Datuming and layer replacement: When are static corrections sufficient?

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ABSTRACT

Time distortions due to heterogeneity in the near surface can seriously degrade the quality of migrated reflection seismic data. Using raypath-based kinematics for simple near-surface models, we examine the errors introduced into data by applying vertical-path, static corrections to finite-difference-modeled, unstacked data. We consider two alternative techniques for near-surface correction. The first one, layer replacement, simulates data that would be recorded at or above the original recording surface with the weathered layer replaced by the higher velocity of subweathering. The second is downward continuation, which aims to simulate data that would be recorded at or below the base of the near-surface layer. We further examine the errors in applying near surface corrections that are estimated from an imperfectly known near-surface velocity model. For the simple models studied, in the presence of an imperfectly known near-surface model, static (i.e., vertical-path) velocity replacement tends to be a more robust approximation to true (i.e., slant-path) velocity replacement than static downward continuation is to true downward continuation. Analytic estimation of timing errors and migrations of variously time-corrected data are the bases for the error analysis.

Introduction

Commonly, the Earth's near surface exhibits considerable lateral velocity variation and a velocity that is lower than that of underlying bedrock. A number of approaches (e.g., field static-, refraction static-, tomographic static-, and residual static-corrections) aim to correct for the distortions a laterally varying low-velocity layer (LVL) introduces into reflection data (Yilmaz, 1987; Cox, 1999). No matter what approach is used, or the quality of the assumptions (e.g., surface-consistency) that are made in derivation of the corrections, ultimately, some form of *correction* is actually applied to the data to reduce the influence of the variable near surface. If the raypaths between two surfaces (such as the Earth's surface and some datum level) are vertical, static shifts are appropriate for upward or downward continuing data from one surface to the other. When the raypaths are not vertical, continuation of data requires that energy be moved laterally in space, as well as shifted in time. Statics applications, however, do not accomplish the necessary lateral shift in space.* As illustrated by Beasley and Lynn (1992), both the apex time and curvature of a diffraction associated with a point scatterer in a homogeneous medium must change when a wavefield is upward or downward continued correctly between two horizontal surfaces. Datuming with statics simply shifts diffractions in time, but does not change their shape. Such an incomplete process leads to degraded final images because migration with the true subsurface velocity model will collapse diffraction patterns whose shapes differ from those present in the vertical-path, static-corrected data.

Strictly, downward (and upward) continuation of data through the near surface should be done with a method that honors wave theory, which treats dynamics as well as kinematics. For the simple models studied here, we can simulate the essential kinematic action of a wave-theoretical approach (Berryhill, 1979; Berryhill, 1984) by basing the time corrections associated with wavefield continuation on slant (Snell's law) raypaths through the near surface. Such slant-path corrections al-

* Throughout, we associate the word *statics* with vertical-path adjustment of data.

ter both times and lateral positions, thus making the appropriate changes in curvature of the diffractions.

Here, we study how vertical-path time-corrected data differ from slant-path corrected data for different datum levels with and without the presence of errors in the near-surface model. We use the term downward continuation to indicate a procedure that shifts the data to a redatum surface below the original recording surface with the true medium velocity. The term velocity replacement indicates a procedure that implements a downward continuation to some surface, again with the true medium velocity, followed by an upward continuation to another surface with a new velocity (the replacement velocity). Although we compare these two techniques with each other, and treat them as if they were different, they are fundamentally the same: redatuming. The correction procedures considered in this paper include downward continuation to or below the base of the LVL, and velocity replacement to or above the original recording surface. Interim levels are not considered here, but may be important choices.

In practice, common-midpoint (CMP) sorted data are typically downward continued, with vertical-path statics, to a floating datum. The floating datum level is locally determined to be approximately the base of the LVL at a given CMP position. Velocity analysis and stacking are performed from that level, followed by a poststack wave-equation technique that upward continues the data to some final datum. This procedure is not duplicated here in its entirety, but the initial downward continuation with vertical-path statics is studied. For the simple models studied here, we find that when the near-surface parameters are known exactly, the technique with the least error is downward continuation with vertical-path statics to the base of the weathering. However, when erroneous values of the near-surface parameters are used, vertical-path velocity replacement to a datum level corresponding to the original recording surface typically has less error than does vertical-path downward continuation to the base of weathering.

We make the assumption that the near surface can be considered, locally, a 1-D medium. The base of the LVL directly beneath each source or receiver, and the recording surface at the same position, are assumed to be locally horizontal. The models are extremely simple, but tests—not shown here—were run, comparing traveltimes computed for dipping bases of the LVL, and we determined that for models similar to the one used in this paper, dips as large as roughly 10° could safely be treated as horizontal. It is also important to note that we consider only the long spatial wavelength component of the base of the LVL. Hence, the work here considers the choice of surface to which the data should be shifted, given a near-surface velocity model derived from a refraction- or tomographic-statics technique. More rapid variation will further degrade the data quality.

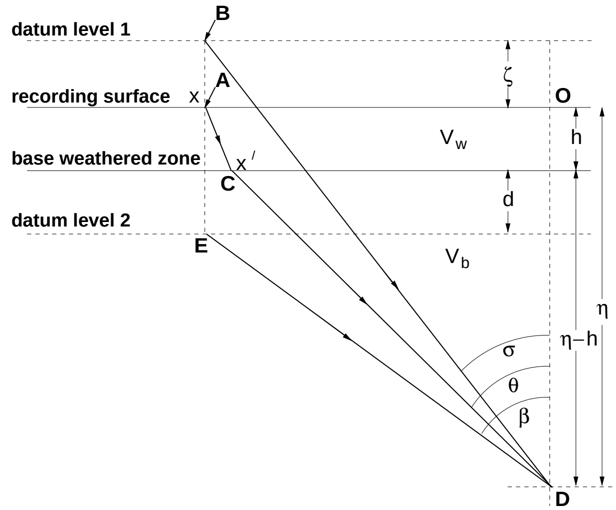

Figure 1. Schematic depth section showing raypaths between a point scatterer and locations on different recording levels.

Due to the wavefront healing that arises for scattering from Huygen's secondary sources on an irregular base of the LVL, the wave-theoretic time distortions caused by a highly variable LVL base are smaller in magnitude than those predicted from ray theory (Perez, 1997). This behavior of wave-theoretic time distortions suggests that there may exist some "effective" smoothed shape of the LVL base that, in conjunction with ray theory, adequately describes some portion of the near-surface influence on reflection seismic data. We will leave it to reflection-based, residual-statics corrections (Wiggins et al., 1976) to correct for much of the remaining, short-wavelength variations.

Velocity replacement

Figure 1 shows the geometry of a subsurface consisting of a homogeneous half-space with velocity V_b, overlain by a horizontal LVL with velocity V_w. The origin is at point O, the x-axis is positive to the left, and the z-axis is positive downward. The LVL has a thickness h, and a new datum level, datum level 1, is located at a distance ζ above the recording surface. The raypath between a source (or receiver) located at point A and a point scatterer located at point D is the path from $(x, 0)$ through (x', h) to $(0, \eta)$. From a ray-kinematics viewpoint, after slant-path replacement of both the LVL and the space between the recording surface and datum level 1 with a layer whose velocity is V_b, the traveltime would be

$$T_{dat} = \frac{\overline{BD}}{V_b}, \tag{1}$$

where $\overline{BD}$ is the distance between the diffractor and the location of the new source or receiver, $(x, -\zeta)$. In practice, vertical-path, rather than slant-path, datuming is typically applied. The one-way traveltime, $T_{original}$, from D to a point located at $(x, 0)$ in the two-layer medium would be statically time shifted by an amount

$$T_{static} = \frac{h}{V_w} - \frac{h}{V_b} - \frac{\zeta}{V_b} \tag{2}$$

to yield

$$T_{adjust} = T_{original} - T_{static}, \tag{3}$$

or

$$T_{adjust} = \frac{\overline{AC}}{V_w} + \frac{\overline{CD}}{V_b} - h\frac{(V_b - V_w)}{V_w V_b} + \frac{\zeta}{V_b}, \tag{4}$$

where $\overline{AC}$ is the distance between the points $(x, 0)$ and (x', h), and $\overline{CD}$ is the distance between the points (x', h) and $(0, \eta)$. No lateral shift takes place. After some geometrical considerations and algebraic manipulation, T_{adjust} and T_{dat} are found to satisfy

$$T_{adjust} = f_1 \cdot T_{dat}, \tag{5}$$

where

$$f_1 = \left(\frac{\eta - h}{\eta + \zeta} \cdot \frac{\cos\sigma}{\cos\theta}\right) \left[1 + \left(\frac{x - x'}{x'}\right)\left(\frac{V_b}{V_w}\right)^2 - \frac{\sin\theta}{x'}\left(h\left[\frac{V_b - V_w}{V_w}\right] - \zeta\right)\right]. \tag{6}$$

The angles θ and σ are defined in Figure 1 as the angles between the vertical and the subweathering ray directions before and after velocity replacement, respectively.

Equation (5) shows that if f_1 is close enough to 1, then vertical-path velocity replacement is an acceptable approximation to slant-path velocity replacement (which, for this simple model, approximates the kinematics of wave-theoretical velocity replacement). The factor f_1 is always greater than 1 for $\zeta \geq 0$, so T_{adjust} always exceeds T_{dat} as long as the final datum level is at or above the original recording surface.

For unstacked data, the total time correction for reflections on any trace would be the sum of time quantities, such as those above, associated with the locations of the source and receiver, for that trace, relative to the position of the scatterer.

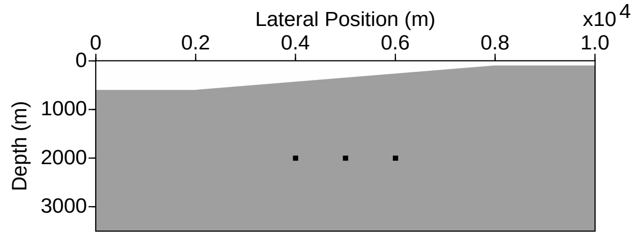

Figure 2. Velocity model.

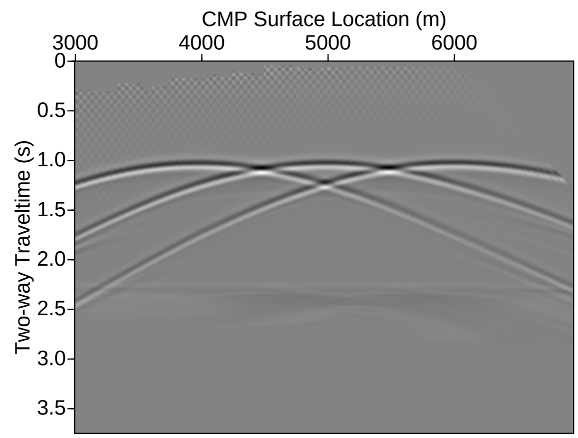

Figure 3. Unmigrated stacked section after static downward continuation to a datum level 620 m below the original recording surface.

Downward continuation

A similar analysis can be made for downward continuation of sources and receivers to a datum level below the LVL. Figure 1 shows such a level at depth d below the base of the LVL. To perform vertical-path downward continuation to the datum level for a source located at $(x, 0)$, we would apply a static shift of

$$\widetilde{T}_{static} = \frac{h}{V_w} + \frac{d}{V_b} \tag{7}$$

to the one-way traveltime, $T_{original}$, to yield

$$\widetilde{T}_{adjust} = T_{original} - \widetilde{T}_{static}. \tag{8}$$

After slant-path downward continuation to the datum level, the one-way traveltime for the path between the points E and D is

$$\widetilde{T}_{dat} = \frac{\overline{ED}}{V_b} \tag{9}$$

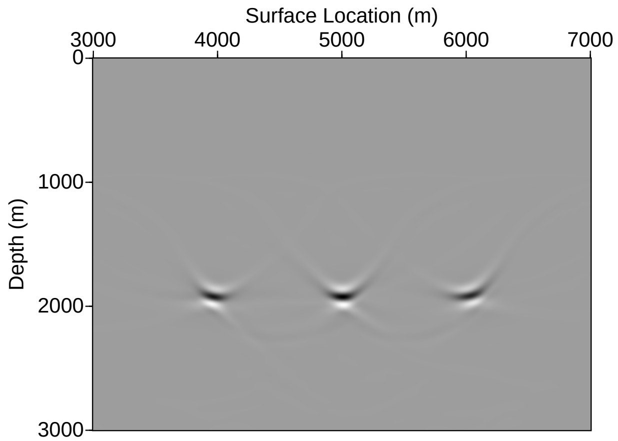

Figure 4. Model data migrated prestack with the true subweathering velocity after static velocity replacement to a datum level corresponding to the original recording surface.

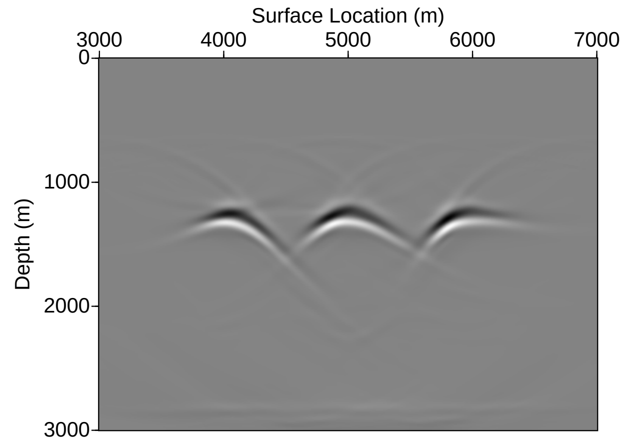

Figure 5. Model data migrated prestack with the true subweathering velocity after static downward continuation to a datum level 620 m below the original recording surface.

The downward-continued traveltimes are related by

$$\widetilde{T}_{adjust} = f_2 \cdot \widetilde{T}_{dat}, \tag{10}$$

where

$$f_2 = \left(\frac{\eta - h}{\eta - h - d} \cdot \frac{\cos\beta}{\cos\theta}\right)\left[1 + \left(\frac{x - x'}{x'}\right)\left(\frac{V_b}{V_w}\right)^2 - \frac{\sin\theta}{x'}\left(h\frac{V_b}{V_w} + d\right)\right]. \tag{11}$$

The angle β is defined in Figure 1 as the angle between the vertical and the subweathering ray direction after downward continuation.

Equation (10) shows that vertical-path downward continuation is close to slant-path downward continuation when $f_2 \approx 1$. Note that, as mentioned in the introduction, while the detailed expressions for the adjustment factors for downward continuation and velocity replacement differ, these two processes differ conceptually only in the choice of final datum level.

Numerical results

A velocity model used in the study is shown in Figure 2. A subweathering layer with velocity V_b=2500 m/s, containing three point scatterers at lateral positions 4000 m, 5000 m, and 6000 m, each at depth 1950 m, is overlain by an LVL with velocity V_w=1000 m/s. Over a portion of the model, the base of the LVL dips at slightly less than 5°. At lateral positions 2000 m and 8000 m, the LVL is 600 m and 100 m thick, respectively, with thickness varying linearly between those two positions. Modeled, acoustic, off-end shot records (60 shots, each recorded by 80 receivers, with shotpoint spacing 50 m and receiver group interval 25 m) were generated with the SU finite-difference code, SUFDMOD2. The first shot is located at the surface position 3000 m with receivers ranging in position from 3025 m to 5000 m. Shots were then moved successively to surface positions with higher values.

Figure 3 shows the data after CMP stacking, but before migration. The diffractions corresponding to the outer diffractors are not symmetric due to finite coverage; the truncated apertures will influence the character of all the subsequent migrations. Figure 4 shows the result of prestack Kirchhoff depth-migration of the data after velocity replacement with vertical-path statics, to a datum level that is the same as the original recording surface (i.e., ζ=0 m), and Figure 5 shows the depth-migrated section after downward continuation to a datum level 620 m below the recording surface, also with vertical-path statics.† Both migrations are performed with the true subweathering velocity. The image of the data after vertical-path velocity replacement is slightly overmigrated (the imaged scatterers show a slight upturn relative to the result—not shown here—of migration of the original data from the surface of the model), whereas

† This datum level is chosen to be below the deepest portion of the base of the LVL. In practice, data are not conventionally migrated from such a deep datum. Most migration algorithms, however, require migration from a horizontal surface, so the data could not be left at the variable base of the weathering. The results shown in Figure 5 are included to illustrate a point about the accuracy of statics corrections to a new datum.

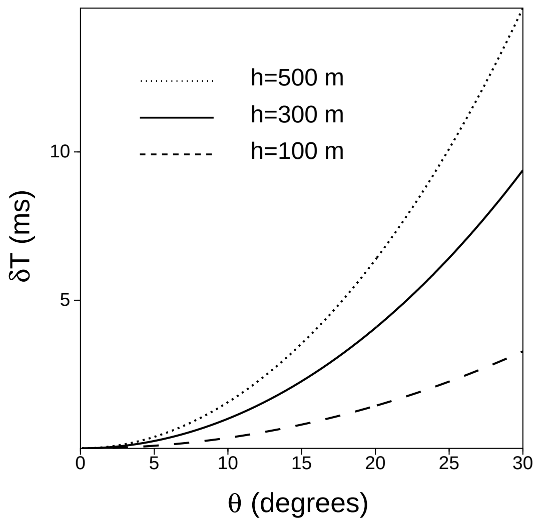

Figure 6. δT (for velocity replacement) versus θ.

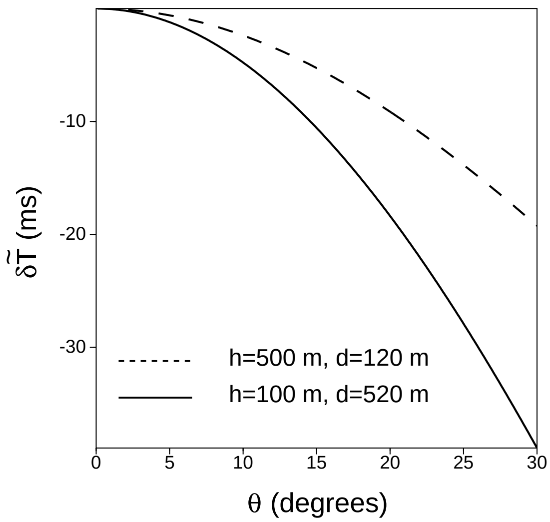

Figure 7. $\delta \widetilde{T}$ (for downward continuation) versus θ.

the image of the data after vertical-path downward continuation is significantly undermigrated. The slight tilting of the imaged outer diffractors is due to the asymmetric coverage illustrated in Figure 3. Despite the fact that the diffractors lie beneath an asymmetric base of the LVL, Figures 4 and 5 show an approximately uniform quality of focusing across the profile. That may be due to the large migration apertures that include data having associated raypaths that span the entire profile at each imaged point.

If we assume that the base of the LVL dips gently enough that it can be considered locally horizontal, then the results in Figures 4 and 5 can be explained with the model shown in Figure 1. Figure 6 is a plot of δT, where

$$\delta T = T_{adjust} - T_{dat}, \tag{12}$$

for vertical-path velocity replacement, versus the raypath angle from vertical in the subweathering layer, θ, for a scatterer depth of 1950 m, V_w=1000 m/s, V_b=2500 m/s, and three different thicknesses, h, of the LVL. The positive differences imply overmigration, as was seen in Figure 4.

Figure 7 is a plot of $\delta \widetilde{T}$, where

$$\delta \widetilde{T} = \widetilde{T}_{adjust} - \widetilde{T}_{dat}, \tag{13}$$

versus θ for vertical-path downward continuation to a level 620 m below the recording surface, for the same diffractor depth and medium velocities as in Figure 6, but for two different LVL thicknesses. The negative values for the differences explain the undermigration seen in Figure 5. As expected, the magnitudes of the errors in Figures 6 and 7 increase with θ. For a given θ and h, the magnitude of the error, $\delta \widetilde{T}$, due to vertical-path downward continuation is greater than the magnitude of the error, δT, due to vertical-path velocity replacement. This explains the poorer quality imaging in Figure 5 as compared with that in Figure 4. From Figure 7, the magnitude of the error is larger, the deeper the datum level d. That observation matches our expectations: where d is large, the vertical-path assumption for a given scatterer depth η and lateral position x of the source or receiver relative to that of the scatterer is poor. When d is relatively small, the error magnitudes for the two techniques are comparable, as shown in Figures 6 and 7, for h=500 m.

Figure 8 is the result of prestack depth migration after vertical-path velocity replacement to a final datum level that is the same as the original recording surface, with a migration velocity estimated from velocity analysis of the near-surface-corrected data, rather than with the true medium velocity. We consider this case because, in practice, the velocity field used to migrate data is typically estimated from the data itself, after preliminary near-surface corrections. The velocity of the subweathering is estimated to be V_b=2383 m/s (the SU code, SUVELAN is used to obtain the velocity), whereas the true subweathering velocity is 2500 m/s. Comparing Figure 4 with Figure 8, we see that migrating the data with a velocity estimated from the data focuses the image better than does the migration with the true subweathering velocity, but the imaged diffractors are located at an incorrect depth of 1820 m, instead of the correct depth of 1950 m.

Such a depth error is expected. Because the rms velocity of the medium is estimated from the data after vertical-path velocity replacement, migrating with that velocity should collapse diffractions in the data. Since the estimated velocity is incorrect, however, the depth of the imaged diffractors will be erroneous. With an underestimated velocity, an event corresponding to a given arrival time will be placed at a depth that is too shallow, just as is seen here.

Figure 9 is the result of prestack depth migrating the data after vertical-path downward continuation to a level 620 m below the original recording surface with a velocity estimated from the data. The velocity of the subweathering in this case is estimated to be V_b=2900 m/s. Comparing Figures 5 and 9, we again see that migrating with an estimated velocity yields better focusing than does migrating with the true subweathering velocity, but the depths of the imaged diffractors in Figure 9 are 1500 m, instead of the correct depth of 1330 m. Here, an overestimated velocity places the imaged diffractors at too great a depth.

Figures 8 and 9, compared with Figures 4 and 5, respectively, show that for this particular set of model parameters, vertical-path velocity replacement is a better approximation to slant-path velocity replacement than vertical-path downward continuation is to slant-path downward continuation, given that each technique continues data to a horizontal surface.

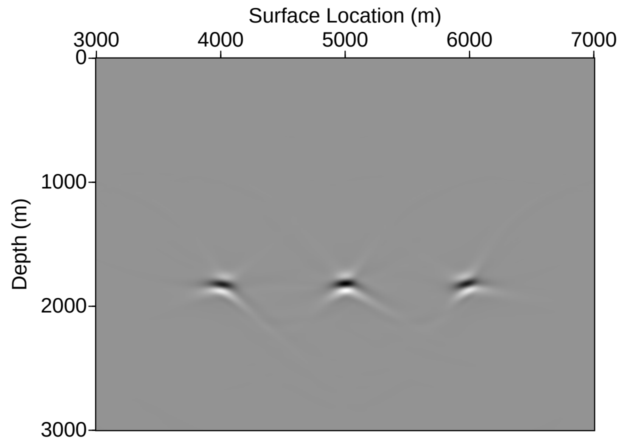

Figure 8. Model data migrated prestack with the estimated subweathering velocity after static velocity replacement to a datum level corresponding to the original recording surface.

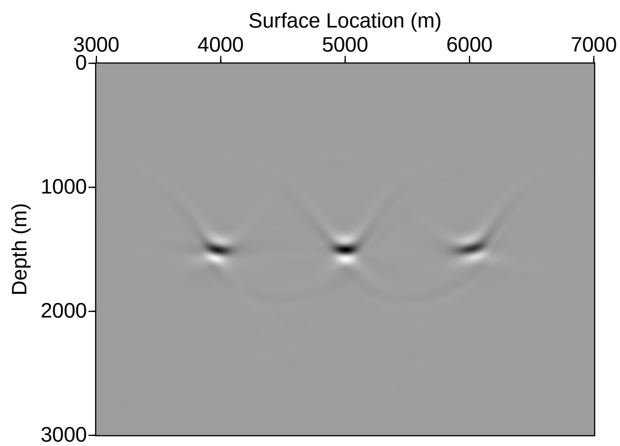

Figure 9. Model data migrated prestack with the estimated subweathering velocity after static downward continuation to a datum level 620 m below the original recording surface.

Errors in the near-surface model

In practice, the physical parameters of the near-surface model are never known exactly. The thickness of the weathered zone, h, the weathered velocity, V_w, and the subweathering velocity, V_b, which are used to estimate static shifts as a function of surface position, can all be expected to have some error. It is helpful to understand the sensitivity of the static-correction procedures to errors introduced into each parameter.

Figure 10 shows the difference between vertical-path velocity replacement and slant-path velocity replacement, δT, for two datum levels, ζ=0 m, and ζ=50 m, along with the difference between vertical-path downward continuation and slant-path downward continuation, $\delta\widetilde{T}$, for two datum levels, d=0 m, and d=100 m. The computations are performed with a nonzero ζ to simulate a situation involving topography, wherein each trace is time-corrected to a horizontal datum level just above the highest source or receiver elevation along the profile. The computations are performed with a nonzero d to simulate a situation involving a laterally variable base of weathering (analogous to what is seen in Figure 2). In such a case, it may be desirable to adjust the data to a horizontal datum level just below the deepest part of the weathered zone. The particular values for ζ and d have been chosen because d=100 m and ζ=0 m correspond to datum levels 100 m below and above

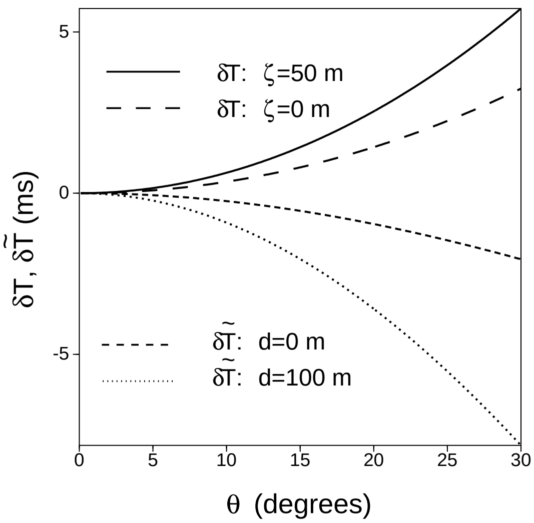

Figure 10. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and no errors in model parameters.

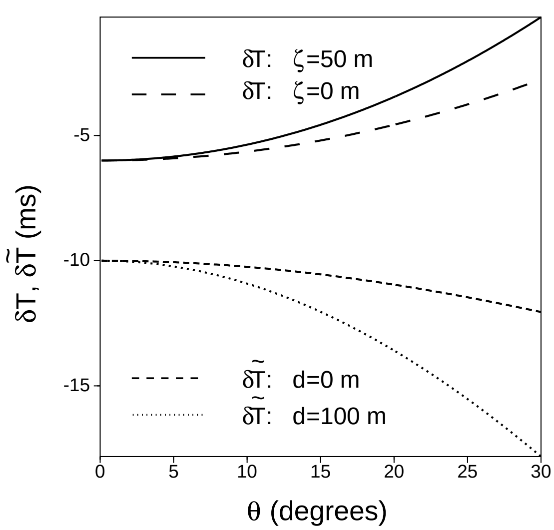

Figure 11. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and $\delta h/h = +10\%$.

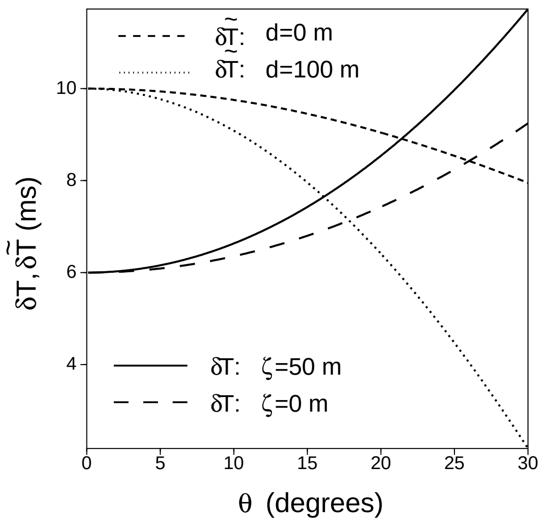

Figure 12. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and $\delta h/h = -10\%$.

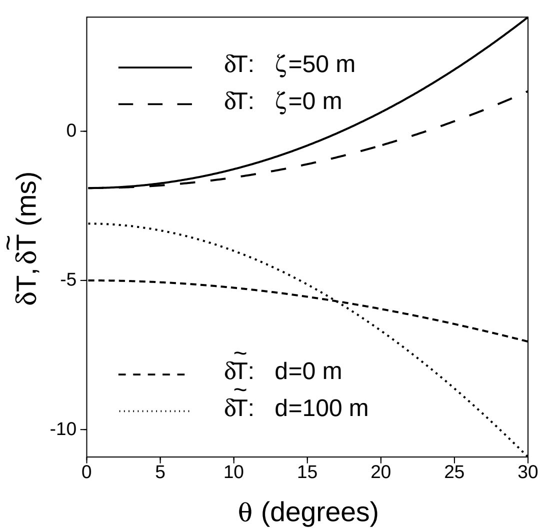

Figure 13. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and $\delta V_b/V_b = +5\%$.

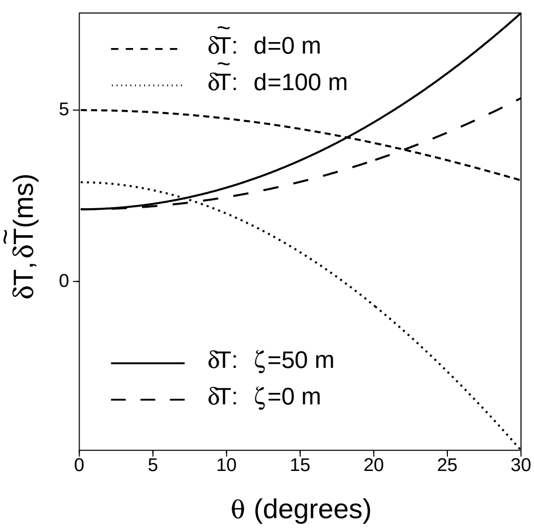

Figure 14. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and $\delta V_b/V_b = -5\%$.

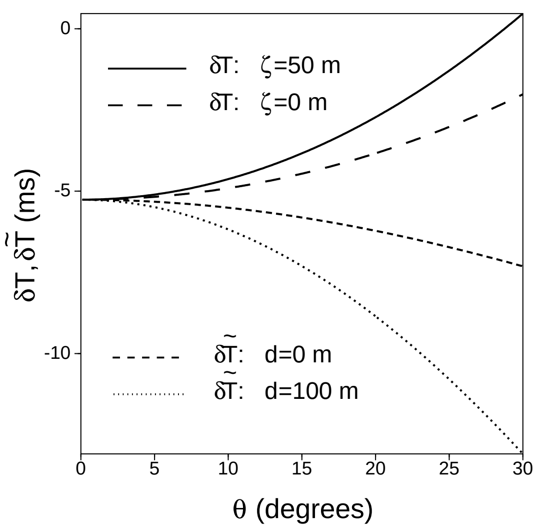

Figure 16. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and $\delta V_w/V_w = -5\%$.

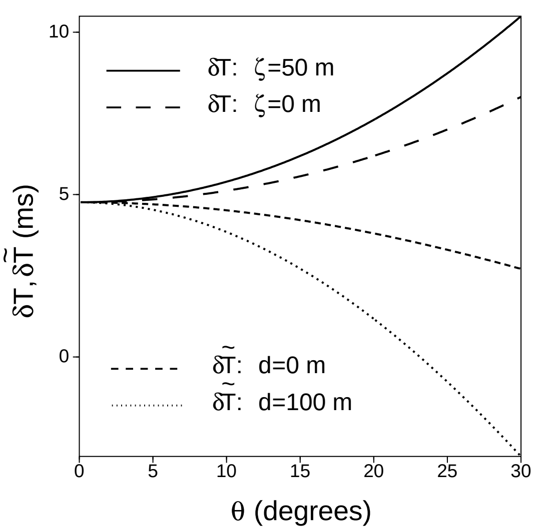

Figure 15. δT (for velocity replacement) and $\delta\widetilde{T}$ (for downward continuation) versus θ for different datum levels and $\delta V_w/V_w = +5\%$.

the base of the LVL, respectively, and ζ=50 m seems a reasonable estimate of maximum surface topographic elevation. The values in Figure 10 are computed from equations (5) and (10) with the parameters corresponding to a medium with h=100 m, V_b=2500 m/s, V_w=1000 m/s, η=1950 m. All errors are zero for vertical incidence and grow in magnitude as the source or receiver is moved laterally away from the diffractor.

Of the four cases, the one with the smallest error magnitude is vertical-path downward continuation to the base of the weathered zone. This is expected, since raypaths are closest to being vertical within the weathered zone. Such a result is consistent with the conventional technique of applying static downward continuation to a floating datum (i.e., datum that follows the base of the weathering) before performing velocity analysis.

Figure 11 is a plot of the same computations, but with a value of h that is overestimated by 10%. Now the near-surface corrections have error even for θ=0, where all propagation is vertical. The error magnitudes for the vertical-path velocity replacements are now less than those for the vertical-path downward continuations; the error magnitude grows as a function of offset for the downward continuation, whereas it decreases, at least to a point, for the velocity replacement. In contrast, Figure 12 is a plot of the computations done with a value of h that is underestimated by 10%. The error magnitudes for the velocity replacement are smaller than those for the downward continuation for small θ, but the curves cross at larger angles.

Figure 13 is a plot of the same functions with the correct h, but with a value of V_b that is overestimated by 5%. For the range of plotted θ, the errors are smaller in magnitude, for the velocity replacement than for the downward continuation. Figure 14 is a plot of the computations done with a V_b that is underestimated by 5%. As in Figure 12, we see a crossover in the error values. Neither velocity replacement nor downward continuation has consistently smaller error in the presence of inaccuracy in V_b.

The values shown in Figure 15 are computed with the correct values of h and V_b, but with a value of V_w that is overestimated by 5%. Here, the downward continuation procedures have smaller error magnitudes than do the velocity replacement procedures. In Figure 16, which shows the same functions with a V_w that is underestimated by 5%, the smaller magnitudes of errors now arise in the velocity replacement.

Figures 11-16 suggest that for simple earth models, such as that shown in Figure 1, vertical-path velocity replacement (to a datum level corresponding to the original recording surface) is typically a more robust method of dealing with long-wavelength near-surface variability than is vertical-path downward continuation (to the base of the LVL or below). Only one case, an overestimation of V_w with perfectly known h and V_b, had smaller errors associated with vertical-path downward continuation. Tests—not shown here—have been run with different combinations of parameter errors shown in Figures 11-16, leading to the same conclusion. Hence, because errors are always present in a near-surface model derived by any number of techniques, perhaps the floating datum to which data are first shifted (before velocity analysis) should be the original recording surface, not the base of the LVL.

Conclusion

Where correction for propagation through the near surface is most needed, the near surface is far more complicated than in the model shown here. Topography and base of weathering can be highly irregular, as can be the weathering velocity. A technique that truly corrects for near-surface influences on seismic data needs to be based on wave theory instead of vertical- or slant- raypaths. The example here, however, indicates that, even when the near surface is laterally smooth, layer replacement using simple vertical-path corrections can be more robust than is downward continuation that is also based on vertical paths. Refraction-statics estimation assumes, and hence derives, near-surface models that are, in some sense, smoothed versions of the true model. Since refraction statics attempts to remove primarily long spatial wavelengths of near-surface variability, our use of simple near-surface models is not necessarily a detriment; subsequent residual-statics corrections help to perform corrections for the higher-frequency near-surface variation. Hence, we expect the above conclusions to have some kind of predictability (in terms of where the datum level should be placed prior to doing velocity analysis) for models with a varying topography and a varying base of the LVL. In the future, we plan 1) to test whether the results shown here apply to more complicated models as a first-order correction, 2) to study the possibility that a surface between the recording surface and base of the LVL may be the optimum (in some sense) redatum level, and 3) to upward and downward continue the data with a wave-equation datuming technique.

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