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Static corrections from shallow-reflection surveys

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ABSTRACT

Shallow seismic reflection surveys can assist in determination of velocity and/or thickness variations in near-surface layers. Static corrections to seismic reflection data compensate for velocity and thickness variations within the "weathered zone." An uncompensated weathered-layer thickness variation on the order of 1 m across the length of a geophone array can distort the spectrum of the signal and result in aberrations on final stacked data. P-wave velocities in areas where the weathered zone is composed of unconsolidated materials can be substantially less than the velocity of sound in air. Weathered-layer thickness variation of 1 m in these low-velocity materials could result in a static anomaly in excess of 3 ms. Shallow-reflection data from the Texas panhandle illustrate a real geologic situation with sufficient variability in the near surface to significantly affect seismic signal reflected from depths commonly targeted by conventional reflection surveys. Synthetic data approximating a conventional reflection survey combined with a weathered-layer model generated from shallow-reflection data show the possible dramatic static effects of alluvium. Shallow high-resolution reflection surveys can be used both to determine the severity of intra-array statics and to assist in the design of a filter to remove much of the distortion such statics cause on deeper reflection data. The static effects of unconsolidated materials can be even more dramatic on S-wave reflection surveys than on comparable P-wave surveys.

INTRODUCTION

The primary purpose of this paper is to show how corrections for static effects on a conventional seismic reflection survey could be calculated precisely and accurately using a near-surface velocity model derived from a detailed shallow-reflection survey along the same line. Specifically, the shallow seismic section displayed in this paper shows static corrections due to relief on the bedrock surface overlain by alluvium that vary 20 ms within 60 m horizontally.

Any velocity or depth variability undetected and/or uncompensated within the weathered layer can result in static effects that degrade seismic reflection data (Berni and Roever, 1989). Accurate datum statics correction can be made once an accurate weathered-layer model is established for an area. Shallow seismic reflection surveys have the potential to identify economically the horizontal and vertical variations in velocity within the weathered layer as well as the depth to bedrock. A weathered-layer model derived from shallow seismic reflection data can possess horizontal and vertical precision on the order of 1 m.

A secondary goal of the paper is to show some possible dramatic effects of intra-array statics and a filtering technique to remove those effects. The effect of statics on geophone arrays 17 to 70 m across, for example, can vary from cancellation of signal to generation of spurious high-frequency noise that can appear coherent. Intra-array static effects that result from short-wavelength fluctuations in the weathered layer are impossible to remove using standard topographic correction procedures. Most topographic procedures assume uniform weathered and subweathered velocities and thickness within geophone group intervals. Intra-array static effects on conventional reflection data can be removed effectively using a filter designed from shallow-reflection data in conjunction with source-wavelet information from the conventional survey.

Most commonly used static-correction techniques for conventional seismic data sets incorporate only attributes of the conventional seismic data itself (Yilmaz, 1987). Iterative statics routines are generally used to improve low signal-to-noise (S/N) portions of conventional seismic data. Using information derived from a poor S/N portion of a data set to improve that same portion using iterative techniques requires assumptions about the nature of the noise. If an accurate weathered-layer model were available, total compensation for static effects could be

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accomplished during the datum-correction portion of standard processing.

The most elementary form of the nonuniform near-surface problem occurs when the surface topography is flat with a variation in thickness in the low-velocity material overlying bedrock (Figure 1). The amount of variation in the low-velocity material is not readily apparent to an observer at the earth's surface. The first-order static correction for the geologic situation is highly dependent on the velocity of the low-velocity material **(V_1)** (Figure 2). The amount of static correction necessary is relatively insensitive to the velocity of the bedrock **(V_2).** Under similar conditions (Figure **1),** it is especially important to know both the velocity and thickness of the low-velocity material (V,).

Near-surface P-wave velocities generally range between 200 and 1000 **m/s** (Birkelo et al., 1987; Knapp, 1986). The static correction for 400 **m/s** material is about 2.0 ms per meter of **low-**velocity material thickness (h) (Figure 2). The significance of the weathered-layer compensation problem becomes evident if velocities on the order of 200 to 300 **m/s** are encountered in near-surface materials. An error of only 1 m in calculating the thickness of near-surface material with a velocity of 300 **m/s** results in a static-correction error of 3.3 ms.

A weathered-zone model derived from shallow seismic reflection data collected in Texas is used to demonstrate the potential effects of uncompensated variation in the weathered layer (using synthetic conventional seismic data) and to assist in removing those static effects. For most conventional seismic reflection surveys, both trace-to-trace and intra-array static effects would be very severe at this locality. A nonuniform weathered layer would not be obvious as the cause for poor data quality obtained by a conventional survey at this site. Some of the static effects observed on the synthetic data suggest intra-array static problems could be identified at other localities.

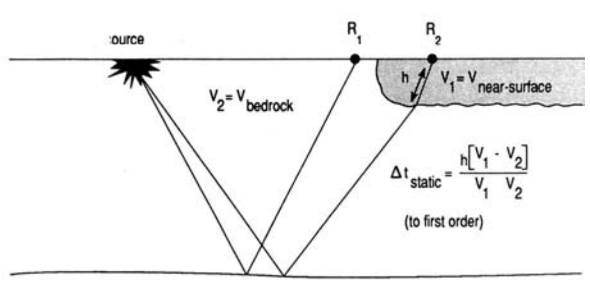

FIG 1. Simple static model with flat topography.

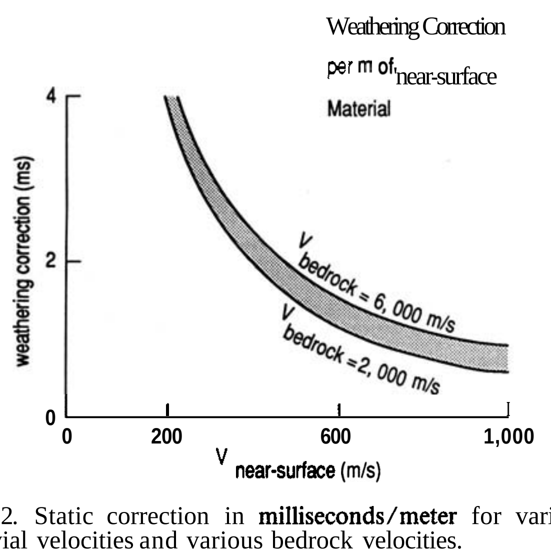

FIG 2. Static correction in **milliseconds/meter** for various alluvial velocities and various bedrock velocities.

DATA FROM THE TEXAS PANHANDLE

A shallow-reflection data set from the Texas panhandle (Miller et al., 1989) is used to demonstrate a procedure for correcting the effects of static irregularities on conventional reflection data sets.

The data-acquisition parameters and equipment were specifically selected to maximize the potential resolving power of the seismic reflection technique at this site (Steeples and Miller, 1990). A **.30-06** hunting rifle, modified with a blast containment device, was fired into the ground to generate a high-frequency seismic pulse. The field geometry consisted of a split-spread source-receiver configuration with station spacings at 1.22 m and a source-to-closest-receiver offset of 3.7 m. The receivers were single, undamped 100 Hz geophones. The sampling interval **was** 1/4 ms. **Pre-A/D,** 24 **dB/octave rolloff** low-cut filters with a -3 dB point of 220 Hz were selected on the **Input/Output** DHR-2400 seismograph to help maximize resolution and reduce the effects of ground roll. [Broad-band recording does not necessarily result in broad-band data. Conversely, narrow-band recording does not always result in narrow-band data (Knapp and Steeples, **1986)].** Close attention was paid to **source-and-**receiver ground coupling. Severe analog low-cut filtering was essential to the reduction of unwanted noise, improved frequency response, and therefore to the final quality of the data.

A bedrock reflection can be identified on raw field data and on CDP gathers (Figure 3) from the shallow seismic reflection survey conducted for environmental reasons in Hutchinson County, Texas (Miller et al, 1989). The reflection comes from

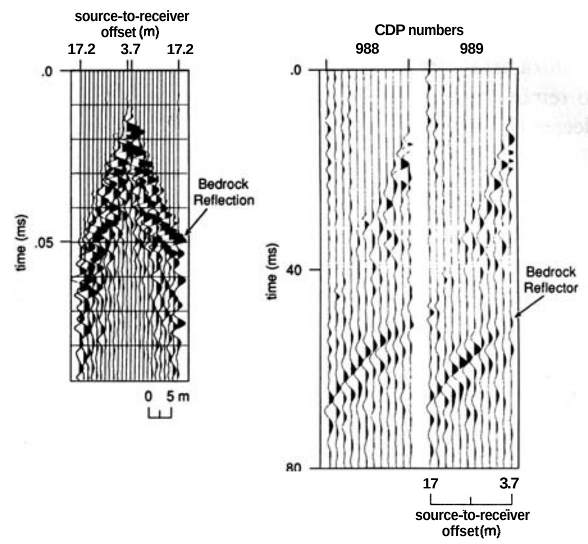

FIG 3. Field file and CDP gather showing excellent quality of reflection from bedrock beneath alluvium. These are raw field data that have not been filtered or static-corrected.

the boundary between alluvial sandy clay (V_p of 225–400 m/s) and Permian carbonate bedrock (V_p of 4000–5000 m/s). The bedrock reflection is sensitive to changes in applied NMO velocity of as little as 50 m/s (Figure 4). An incorrect NMO velocity leads to lower frequency, smaller apparent reflection amplitudes, and decreased depth accuracy for the reflection (Figure 5).

Near-surface static problems can be seen in the CDP gathers even with group intervals of only 1.22 m. The hyperbolic shape of the 50 ms reflection at CDP 989 (Figure 3) is distorted by static effects. This distortion is most noticeable on the trace with source-to-receiver offset of 15.8 m, which is visibly delayed. The problems encountered in obtaining high-quality shallow data can be extrapolated directly in scale and complexity to conventional reflection surveys that might be conducted at this site.

The general processing flow for the shallow data was similar to basic petroleum-industry procedures. The main distinctions were in the detail placed on near-surface velocity analysis, the extra care in muting, the conservative approach to automatic and residual static corrections, and the lack of extensive wavelet processing, velocity filtering, and deconvolution. The dry alluvium that overlies the bedrock caused lateral variations in stacking velocity of more than 40 percent over a surface expanse of less than 50 m in some areas. Trace editing was based on both S/N ratio and consistency of reflection-wavelet characteristics. The final coherency of the stacked data was improved by prestack surface-consistent and residual statics routines with 1 ms (equivalent to about 1/6 of a wavelength) maximum allowable static shifts. The statics operation enhanced the subtleties previously suspected on preliminary stacked sections. No processing procedure after the detailed velocity analysis altered the general apperance of the data.

STATIC CORRECTION FROM SHALLOW REFLECTIONS

Our procedure involves using the detailed near-surface velocity-depth model derived from the shallow-reflection data to calculate a static-correction table for a deeper conventional suvey. A high-quality CDP stacked section focusing on bedrock is essential to define a weathered-layer model at this site for use with a conventional survey (Figure 6a). NMO velocity within the alluvium varies from 225 m/s to 400 m/s and the depth to bedrock varies from 4 to 14 m. One test hole drilled along the line encountered bedrock at 7.3 m, and this was used to verify the accuracy of depths calculated from the seismic data. The stacking velocities for the shallow seismic data were used to build a velocity model for the upper 15 m along the line (Figure 6b).

The thickness and velocity of the alluvial material derived from the shallow-reflection data (Figure 6c) were used to calculate static corrections (Figure 6d) for the synthetic conventional reflection data set. A horizontal datum was selected beneath the deepest bedrock trough. A static-correction diagram was generated which incorporates surface elevation and depth to bedrock with an accurate weathered-layer velocity model.

Static corrections obtained with the shallow-reflection data (Figure 6d) are notably different from those obtained using conventional techniques (Figure 6e). The conventional technique used to determine the datum statics (Figure 6e) assumes a uniform near-surface material. Conventional datum statics at this site compensate for surface elevation only. The values used for average velocity from the surface to the datum (same datum as described during the shallow-reflection static operation) were approximated from direct and refracted velocities that would be recorded on a conventional survey with 15 m group intervals.

The shallow-reflection technique, as applied in this paper, does

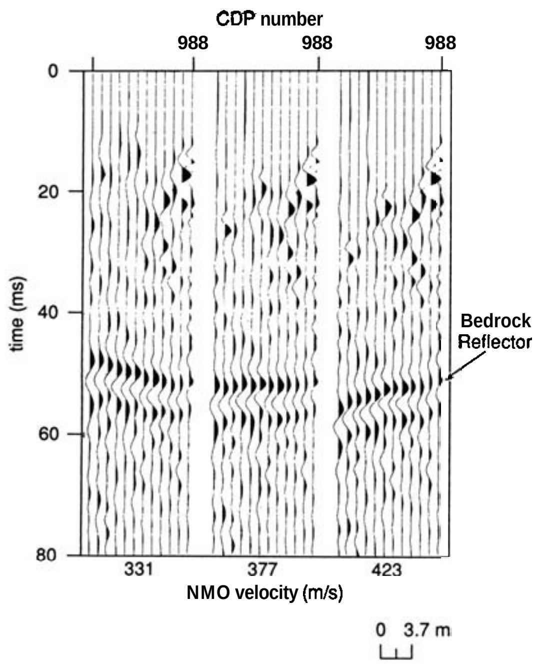

FIG 4. Three different NMO velocities applied to CDP gather 988 from Figure 3.

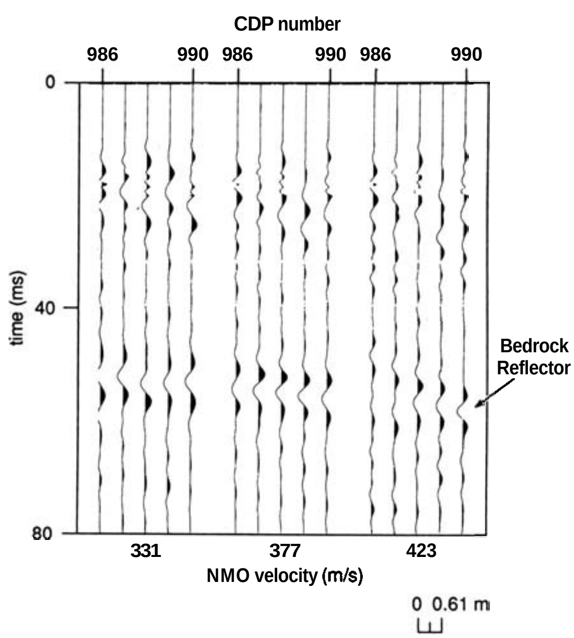

FIG 5. 12-fold stack at five CDPs showing spatial, amplitude, and frequency effects of incorrect stacking velocity.

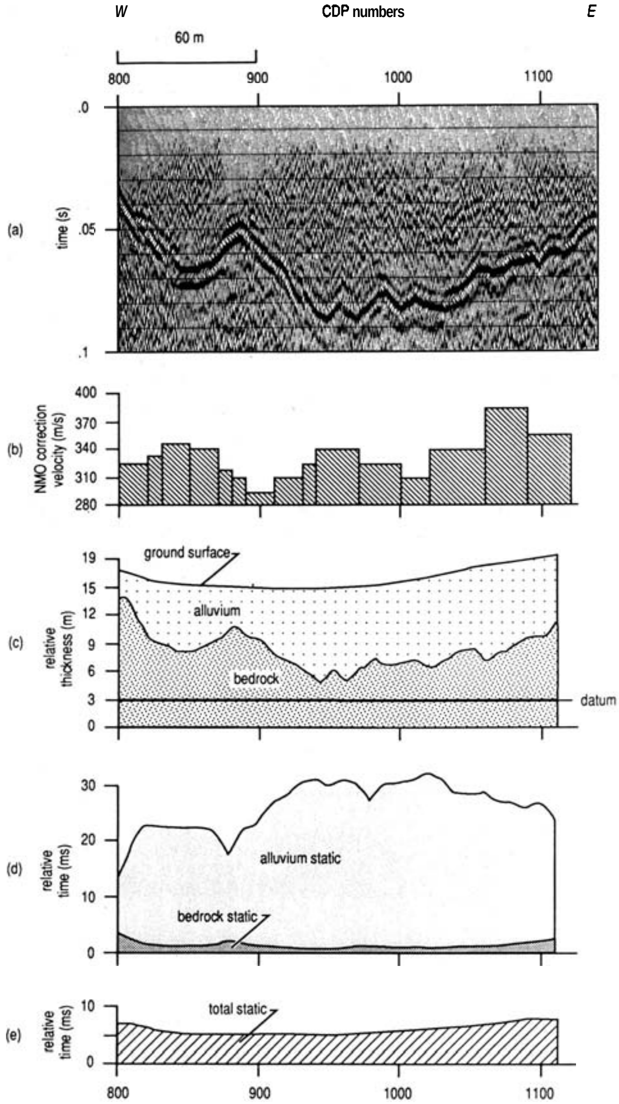

FIG 6. Nominal 12-fold CDP stacked seismic reflection section with derived velocity and geologic and static information as well as an approximate statics-correction diagram for conventional datum statics. (a) Seismic reflection section. (b) NMO velocity function. (c) Interpreted geologic cross-section. (d) Datum statics derived from shallow-reflection data. (e) Approximate datum correction using estimated information available from a conventional data set only.

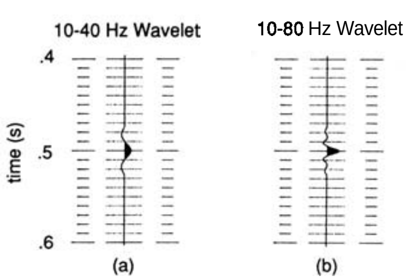

FIG 7. Synthetic traces with a single simple reflection at 500 ms (a) using a 10–40 Hz Klauder wavelet, and (b) using a 10–80 Hz Klauder wavlet.

not provide the necessary information to determine all of the static correction needed for most conventional reflection surveys. The correction datum in this case is only about 15 m below the surface, and any velocity or structural changes below that depth were not addressed, nor could they be with these data.

SYNTHETIC DATA USING CALCULATED STATICS

Once the magnitude of the static corrections implied by the data of Figure 6 was realized, effects beyond those of incorrect reflector times were explored on synthetic conventional seismic-reflection data. Lower amplitudes and frequencies as well as spurious doublets can be side effects produced by static anomalies within an array.

Simple synthetic seismic reflection data traces were generated using the static values (Figure 6d) for the Texas site. The intra-array effects for three different array lengths were calculated using wavelets of two different peak frequencies. Effects caused by statics were examined along a twelve-geophone linear synthetic array. In generating the traces, a single simple reflection at 500 ms was assumed (Figure 7). Zero-phase Klauder wavelets truncated to a length of 51 samples were used. The frequency bands of the wavelets were 10–40 Hz and 10–80 Hz (Figures 7a and 7b), respectively. The Fresnel zone size for the synthetic data at the top of bedrock is only about 3 m in radius, so the use of simple ray theory and linear addition of adjacent geophone elements were assumed adequate for modeling the static effects. Because of the extremely low near-surface velocities, near-vertical raypaths were assumed.

Typical array lengths for conventional surveys have tended to become shorter as the number of recording channels has increased and attainable reflection frequencies have increased. It is well known that large arrays tend to attenuate the higher reflection frequencies. For each of three different array lengths, 17.5, 35, and 70m, chosen for example purposes, the static values at each geophone location were picked from Figure 6. Twelve time-shifted copies of the traces in Figure 7 were produced for each array (Figures 8a, 8c and 8e; 9a, 9c, and 9e). These copies were then summed to form the synthetic array traces (Figures 8b, 8d, and 8f; 9b, 9d and 9f).

The near-surface effects on the lower-frequency wavelet were not as severe (Figure 8) as on the high-frequency wavelet (Figure 9). The near-surface effects on the lower-frequency wavelet consisted of a bulk time shift of about 15 to 20 ms and a slight distortion of the wavelet shape. The distortion manifests itself as a wider, lower-frequency wavelet with lower-amplitude, asymmetric side lobes. Using the higher-frequency wavelet, a bulk shift of about 20 ms was observed. The big difference between the two wavelets was in the amount of distortion. Using the higher-frequency source pulse, even the shortest (17.5 m) array had a distorting effect on the wavelet (Figure 9b), and the statics associated with the longest array (70 m) completely destroyed any resemblance to the original wavelet (Figure 9f). In fact, the array output of Figure 9c shows an apparent doublet being introduced into the data.

The wavelet distortions observed in the synthetic data show that simple geophone arrays can cause noticeable degradation of data quality in field areas where very low seismic velocities characterize the near-surface structure. The effects are especially severe when a wide-bandwidth signal is desired. In the synthetic example (Figure 9f), using a 70 m receiver array produced

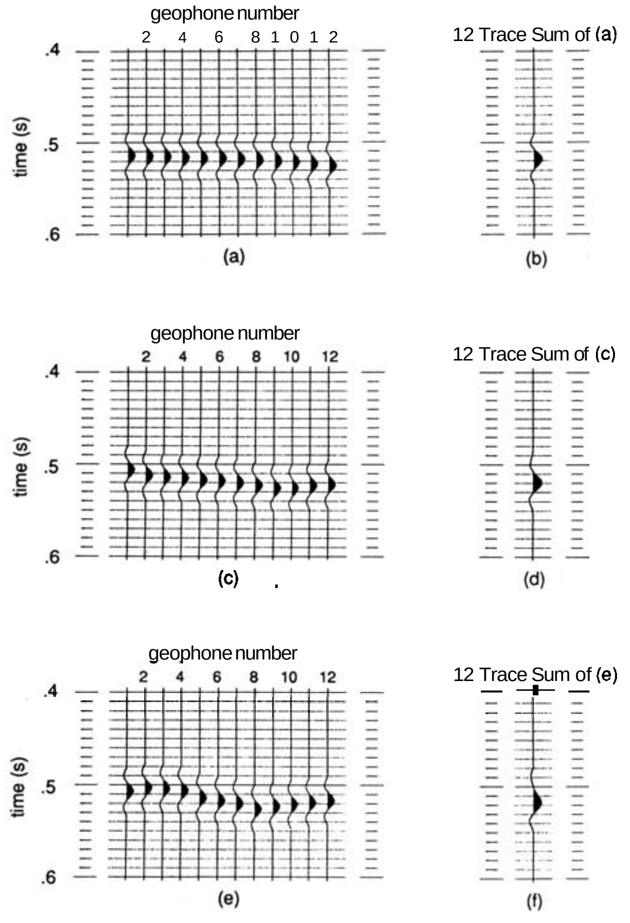

FIG. 8. Synthetic traces with intra-array statics calculated from west Texas shallow-reflection data applied to synthetic low-frequency (**10–40** Hz) data. (a) 12 individual geophone traces, 17.5 m array. (b) Summed array output of 12 traces from (a). (c) Individual geophone traces, 35 m array. (d) Summed array output of 12 traces from (c). (e) Individual geophone traces, 70 m array. **(f)** Summed array output of 12 traces from (e).

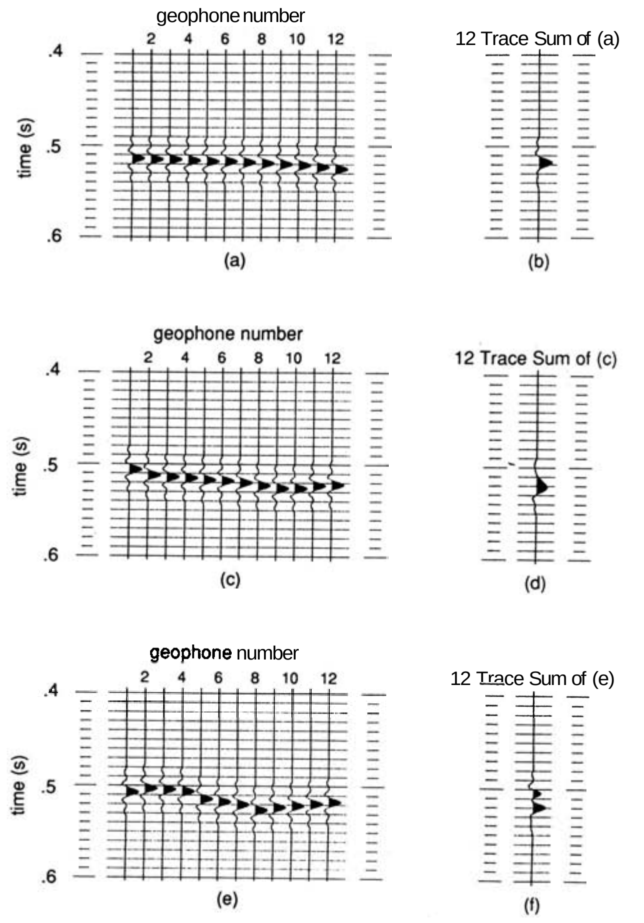

FIG. 9. Synthetic traces with intrarray statics applied to **high-**frequency (10–80 Hz) wavelet data. (a) 12 individual geophone traces, 17.5 m array. (b) Summed array output of 12 traces from (a). (c) Individual geophone traces, 35 m array. (d) Summed array output of 12 traces from (c). (e) Individual geophone traces, 70 m array. **(f)** Summed array output of 12 traces from (e).

disastrous results. Such doublets occurring at random in a seismic shot record could destroy event coherency. The scenario where such doublets persisted over several traces would be even more problematic. Such coherent static artifacts could cause misinterpretation of small phase-sensitive stratigraphic features, such as reefs or sand channels, whenever the reflection frequency was high enough, throughout the section. In other words, if the section contained one or more high-frequency reflections in the presence of low-frequency reflections, it would be possible for static-caused doublets to appear on some reflections but not on others.

DEPHASING THE STATIC ARTIFACTS

It has been shown that the desired information in a seismic reflection section can be distorted by introducing intra-array statics. If this problem exists in field data, one can theoretically compensate for it in the data-processing stage by application of a dephasing operator. In this section, some of the basic theory behind this problem is discussed and a simple method of calculating a dephasing operator is described for the zero-phase examples.

The static shift at each geophone can be described mathematically by a convolution of the whole seismic trace with a shifted delta function. Hence, the response of a geophone group can be written as

$$f_s(t) = g(t) * h_s(t), \tag{1}$$

with

$$h_s(t) = \delta(t - \tau_0) + \delta(t - \tau_1) + \ldots\ldots + \delta(t - \tau_n) \tag{2}$$

where τ_n**'s** define static shifts associated with the nth geophone. The τ_n**'s** are taken from the appropriate locations in Figure 6d.

The convolution of the unshifted trace $g(t)$ with the operator $h_s(t)$ introduces unwanted distortion of the seismic trace. To remove this effect, the operator $h_s(t)$ must be inverted. The inverted operator is then applied to $f_s(t)$ to regain the **un-**

distorted trace $g(t)$. Application of this operator is relatively easy in the frequency domain. Equation (1) can be rewritten in the frequency domain as

$$F_s(\omega) = G(\omega)H_s(\omega). \quad (3)$$

To recover $g(t)$ from the data, all that needs to be done is to invert $H_s(\omega)$ to find the dephasing operator and then to multiply this operator by the transformation of the observed data, i.e.,

$$G(\omega) = F_s(\omega)/H_s(\omega). \quad (4)$$

The desired result $g(t)$ can now be recovered by inverse Fourier transformation of $G(\omega)$. Thus, for a wavelet with a stable inverse, the problem reduces to a simple frequency-domain deconvolution problem.

Two examples (Figure 10) from the high-frequency synthetic-trace calculations of the previous section demonstrate that this dephasing procedure can potentially both remove the bulk 20 ms static shift and perform a phase correction on the distorted wavelet. Although the corrections applied in Figure 10 are not perfect, they do restore the general character of the initial wavelet (Figure 7) and suppress the high-frequency doublet. Such a doublet would, of course, cause problems in processing and interpretation if not dealt with.

The dephasing procedure described here is very simplistic The intents of this section were to point out the simple theoretical relationship between the distorted output trace and the static shift at each geophone, and to show that this information can indeed be used after the geophone signals have been mixed in the field. If detailed statics information were available, the use of more robust algorithms could compensate for deficiencies in the simplistic approach used here.

DISCUSSION AND CONCLUSIONS

In the foregoing sections, the possible dramatic effects of variations in depth to bedrock on seismic reflection data quality were demonstrated. The P-wave static variation due to the presence of unconsolidated materials overlying undulating bedrock can easily be greater than 1 ms per meter of thickness variation. If the wavelength of the bedrock undulations is less than the geophone-array length, intra-array statics can cause a decrease in bandwidth and amplitude of the recorded data. Under extreme conditions, spurious high-frequency events can be introduced into the data. These events could cause misinterpretation of sand lenses, reefs, or other phase-sensitive stratigraphic variations deeper in the section. It may be possible, however, to compensate for some of these effects by dephasing the data traces if detailed and accurate subsurface geometries are known, such as those from very high-resolution reflection surveys.

The effects observed in these simple synthetic calculations may be present but unrecognized in poor data areas with extremely low near-surface velocities. The static effects become much more problematic as the reflection data are pushed to progressively higher frequencies.

While the data shown here provide a velocity model for only the upper 15 m, a shallow-reflection survey to image reflectors at depths approaching 100 to 200 m could be designed, depending upon the geographic locality and the thickness of the weathered zone. The survey shown in this paper was acquired with a seismograph having fixed-gain (i.e., not floating point) amplifiers. The geophone interval and 24 channels limited maximum offsets to 17 m. Seismographs with floating-point amplifiers and 48+ channels can enhance data from deeper reflectors and allow more rigorous applications of the techniques discussed here.

At least three options are available to implement shallow-reflection statics. One method involves running a separate reflection survey to obtain the necessary shallow data with the degree of detail shown in this paper at a cost per mile on the order of a conventional survey (including processing). Another method is to record the shallow data as part of the conventional data by using hundreds of channels with very small geophone arrays (no more than 2–3 m across) and group intervals (no more than 3–5 m). Perhaps the most cost-effective method is to use the shallow-reflection survey only where quality of the conventional data suggests that a near-surface statics problem exists. The conventional data could then be reprocessed to incorporate statics information obtained from the shallow survey.

This paper has addressed the problem only in the case of receiver statics. If source arrays were to be used, the source array static could be treated similarly. The effects of a nonuniform near surface could certainly compound the statics problems if both source arrays and receiver arrays were used.

One potentially serious statics problem caused by very low near-surface velocities that has not been addressed here relates to shear-wave data. Since shear-wave velocities in alluvial materials are typically only 0.15 to 0.50 as large as the corresponding P-wave velocities (Hasbrouck and Padget, 1982), static irregularities can easily be as much as seven times larger on S-wave reflection data than on P-wave data in the same location. A 1 m change in thickness of the near-surface weathering layer could introduce an error on the order of 10 ms, assuming an S-wave velocity of 100 m/s. Relating this to the synthetic examples shown in the preceding sections, the doublet shown in Figure 9e could be developed in S-wave data with weathering-layer thickness undulations of less than 2 m in amplitude. With

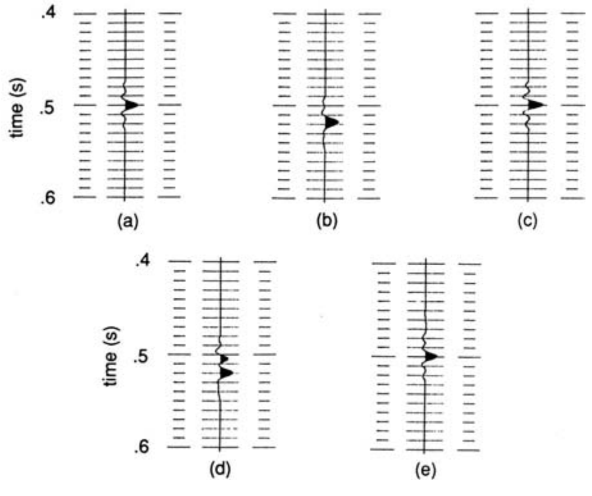

FIG. 10. (a) Original high-frequency (10–80 Hz) reflector. (b) Array output of 17.5 m array showing bulk shift and distortion effects due to intra-array static shifts. (c) Dephased version of trace (b) showing bulk shift removal and removal of wavelet distortion. (d) Array output of 70 m array. (e) Dephased version of trace (d).

increased use of multicomponent recording, shallow S-wave reflection surveys could become a fertile area for S-wave statics research.

It is important to note that no conventional static-correction method provides the detail necessary to make the corrections obtainable from Figure 6d. Even shallow refraction static surveys do not contain sufficient information to develop the velocity model of Figure 6b.

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