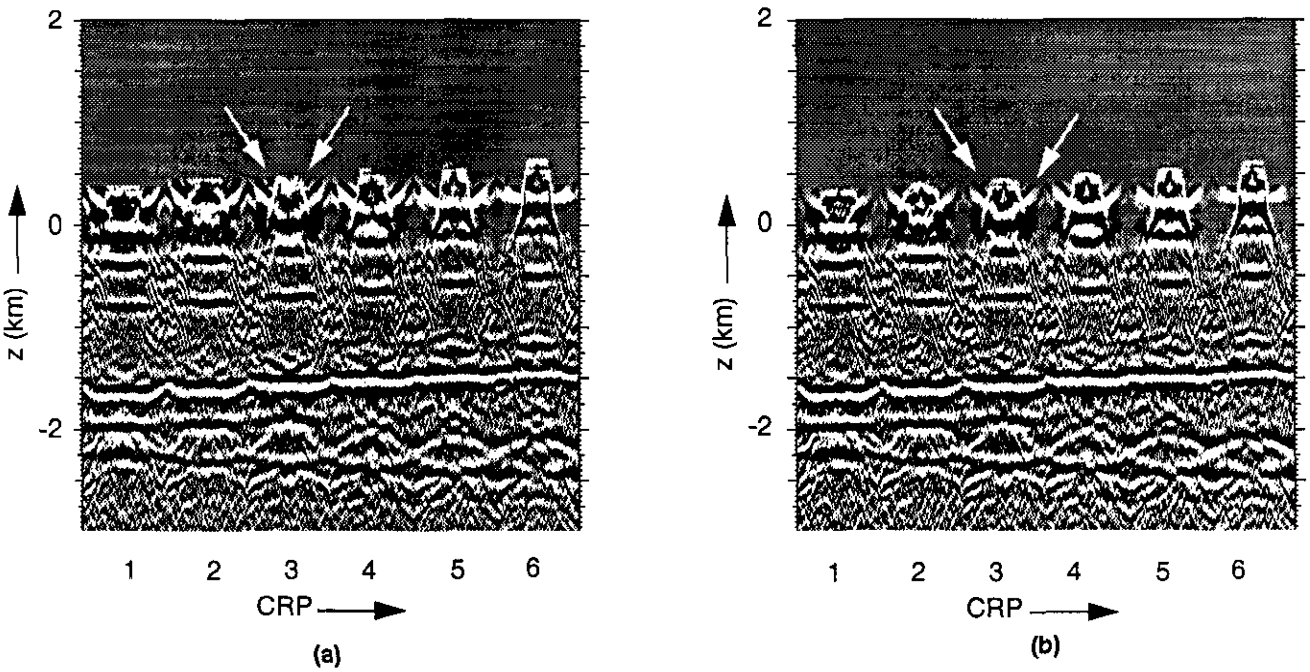


Fig. 6. Common-reflection point (CRP) gathers corresponding to the window in Figure 5, containing offsets ranging from –3600 m to 3600 m. The ambiguity of the event indicated by the arrows is due to significant diving wave or refraction strength at the far offsets.

of estimating near-surface migration velocities nearly impossible. To make matters worse, errors or uncertainties in estimating the near-surface interval velocity affect the reliability of deeper velocity estimation, so that using incorrect migration weights can easily lead to unreliable migration velocities for all depths.

We note the presence of nonflat events on the CRP gathers in Figure 6, even though we used the correct migration velocity. These result from the migration of events that have undergone some refractions before or after reflection. Such events are presently a source of annoyance to the interpreter.

Conclusions

When seismic data have been acquired along an irregular topographic surface, it is desirable to honour the topographic variations while processing the data. We have shown the effects on an important processing step (migration) of only partially honouring the topographic variations. Even if the data are migrated directly from topography, without using any processing steps taken to "move" the data from topography to a flat datum (either by wave equation datuming or by the simpler but less correct procedure of static-shifting traces upward to the datum), the quality of the imaging can be seriously compromised if the weights used in the migration have not also been computed from topography. If, in addition, the migration is performed before stack, with the two-fold objective of imaging and velocity estimation, the use of migration weights where depth is computed from the surface topography will result in a more complete accomplishment of both objectives than when depth is measured from a flat datum above the topography.

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