Part I

Static corrections—a review

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In many onshore exploration areas, the land surface is covered with a relatively thin layer of material of low seismic velocity. Commonly known to geophysicists as the weathered layer, it is generally related to aerated material above the water table or to geologically recent unconsolidated sediments on a substratum of harder consolidated rocks. This seismic layer, despite the geophysicist's terminology, appears to have very little to do with the geologic weathered layer. However, variations in the physical properties of this upper layer can cause a dramatic deterioration in the quality of land seismic data (Figure 1) if we do not acknowledge the problem and take appropriate action during data acquisition and processing.

There are many concerns and issues associated with the near surface but, in this three-part tutorial series, I shall be concerned with the problems of velocity and thickness variations in the low-velocity, near-surface layers-or, more particularly, with their measurement and compensation of the data for their presence. Part I deals with the variability of the near-surface velocity distributions and how it affects the seismic data. Also considered are the types of data available from which the near-surface velocity distribution may be determined. Concluding the first part is a discussion of the datum, field statics and drift statics. Next month, Part II will consider refraction statics, and in March Part III will focus on residual statics, statics and velocity analysis, plus some guidelines for choosing a method.

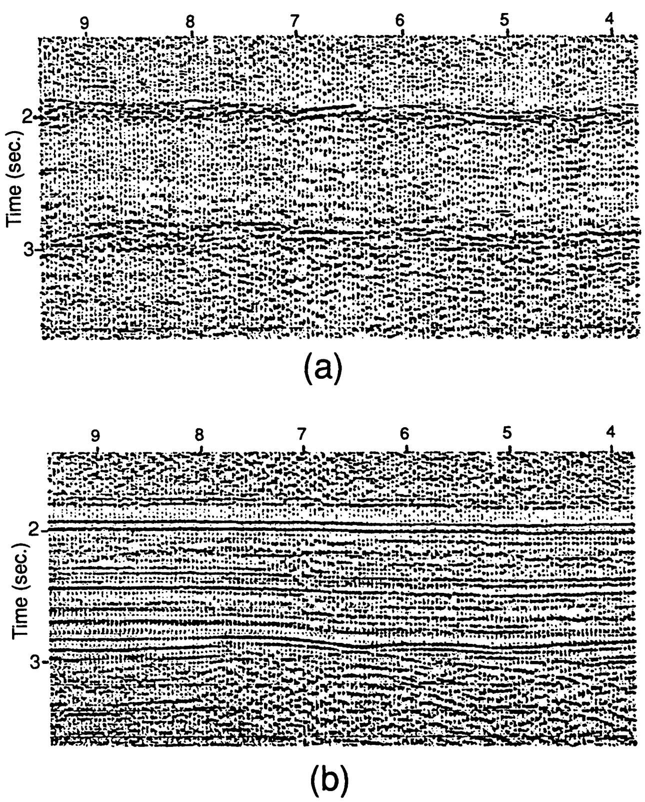


Figure 1. (a) Part of a seismic line processed without static corrections. (b) Same data processed with static corrections. Note how the resolution and continuity of events are improved in the latter (from *Residual statics analysis as a general linearproblem* by R.A. Wiggins et al., GEOPHYSICS 1976).

Problems caused by the near-surface low-velocity layer have been known for over half a century. Some of the earliest papers in geophysical prospecting were concerned with attempts to determine their thickness and velocity, or compensate those early seismic records for the time delays caused by the low-velocity layer. In predigital days, field statics and refraction statics were thought to be the complete statics solution; then, in the wave of the success of residual statics programs (first developed in the 1970s), it was felt that statistical methods alone were the answer. However, the consensus today within the exploration industry is that each method has its own place in adding to the complete statics solution.

Despite the many technologies that deal with different aspects of the near surface, related issues are still with us. Two of the most difficult, and most often cited, problems are:

- Need for more accurate near-surface velocity models
- Need for models of the near surface to allow adequate acquisition design

Before we can model the near surface, we need to measure it so that our models bear some relationship to reality. What we usually measure are the velocities and bed thicknesses, or some kind of averages of these since we tend to ignore very thin beds even though their presence or absence can affect the apparent phase of the data (see *A simple approach to high resolution profiling for coal* by A. Ziolkowski and WE. Lerwill, *Geophysical Prospecting* 1979).

Another aspect of the near surface which we shall not discuss is the question of ground roll, even though the frequency and velocity of these surface waves are governed by the thickness and elastic properties of the near surface. Acquisition parameters are usually selected so that the nuisance value of ground roll is minimized, although, as we shall see, the way we choose to overcome the problem can lead to a loss of temporal resolution. Today, we are acquiring seismic data in more rugged areas and areas that were formerly "no data" areas, and pushing existing technologies to the limit of their usefulness in the process. However, we still experience problems in more normal areas, some with a long history of seismic activity. "Why is this?" you might well ask. The principal reasons are:

- Need for higher resolution data demands better static corrections among other things
- Failure to consider the near surface and its problems at the survey planning stage can result in not acquiring the necessary data to address the issue
- Ignorance of the problem
- Lack of awareness of the available technologies
- Cost cutting

Static corrections are most important in the processing of land data for they lead to improved quality in subsequent processing steps which, in turn, impact the integrity, quality, and resolution of the imaged section. Errors in the static correction lead to a loss of seismic resolution, both temporal and spatial, and a less-than-optimum interpretation of the seismic data set. Also, if static corrections are not properly derived, then a whole catalog of problems can beset the interpreter (such as lines with variable datums, seismic events which mistie at intersections, false structural anomalies remaining in the data, false events being created out of noise, and lastly the data quality not being optimized). Therefore, a good statics solution is desirable for two reasons: to obtain the correct structural interpretation and to obtain a high-resolution section which can be used for stratigraphic interpretation. It should be stressed that either of these criteria can be met without satisfying the other by application of one or another of the different statics technologies that are available; however, it is most desirable to satisfy both.

A literature search has yielded only one tutorial on the subject of static corrections-a 1989 article by Brian Russell which appeared in the CSEG *Recorder*, a publication not widely available. The purpose of this three-part series, then, is to attempt to correct this lack of up-to-date, easily accessible information on this important subject. The articles will consider the problem of velocity and thickness variations in the low-velocity, near-surface layers; discuss the types of data available for determining static corrections; analyze altenative approaches; and review available technologies.

Near-surface concepts. In many exploration areas, the surface is covered with a relatively thin and uniform low-velocity layer, but frequently we know that this is not the case. Some of the near-surface conditions which are frequently met are illustrated in Figure 2. They include, but are not limited

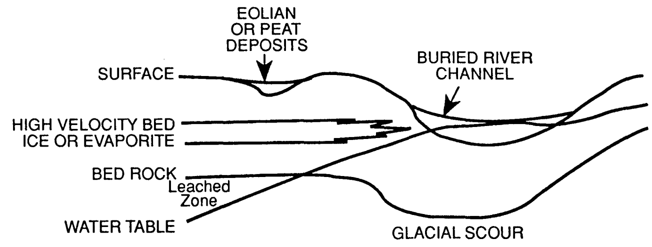


Figure 2. Some of the frequently encountered near-surface conditions which, if not adequately modeled, result in errors in the computed static corrections and a degraded seismic image.

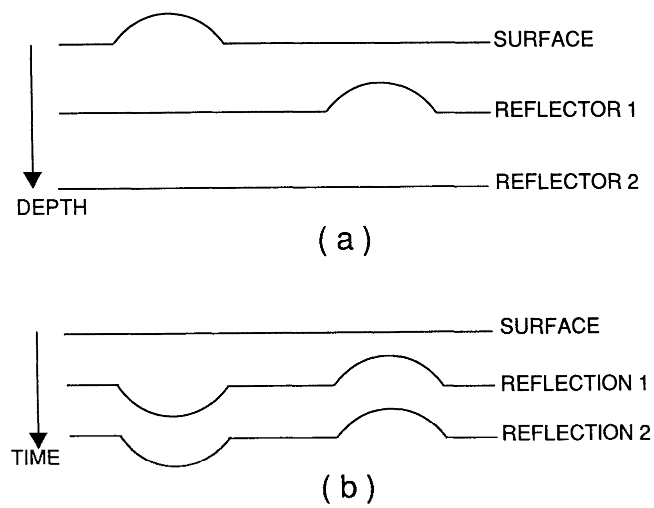


Figure 3. (a) A depth model. (b) The model's seismic time response, illustrating the fundamental issues of the statics problem. Changes in the elevation and thickness of the near-surface low-velocity layer produce time structures on reflections from flat reflectors. Lateral variations in the interval velocity of the near surface have similar effects.

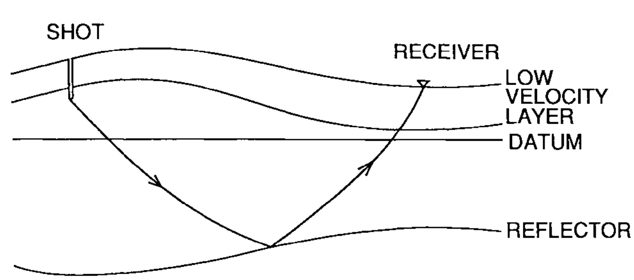


Figure 4. Near-surface model with a seismic raypath being shown between source and receiver.

to, elevation changes, sand dunes, other eolian deposits, buried river channels, buried glacial scours, permafrost, evaporites, variable water table, leached zones, volcanics, peat deposits, and coal seams. All present potential problems. The presence of low- or high-velocity layers by themselves do not pose problems. The problems occur because of the variability in both the thickness and velocity of the near-surface layers and our ability to adequately define those variations or compensate for them.

The simple model shown in Figure 3 illustrates the essence of the near-surface problem. The depth model has a variable overburden thickness due to elevation changes and other effects and its interval velocity is assumed constant. The attitude of the seismic reflections clearly do not represent the structural attitude of the reflectors in the depth model. Similar effects could be produced by holding the overburden thickness constant and varying its interval velocity. Where the overburden is thicker (or of lower interval velocity), a seismic wavelet takes longer to travel through the layer and conversely where it is thinner (or of higher interval velocity), a seismic wavelet requires less time to traverse the layer.

Seismic recording involves a source and receiver, usually many receivers, separated by some offset distance. The raypath for a single reflection on a seismic recording is shown in Figure 4. From this and Figure 3, we can see that the traveltime of a wavelet along the raypath is influenced by the surface elevations of the geophone and shotpoint, by the velocity and thickness of the near-surface layers above the datum, by the depth and dip of the reflector itself, by the distance separating the source and receiver, and lastly by the average velocity between the datum and the reflector.

During processing, each of the above effects usually undergoes one or two corrections at a time, until the seismic data provide a quality image of the subsurface. With conventional multifold data, a number of traces are added together in such a way that the summing, or stacking, enhances primary reflections at the expense of noise or unwanted signal. Corrections applied to the seismic traces so that the data can be properly stacked are of two types, static and dynamic. Static corrections involve a constant time shift to the data traces whereas dynamic corrections involve time variable shifts. Corrections made to each seismic trace for elevation effects (elevation static) and near-surface low-velocity effects (weathering static) by conceptually moving the shots (shot static) and receivers (the receiver static) to a common reference surface (the datum plane) are greatly simplified if it is assumed that energy travels vertically in the interval above the datum plane.

In conventional seismic surveys, shot-receiver separation is usually less than or approximately equal to the depth to reflector so, with reference to Figure 4, we see that in practice the raypaths in the near surface tend to be almost vertical. Such an assumption results in static, rather than dynamic, corrections with very little residual error in most cases. This assumption allows all traces from a common shot location to receive the same shot static and all traces from a common receiver location to receive the same receiver static. The static corrections then are said to be surface-consistent. The assumption of vertically traveling energy is most closely approximated for small offsets, for small elevation changes, for

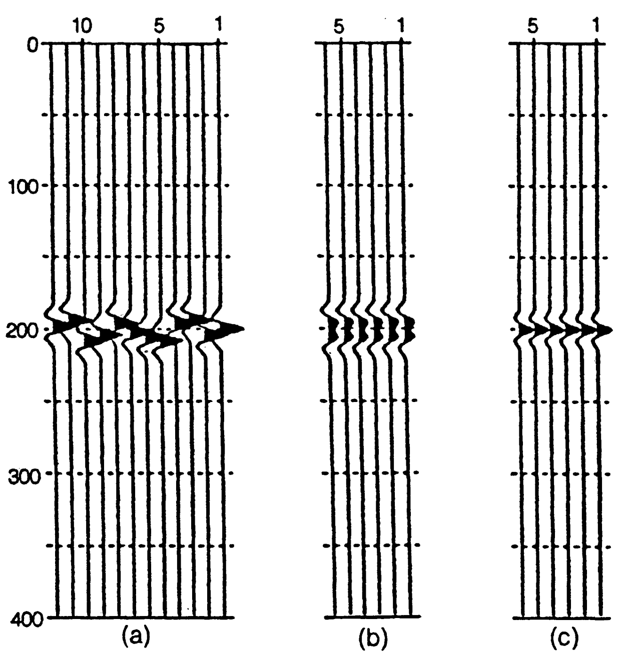


Figure 5. Effect of statics on the stacked trace. (a) Synthetic 12-trace gather, after NMO corrections, but containing uncorrected static anomlies. (b) Stack of the 12 traces repeated so the degraded reflection is clearly seen. (c) Stack of the 12 traces after statics correction, once again repeated so that the reflection is clearly seen (from *Static corrections-a tutorial* by B.H. Russell, *CSEG Recorder* 1989).

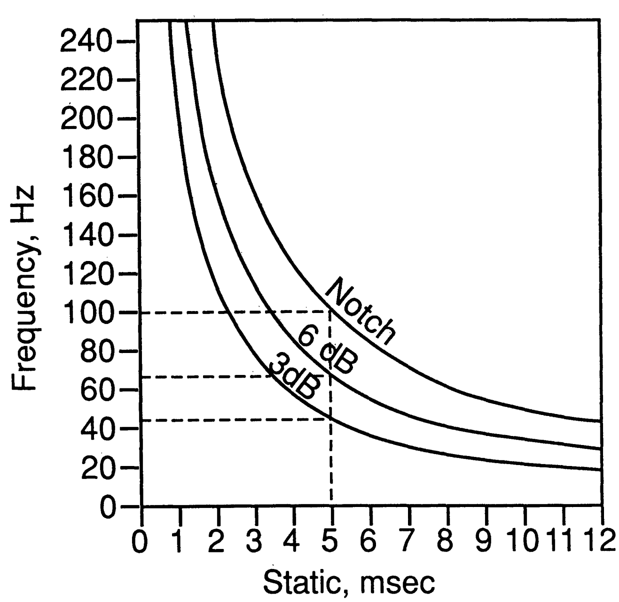


Figure 6. A small static shift between two traces acts as a high-cut filter. The frequency attenuation, when two traces are summed (or the output from two geophones in an array are summed), is a function of the static shift between them.

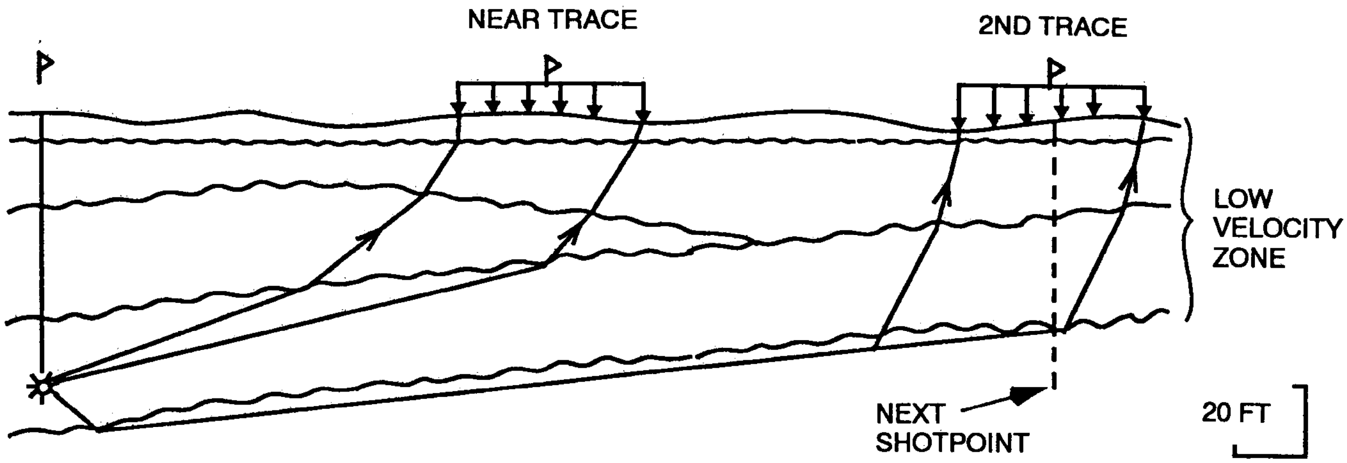


Figure 7; The field geometries used in conventional seismic profiling do not sample the very near-surface layers adequately enough to permit a sufficiently detailed velocity model to be determined from the directly arriving seismic energy.

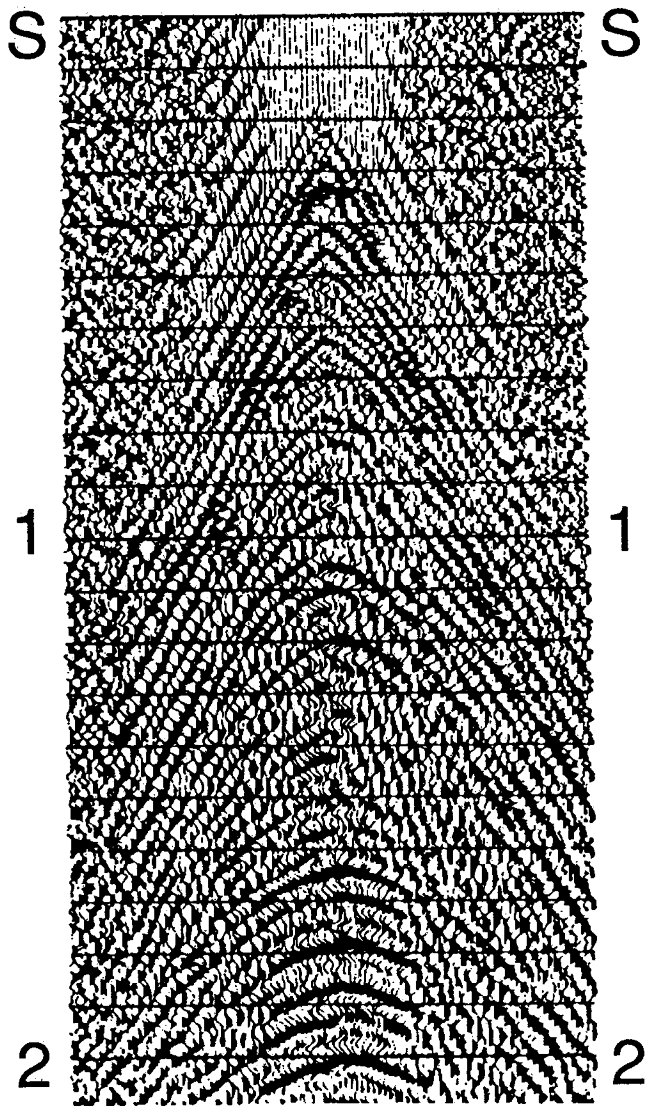


Figure 8. A vibroseis record where the first breaks (onset of seismic energy) cannot be distinguished. In such areas, it is necessary to use an additional source of information if the near-surface velocity model heeds to be derived (from *Seismic Data Processing* by 0. Yilmai, SEG, 1987).

small elevation differences between topographic surfaces and datum, and in those situations where there is a relatively thin veneer of low-velocity material at the surface. The assumption of vertical raypaths breaks down for data recorded in the most rugged terrains where elevation changes along the line are large with respect to the distance between geophone groups, for large differences between topographic surface and datum, where the velocity at the surface is relatively high and, lastly, for offsets which are long with respect to the depths to the reflectors.

Static anomalies cause the primary events to be misaligned and so the stack process, rather than enhancing the primary signal, destroys or corrupts it. Figure 5 illustrates the effect that static anomalies have on the stacked trace. In Figure 5a, a theoretical 12-trace gather is shown, prior to stacking, which contains some small static anomalies. These anomalies cause the primary event to be misaligned across the gather so that when the traces are stacked, a double event of low amplitude is produced (Figure 5b) rather than the single high amplitude event (Figure Sc) which would be the desirable outcome of the stacking process. In real data, these short-period static anomalies act as high-cut filters on the amplitude spectrum and also cause phase distortion of the wavelet shape.

Figure 6 relates the magnitude of the static shift between two summed traces to the attenuation of different frequencies. Consider, for example, traces 1 and 2 in Figure 5a. The seismic wavelet has a dominant frequency of about 70 Hz, and there is a time shift of about 5 ms between the two traces. Summing just these two traces without any static correction results, according to Figure 6, in the rejection of the 100 Hz data from the amplitude spectrum of the summed trace (i.e., there is a notch at 100 Hz). The data close to the dominant frequency (about 70 Hz) are reduced by about 6 dB-i.e., its amplitude will be half of what it would be with a static correction applied, while the signal at lower frequencies is little affected. We thus see that the higher frequencies are more severely attenuated than the lower frequencies. This helps explain why we so rarely see frequencies above about 70 Hz in land seismic data when the commonly used sources are capable of producing frequencies in excess of 100 Hz-for static shifts of 4-5 ms are easily overlooked in processing and easily produced within a typical receiver group length by

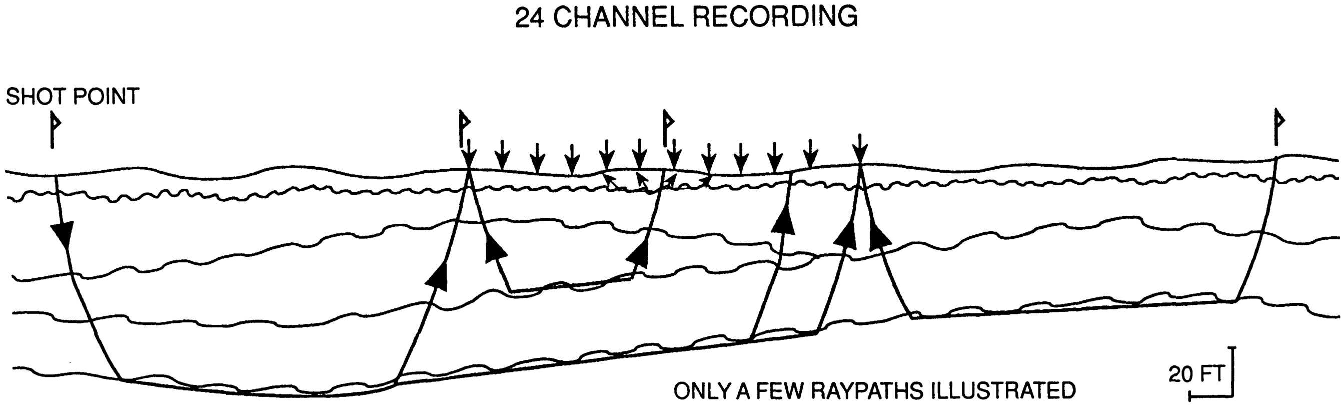


Figure 9. The field geometry of a low-velocity layer survey, showing typical geophone and shot positions, permits the velocity model of the near surface to be determined by refraction analysis of the field records. Compare the scale of the geometry to that shown in Figure 7.

variations within the soil layer.

The above serves to illustrate that as we strive for higher resolution data, for detailed stratigraphic exploration, close attention needs to be given to static corrections which are conceptually very simple. We derive the thickness and velocity of the near-surface layer and, given the elevations of all shot and receiver locations, we compute and apply the static corrections to each trace in a surface consistent manner. The commonly available methods to do this assume that the near surface consists of one or two low-velocity layers. This limitation does not pose a serious problem since most of these techniques can be used iteratively (i.e., the first layer is analyzed and a correction made before considering the second layer). However, if the near-surface model is inadequately defined (and it is usually oversimplified), there will be trade-offs between the velocities and thicknesses of the layers in the model which result in errors in the computed static corrections and a less-than-optimal seismic image.

Data sources. How well we define the surface model or derive the static corrections depends on the four types of data commonly available: the seismic data themselves, uphole times from deep dynamite shooting, separate low-velocity layer (LVL) surveys, and uphole velocity surveys.

Conventional seismic data are used in two very different ways. There are refraction-based techniques which use the first break information in a deterministic way to estimate the near-surface model from which the static corrections are computed. Then there are the reflection-based techniques which statistically derive residual static corrections to enhance the coherency of the reflection. The long group lengths and the source to near-receiver offsets of conventional seismic field geometries are usually such that the data fail to adequately sample the uppermost layer(s), the zone in which most variations of velocity and thickness occur, for deterministic techniques (Figure 7). It is common practice then, when a deterministic approach is to be taken, to supplement the conventional seismic data with other information to help determine the near-surface model, or to combine refraction and residual techniques. when surface sources such as vibroseis are used, the first breaks on the field records are sometimes so poor (as in Figure 8) that it is imperative, if one

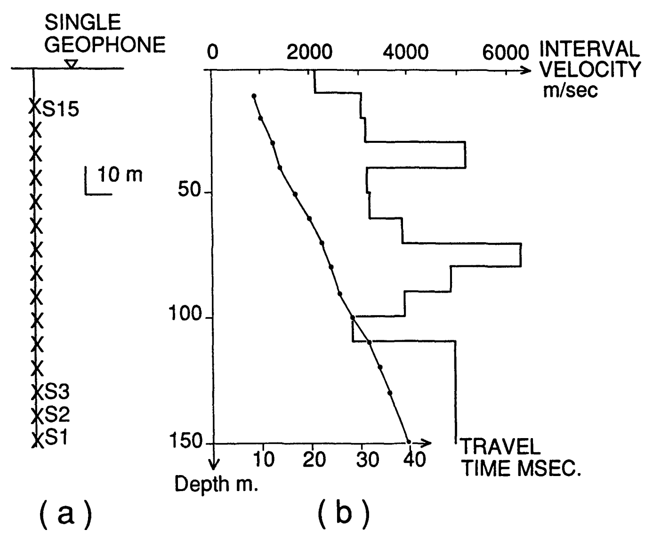


Figure 10. (a) Acquisition geometry of an uphole velocity survey. (b) Results of the survey. These surveys are useful for calibrating the results of refraction interpretations, particularly in areas where the low-velocity layer contains one or more high-velocity layers.

wishes to use a deterministic approach, to employ either an LVL or uphole survey to obtain near-surface velocity information. Some acquisition geometries, such as crooked line, result in nonlinear first break data so that conventional refraction analysis of first breaks cannot be undertaken and it is then common practice to employ a separate LVL crew.

Uphole times from deep-hole dynamite shooting are an additional source of information which is available at no extra cost. This measurement provides an average vertical velocity over the uppermost few tens of feet with one sample every few hundred feet along the line depending on shothole depth and spacing. Examination of adjacent uphole times from a survey will give an indication of the consistency or variability of the near surface. Unfortunately, these measurements, which all too often'contain relatively large recording errors, do not allow us to define a detailed near-surface model and

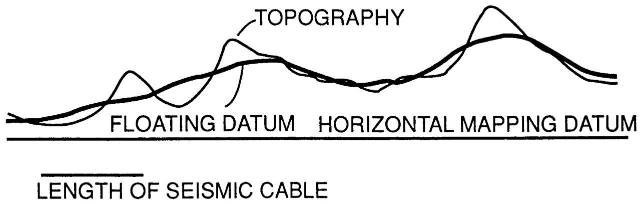


Figure 11. The floating datum is usually a running average of the topography over the length of the recording cable.

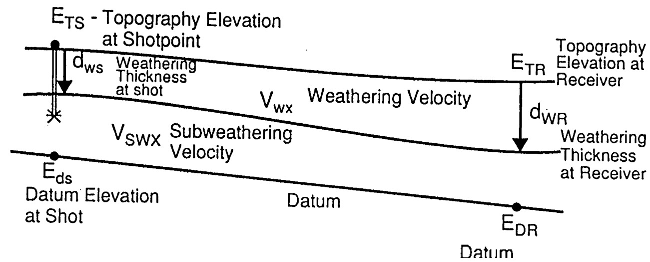


Figure 12. Field static computations. Uphole time *(tub)* is measured (except for surface source techniques where it is zero). Shot elevation static $t_{es} = (E_{ts} - E_{ds}) / V_{swx}$. Shot weathering static $t_{ws} = d_{ws} / V_{wx} - d_{ws} / V_{swx}$. Receiver elevation static $t_{er} = (E_{tr} - E_{dr}) / V_{swx}$. Shot weathering static $t_{wr} = d_{wr} / V_{wx} - d_{wr} / V_{swx}$. The shot static, $t_{es} + t_{ws} - t_{uh}$, is subtracted from the seismic trace; the receiver static, $t_{er} + t_{wr}$, is also subtracted. Weathering statics are not always included and elevation statics are sometimes applied with only an approximate near-surface velocity. In such cases, any deficiency in the statics correction is remedied by the application of residual statics corrections.

then the computed average velocities cannot be reconciled with the near-surface velocities determined by other methods.

Separate LVL surveys enjoy enormous popularity in some areas of the world (see *Determination of static corrections* by A.W. Rogers, in *Developments in Geophysical Exploration Methods,* Applied Science Publishers, 1981). They are small scale refraction surveys employing single geophones rather than groups, with spread lengths on the order of a few tens of feet to a few hundred feet. Figure 9 shows an example of a field geometry which would be repeated perhaps every one-quarter mile. There is a range of different sources available which are suitable, not only for LVL work, but also for high-resolution seismic profiling. R.D. Miller et al. compared them in *Field comparison of shallow seismic sources* (GEOPHYSICS 1986). It is necessary to ensure that the source is powerful enough to provide adequate penetration and that a long enough spread length is used such that the deepest zone of investigation overlaps with the shallowest refractors on the conventional data. Less attention needs to be given to the choice of geophone since the response characteristics of the geophones used in conventional reflection surveys (10, 14, 20, and 28 Hz) do not become nonlinear until around 500 Hz. The data provided by these LVL surveys, then, fill in the zone inadequately sampled by the first break information on the conventional seismic record.

In uphole velocity surveys, a small charge (a blaster cap or up to 4 oz of dynamite) is detonated at incremental depths of say 20 ft in a hole from a total depth of say 300 ft up to the surface (Figure 10). A geophone at the surface measures a series of uphole times from which interval velocities are calculated. By itself, an uphole survey doesn't determine layer boundaries with precision, so it is best used in conjunction with other information to ensure that measurements are made close to horizon interfaces. The cost of uphole surveys usually limits the number conducted in a given survey area, and the resultant sparse spatial sampling makes them unsuitable for mapping lateral velocity variations and rapid changes in thickness of the near-surface layers.

The datum. Before static corrections can be computed and applied, it is necessary to select a suitable reference datum. Seismic reflection theory is based on a horizontal datum, but the datum of field data is the topography. A floating datum is usually used until after the normal moveout (NMO) correction as a compromise between reality and theory.

The floating datum is chosen so that the field statics are kept small. This can be achieved by selecting a datum for each gather which is the mean of the elevations of the receivers

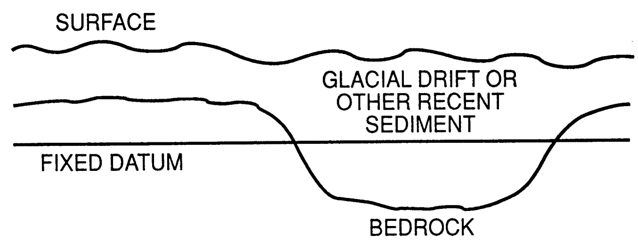


Figure 13. Relationship between the surface topography, the fixed datum, and the base of the drift layer (which may be stratified). Drift statics compensate for all of the low velocity layer, even that below the fixed datum.

which contribute to the gather. The extension of this concept to every gather in the seismic line results in a variable or floating datum which is a running average of the receiver elevations, the averaging taking place over a spread length. With rugged topography and for 3-D surveys, it may be desirable to generate a floating datum surface to avoid different datum elevations at line intersections. Such a surface is formed by averaging the topography elevations lying within a circle of inclusion whose diameter is equal to the spread length.

Since the interpreter would like all the seismic data in a project area to be referenced to the same horizontal datum to facilitate mapping, the floating datum is corrected to the horizontal datum after the NMO correction has been applied, often after the data has been stacked. Figure 11 illustrates the relationship between topography, floating datum, and horizontal mapping datum. Only in areas of very low topographic relief lying close to the horizontal datum is the floating datum dispensed with and the horizontal datum used in processing.

Field statics. As we have seen, from a complete knowledge of the locations and elevations of the shots and receivers, and the velocities and thicknesses of the near-surface layer(s), a complete statics solution can in theory be obtained. This computation is referred to as the field static to differentiate it from other static computations. In practice, it is used to describe the initial static corrections made to the field data when correcting the field records from the topography to the floating datum on the basis of either uphole velocity survey results, LVL survey results, or the refraction analysis of the first breaks. Sometimes it is no more than an elevation static applied using some average velocity which takes no account of variations in the near-surface velocity regime.

The uphole velocity survey as illustrated in Figure 10 yields a model of the near-surface layers' thicknesses and velocities directly. The LVL survey results are analyzed by one of the refraction analysis techniques to yield the model of the near-surface velocities and bed thicknesses. Or the first breaks of the seismic data themselves are analyzed directly to determine the near-surface model.

Once the near-surface model has been determined, then the elevation and weathering corrections at both the shot and receiver locations can be simply determined as shown in Figure 12 where the conventional situation of the datum lying beneath the weathered layer is shown. However, it is equally likely that a floating datum, at least, will lie above the topography or within the weathered layer.

It is desirable to keep static corrections as small as possible before the NMO correction. In most surveys, this is easy since the topography is frequently of low relief, resulting in relatively small field static corrections. Where there is a thick low-velocity layer or rugged topography or both, it may be necessary to apply only an elevation correction from the topography to a floating datum, reserving a much larger static until after NMO correction.

Drift statics. The term drift statics arose to describe the static corrections necessary to compensate for glacial drift. In areas where glacial drift occurs at the surface, the topography, drift, and datums frequently exhibit the relationships shown in Figure 13. In such areas there is no dry aerated layer; the low-velocity layer is the glacial drift, or boulder clay, which exhibits considerable variation in velocity and thickness and overlies much higher velocity bedrock. Static corrections must compensate for the whole of this low-velocity layer, even that below the fixed datum, to avoid serious distortions in the seismic data.

Drift statics is now used more widely than merely to describe the static corrections in areas of glacial drift; it is often applied to statics from any area where there is a sharp irregular boundary between low-velocity surface sediments and bedrock, particularly when the surface extends below the fixed datum. LE

Parts II and III of this tutorial will be published in the February and March issues of TLE.

Part II

Static corrections—a review

Refraction statics. One of the reasons for deriving and applying static corrections is to ensure structural integrity in the processed section. Static anomalies whose spatial wavelengths are longer than a spread length are not uncommon and if not corrected produce false structures in the seismic section (Figure 14). Refraction statics are effective for correcting these long spatial wavelength anomalies, and they are also effective against shorter spatial wavelength anomalies.

Refraction methods allow us to derive estimates of the thicknesses and velocities of the near-surface layers by analyzing the first breaks on the field records. There are many methods which have been proposed over the years, but all are based on the same basic principal of refracted energy.

The key concept in seismic refraction is that when a seismic ray crosses a boundary between two formations of different velocities, then the ray is bent according to Snell's law (Figure 15) which states that the ratio of the sines of the incident and refracted angles is equal to the ratio of the velocities of the two formations. As long as the velocity of the lower layer is faster than the velocity of the upper layer, the refracted ray will be bent toward the horizontal and there will come a point, as the angle of incidence is increased, at which the refracted angle is 90°. When this critical angle is reached, the ray will travel horizontally in the second layer close to the formation boundary. Energy traveling in the faster medium close to the boundary continuously excites waves in the upper layer which are transmitted back to the surface. Energy refracted in the faster layer arrives at the surface before the direct arrival, and it is known as the refracted or headwave. This situation is shown in Figure 16 with the time-distance plot of the first arrivals used to determine the velocities of the layers involved (the inverse of the slope on the graph). The thickness of the surface layer can be computed from the slope and intercept-time values.

The most common extensions of the theory from the situation depicted in Figure 16 are first to a multilayered solution, then to a dipping layer solution, and finally to the situation where the velocity of the top layer increases with depth. (The reader who wishes to consider the formulas associated with these and other extensions of the concept is referred to *An Introduction to Geophysical Prospecting* by MB. Dobrin or *Seismic Refraction Prospecting,* edited by A.W. Musgrave, SEG, 1967.) Refraction techniques whose theory is based on the assumption of planar refractors are collectively referred to as linear techniques, while those methods which allow rapid changes in refractor geometry and velocity are collectively referred to as nonlinear techniques.

In the real world, the topography is never flat, the refractor is never planar, the velocity of the low-velocity layer probably changes both laterally and vertically due to compaction and lithology variations, and finally the subweathering velocity probably varies laterally also. So, instead of the simple

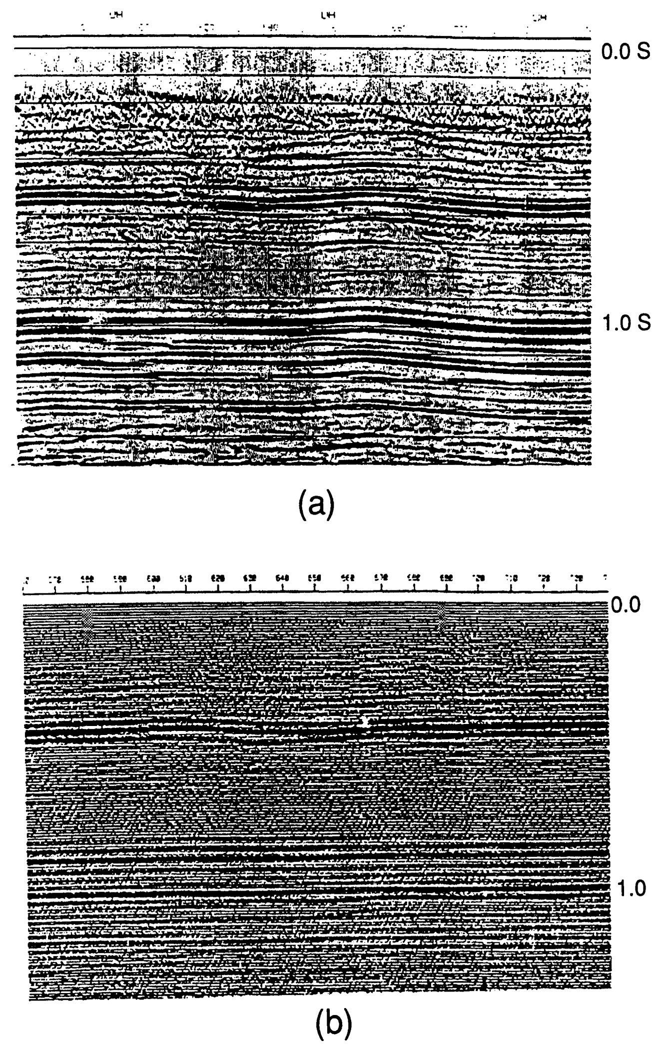


Figure 14. A seismic section showing the effects of different statics correction technologies on the structural integrity of the data. (a) A false time structure remains when the residual statics technique fails to detect and compensate for a static anomaly of long spatial wavelength. (b) The anomaly is removed by a refraction technique.

Part I of this three-part tutorial series dealt with the variability of the near-surface velocity distribution and how it affects the seismic data. Also considered were the types of data available from which the near-surface velocity distribution may be determined. The datum, field statics, and drift statics were discussed. Part II focuses on refraction statics. Next month, Part III will cover residual statics, statics and velocity analysis, and some guidelines for the choice of method.

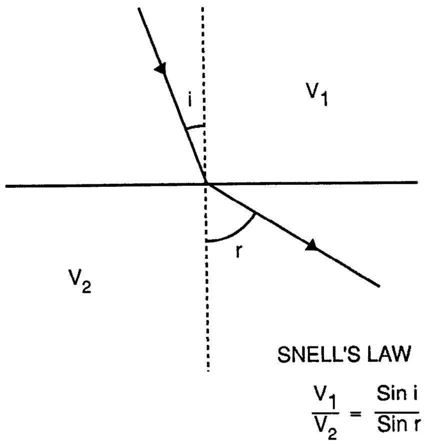


Figure 15. Refraction of a seismic ray at the boundary between two rocks exhibiting different velocities.

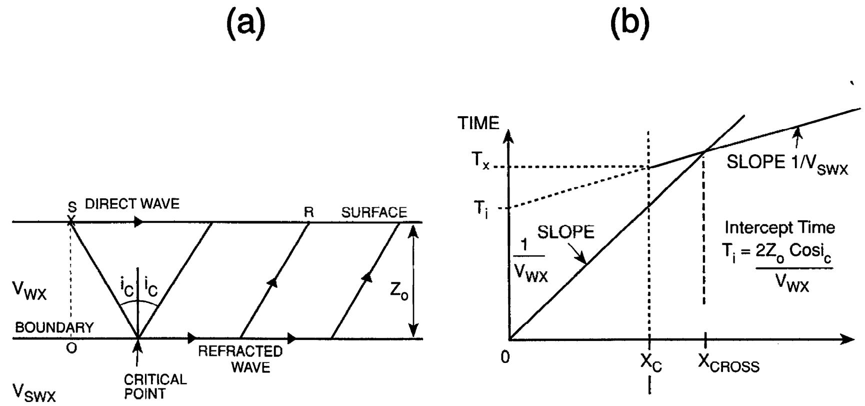


Figure 16. Refraction of a seismic ray (a) at the critical angle of incidence and the associated time-distance plot of first arrivals (b).

relationship depicted in Figure 16, in which the velocities of the weathered layer and subweathered layers are the inverse of the slopes of a graph and the low-velocity layer thickness is a linear function of the intercept time, we have the arrival time of the first energy being some unspecified nonlinear function of: thickness of the low-velocity layer, velocity of the low-velocity layer, velocity of the subweathering layer, and source/receiver separation. Those deviations of the subsurface from the theoretical linear model introduce errors into the computation by linear techniques of both the thickness of the weathered layer and the refractor velocity. In *Inversion of refraction arrivals: A few problems (Geophysical Prospecting* 1990), L. Zanzi analyzed some of the errors and concluded that by far the greatest errors came from curved refractors at depth. He also concluded that, of the common methods of refraction analysis, the technique developed by D. Palmer *in The Generalized Reciprocal Method of Seismic Refraction Interpretation* (SEG, 1980) appeared to be the most accurate. It should be noted, however, that Zanzi did not consider all methods, and the results that he presented were based on a theoretical analysis of errors, illustrated with one or two model examples.

In general, the statics methods based on a theoretical linear model are derived from early techniques when calculations were done manually and, as a result, they derive static correlations from the data without first deriving the near-surface low-velocity layer model. This may be achieved according to:

$$T_{\text{static}} = \frac{T_i}{2}\sqrt{\frac{V_{swx} - V_{wx}}{V_{swx} + V_{wx}}}$$

The terms are as defined in Figure 16. The techniques based on this formula use different methods of estimating the intercept time T_i directly from the seismic data and rely on the large level of redundancy in CMP data to overcome the noise problems associated with automatic picking.

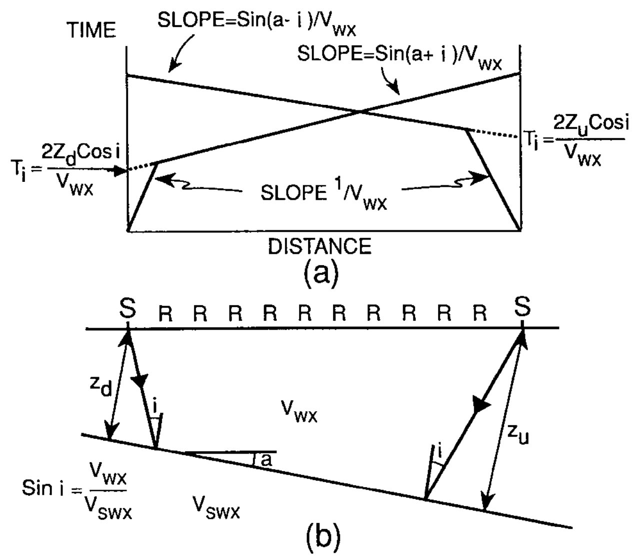


Figure 17. (a) A time-distance plot showing that refractions along a dipping interface from opposite directions produce different slopes (giving apparent velocity) and different intercept times. (b) In LVL surveys, it is necessary to record the refractions shooting both updip and downdip if velocities, dip, and depths are to be determined. The multiplicity of data in conventional multifold seismic acquisition permits a plot such as (a) to be constructed from data in the common receiver plane without the need for reverse shooting in the field.

S lope/intercept method. This technique adheres to the key concepts of the seismic refraction method and is described in some detail by W. A. Knox in *Multilayer near-surface refraction computations (Seismic Refraction Prospecting* SEG, 1967). Figure 17 illustrates the extension of the method to a single dipping refractor for which both forward and reverse profiles are illustrated. This basic method was originally carried out by manual computation, along with extensions to multiple layers and continuous increase of velocity with depth within the different layers. The method now forms the basis of a number of commercially available software packages. These systems are limited to either a three- or four-layer case and can handle dipping refractors.

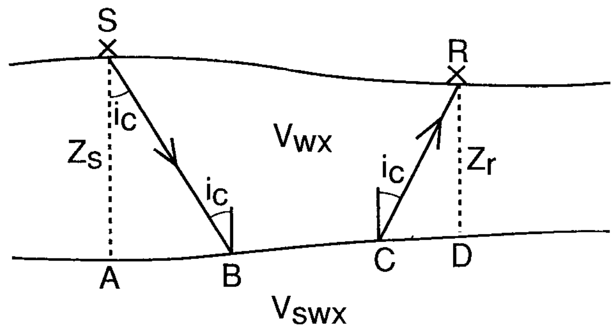


Figure 18. The intercept time T_i is the sum of two delay times, one at the shot (t_s) and the other at the receiver (t_r). $t_s = t_{sb} - AB / V_{swx} = Z_s \cos i_c / V_{wx}$. $t_r = t_{cr} - CD / V_{swx} = Z_r \cos i_c / V_{wx}$. Delay time theory requires the surface and refractor to be approximately horizontal.

Delay time methods. Delay time is not an observable quantity; it is defined as the time between the shot or receiver and the refractor minus the time necessary to travel the normal projection of the raypath on the refractor. It is explained in Figure 18. (For further details, see the articles by K.M. Barry and L.W. Gardner in *Seismic Refraction Prospecting*, SEG, 1967). The Fan technique *(see A novel method of deriving weathering statics from first arrival refractions* by G.W. Hollingshead and R.R. Slater, paper presented at SEG's 49th Annual Meeting, 1979) and the Chronos method *(see First arrival picking on common-offset trace collections for automatic estimation of static corrections* by F. Coppens, *Geophysical Prospecting* 1985) are based on the delay time. They produce, from picked first breaks, estimates of the intercept time along with weathering and subweathering velocities at every receiver location (Farr) or shot location (Chronos) from which the statics are computed. In the Farr technique (Figure 19) first breaks are picked on common shot records and T_i estimated from common-receiver gathers. Figure 20 illustrates the Chronos method where picks are made on common-offset gathers.

Both techniques were designed to compute static corrections for a constant velocity weathering layer of slowly changing thickness overlying a refractor of constant velocity. When these conditions do not obtain, then unacceptable errors arise in the computed statics.

Reciprocal methods. A number of reciprocal methods have appeared over the years which have a common origin in the method described by L.V. Hawkins *in The reciprocal method of routine shallow seismic refraction investigations* (GEOPHYSICS 1961). The basis of the method is what Hawkins called the time-depth term which is similar to the delay time except that the surface and refractor are no longer assumed to be approximately horizontal so that the depth terms of Figure 18 (Z_s and Z_r) are no longer vertical, but perpendicular to the refractor. Differences in traveltimes over similar raypaths are used to estimate the time-depth term and, hence, the intercept time and static.

The Generalized Reciprocal Method of Palmer is probably the most commonly used derivative method; it is illustrated in Figure 21. Arrival times at two geophones, separated by what is termed the XY distance, are used in refractor velocity analysis and time depth calculations. At the optimum XY spacing (determined by tests), the forward and reverse rays emerge from near the same point on the refractor, so the refractor need only be planar over a very small interval. The depth calculation does not need an accurate determination of the optimum XY spacing, but it is critical for the derivation of an average velocity and for the detection and accommodation of hidden (thin) layers and velocity inversions (a low-velocity layer beneath one of higher velocity).

Figure 22 illustrates the ABCD method described by M.S. Bahorich et al. in *Static corrections on the southeastern Piedmont of the United States* (GEOPHYSICS 1982). It directly estimates the relative receiver static between two adjacent geophone positions and is used in conjunction with techniques that directly derive the absolute source and receiver statics at infrequent intervals. For example, one might have uphole surveys every mile along a line to provide absolute estimates of the static corrections and use the ABCD method to give variations in statics along the line between upholes. Approximations made in the formulation result in small errors in the differential statics estimates of up to about 5 percent. The technique relies on the redundancy of the CMP method to statistically obtain robust estimates of the differential statics between adjacent geophone groups which are then tied to the sparse absolute measurements to provide continuously varying static corrections along the line. The authors claim that the method also works well on crooked line shooting where the source and receivers are not in a straight line.

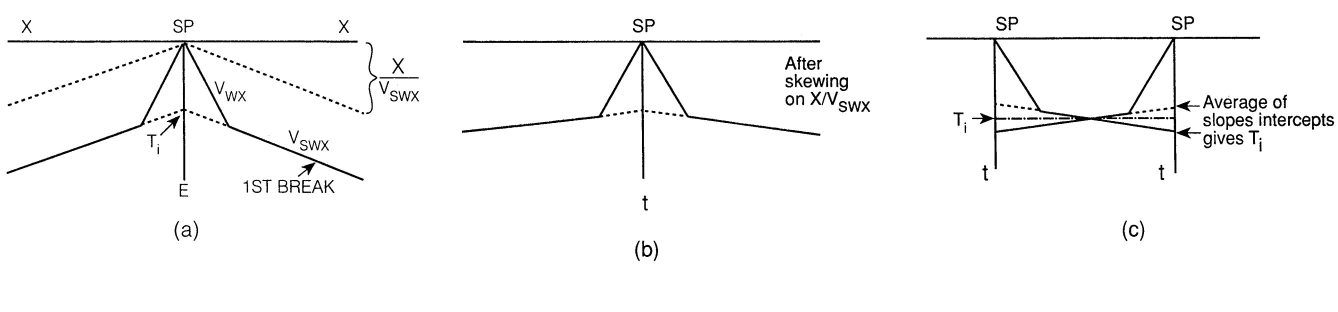


Figure 19. Determination of intercept time by the Farr technique, (a) first breaks are shifted according to X/V_{swx} which results in (b) first breaks being approximately horizontal. Deviations due to changing refractor velocity and poor field geometry are detected from these displays. If V_{swx} is not known, the intercept time is estimated as shown in (c). The static correction is computed from the intercept time (from Hollingshead and Slater).

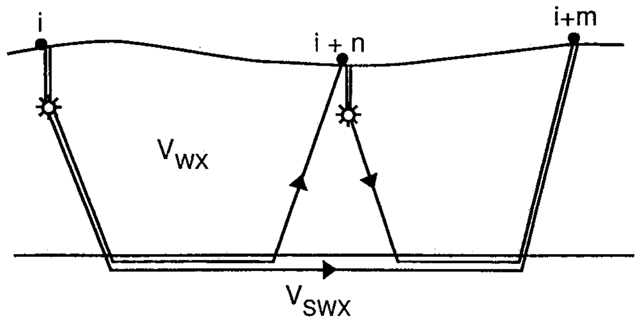


Figure 20. In the Chronos method, the delay time at position $i + n$ can be computed from picked traveltimes between i, $i + n$, and i + m. If dip is zero at position $i + n$ and if shot depth is zero, D_S is equal to geophone delay at position $i + n$.

$$T_{\mathrm{static}} = D_s \sqrt{\frac{V_{swx} - V_{wx}}{V_{swx} - V_{wx}}} + \frac{Z}{V_{swx}}$$

where Z is the elevation of the earth's surface above the datum plane (from Coppens).

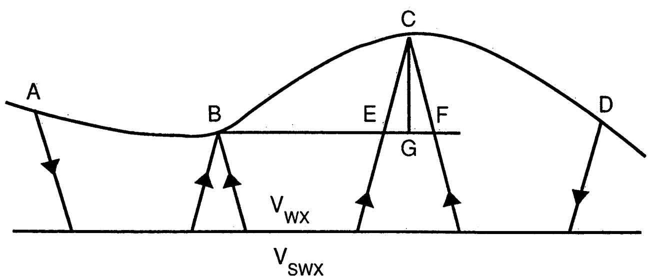


Figure **22.** ABCD method with the source-receiver configuration used to obtain data for static correction. The relative ABCD static correction between point B and point C is the traveltime from point G to point C. $T_{GC} \cong [(T_{AC} - T_{AB}) - (T_{BD} - T_{CD})]/2$ (from Bahorich).

Tomographic methods. Previous approaches to computing statistics used the first break information to derive a model of the near surface based on some theoretical assumptions such as horizontal surfaces or constant velocities. However, when such linear methods are applied at various discrete intervals along a line, one quickly appreciates that horizons are not flat and velocities are not constant. Another approach to the computation of statics is to assume a model, compute what the first breaks would be by ray tracing through the model, and then modify the model in order to minimize the differences between observed and modeled first breaks. Such is the tomographic approach.

D. Hampson and B. Russell called their version of this approach generalized linear inversion (First-break interpre*tation using generalized linear inversion, Journal of the* CSEG 1984), while K.B. Olson described an identical method which he called inverse modeling *(A stable and flexible procedure for the inverse modeling of seismic first arrivals, Geophysical Prospecting* 1989). W.N. De Amorin et al. used a one-layer model in a tomographic approach which they called numerical equivalent *(Computing field statics with the help of seismic tomography, Geophysical Prospecting* 1987).

Figure 23 shows the scheme used by both Hampson and

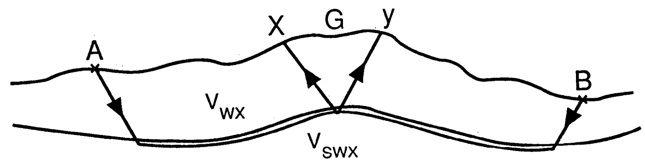


Figure 21. In the Generalized Reciprocal Method, receivers x and y are selected from the field data so that refracted waves from source positions A and B emit from the same point on the refractor (from Palmer).

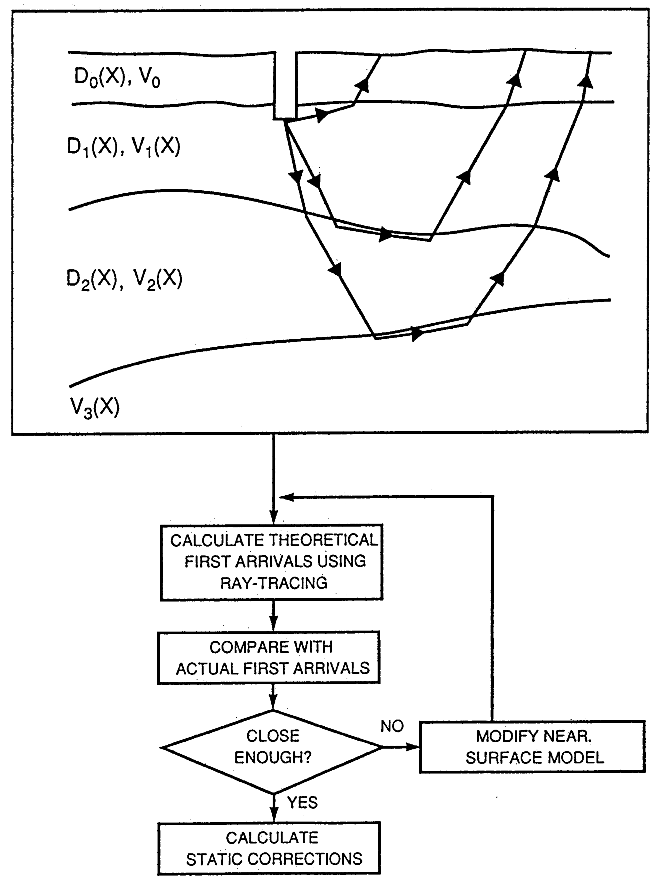


Figure 23. The generalized linear inversion method is a tomographic scheme which allows variations in the thickness of all layers except the first.

Russell and by Olson. The model allows for both bed thickness and horizontal velocity variations. The interpreter/processor must specify how many layers are in the near surface and estimate their thickness and velocity. The method is ideally suited to those areas where the near surface is restricted to two or three layers whose parameters vary over a predictable and limited range.

The numerical equivalent technique uses the concept of tomography to derive velocities to attribute to cells of width equal to the geophone group interval, bounded on the top by the topographic surface and on the bottom by a horizontal refractor at the base of the LVL (Figure 24).

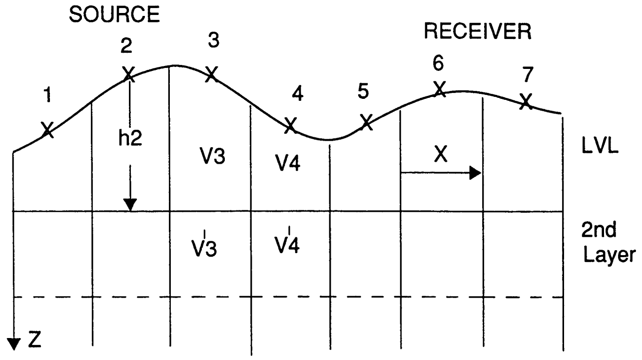


Figure 24. Model used by the numerical equivalent technique. Cell velocities are iteratively adjusted to minimize the square of the error between observed and computed first break traveltimes. Field statics are then computed from the model (from de Amorin et al.).

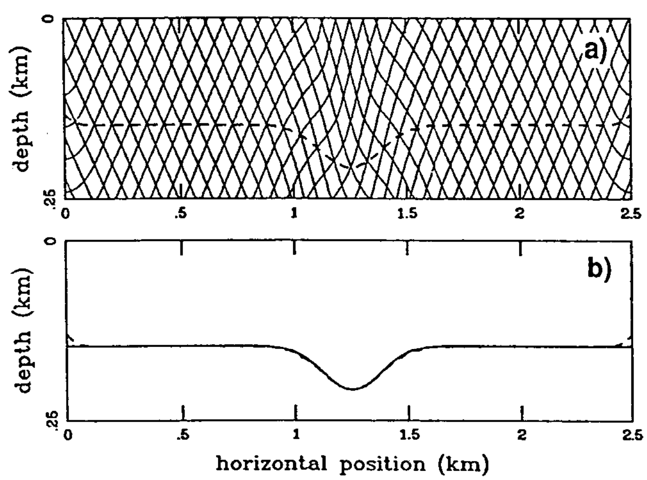


Figure 25. (a) Superposition of the two reconstructed wavefront systems. Dashed line is the locus satisfying the refractor imaging condition. (b) Comparisons of true (solid) and imaged (dashed) refracting interfaces (from Aldridge and Oldenburg).

The difference between the observed and computed first break traveltimes is minimized by iteratively adjusting the velocities. From this model, field statics are estimated. It should be noted that the base of the LVL is held fixed, and the velocities do not vary vertically, nor are there multiple layers-hence, the numerical equivalence. The authors claim that the technique, which requires no supplementary field acquisition procedures, produces acceptable static corrections with little interpretational effort.

Wavefront reconstruction methods. Another approach to determining the near-surface model is by imaging the data. Early wavefront reconstruction techniques determined the position of the refractor from the intersection points of wavefronts for forward and reverse shooting (see The plus-*minus method of interpreting seismic refraction sections* by J.G. Hagedoom, *Geophysical Prospecting* 1959).

In Downward continuation of refracted arrivals to determine shallow complex structure (SEG Expanded Abstracts, 1985), N.R. Hill described a method for imaging irregular refracting interfaces by the downward continuation of refracted arrivals where they constructively interface. Recently, Aldridge and Oldenburg *(Refractor imaging using an automated wavefront reconstruction method,* GEOPHYSICS 1992) have described a computerized version of Hagedoom's original approach (Figure 25).

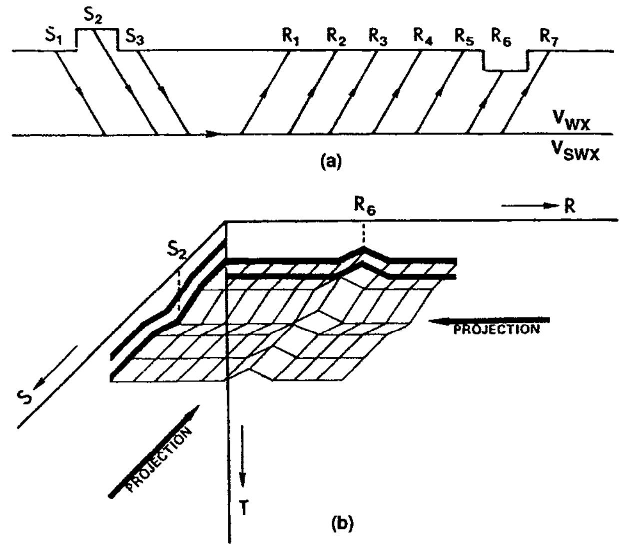


Figure 26. Time-term technique4 (a) Source and receiver statics model. (b) Grid of skewed (similar to the shift in the Farr technique) first arrival times showing projections for statistical averaging to obtain shot and receiver statics (from Chun and Jacewitz).

The time-term technique. In all of the previous techniques, the statics are derived according to some model of the subsurface. The time-term method of J.H. Chun and C.A. Jacewitz (in *The weathering statics problem and first arrival time surfaces, Abstracts for SEG 's 51st Annual Meeting* 1981) does not require that a model be generated. It derives the statics from a statistical analysis of the first breaks.

Referring to Figure 16, the total traveltime T_{jk} from shotj to receiver k can be thought of as

$$T_{jk} = S_j + R_k + X_{jk} / V_{swk}$$

where S_j is the shot static, R_k is the receiver static, X_{jk} is the shot-receiver separation, and V_{swx} is the refractor velocity.

Figure 26 illustrates how the time-term technique conceptually views the data. The problem is set up as a system of linear equations and solved by Gauss-Seidel iteration to provide a surface-consistent solution. The redundancy of CMP data leads to a number of estimates of S_j and R_k which statistically reduce any errors from the automatic picking of the first breaks.

Chun and Jacewitz actually measured the T_x of Figure 16 and applied a compensation factor, which is susceptible to variations in V_{wx}, to estimate T_i. The authors indicated how both vertical and lateral variations in V_{wx} could be accounted for. Displays from the method provided interpretive information to help the user recognize a number of situations which affect the linear technique such as changes in refractor elevation, high-velocity inclusions occurring in the low-velocity layer, and a variable refractor velocity.

Refraction statics summary. Refraction analysis of first breaks, for the derivation of a near-surface velocity model from which static corrections can be calculated, has progressed a long way from the original slope/intercept method. Most methods, though, produce almost identical statics solutions. The advantages of the more recent methods lie in their speed of application. For example, Amoco recently compared a slope/ intercept method with a tomographic method. The statics produced were almost identical. However, it took the geophysicist three days to obtain his statics using the slope/intercept method and only about three hours, on the same data set, using the tomographic software. So far, refraction analysis has taken place in the natural domain of the recorded data, the time-distance domain. Recently, though, Refraction sta*tics in the wavenumber domain* by L. Zanzi and A. Carlini (GEOPHYSICS 1991) demonstrated that if the computations are undertaken after Fourier transformation, then much time is saved without any reduction of accuracy. This reduction in computing time enables advantage to be taken of the redundancy inherent in CMP data to obtain a robust solution.

As a deterministic technique which aims to derive the near-surface velocity model, refraction statics suffers from an inability to detect velocity inversions (a low-velocity layer beneath a high-velocity layer, such as seen in Figure 10 in Part I) although some of the specific methods provide diagnostic material which implies the presence of an inversion. Another drawback is their inability to resolve thin beds (known as the hidden layer problem); and the interpretation of velocity increases with depth within a layer can be problematic with some implementations. The inability to deal correctly with velocity inversions can limit the technique's usefulness in areas with high-velocity rocks at or near the surface, but uphole velocity surveys can be the ideal way to supplement refraction data in such circumstances.

Many refraction techniques require time-distance measurements over the same interval in both directions to uniquely determine the velocity and dip of the refractor. In the split-spread technique, this is clearly not a problem. If acquisition is in the end-on roll-along mode, then using the redundancy of data in the CMP method together with reciprocity, both forward and reverse profiles can be constructed from single-ended profiles.

A common statics problem is misties between survey lines. This has serious consequences for the structural integrity of any interpretation made from the data because the interpreter cannot correct the misties in the absolute certainty that his corrections are right. When using deterministic methods, and refraction techniques in particular, it is necessary to ensure spatial consistency of the near-surface model throughout the survey area-before computing the static corrections-in order to avoid introducing misties.

Part III

Static corrections-a review

Residual statics. The application of elevation statics, or field statics, or field statics followed by refraction statics never leaves the seismic data completely free of static anomalies. These "residual" static anomalies are due to unaccounted for variations in the low velocity layer. No matter how well the deterministic technique may derive velocities and thicknesses of the near surface, it leaves something to be desired. There are two reasons for this:

- The model is a simplification of the geology resulting in a tradeoff between thicknesses and velocities which result in inexact static corrections.
- The static correction is an approximation for a more complex problem.

Residual static anomalies are compensated for by using statistical correlation techniques which seek to enhance the quality of the stacked traces by first correctly aligning the reflections.

Most residual statics techniques are surface consistent and are based on the concept that the times on each trace consist of a shot static, a receiver static, NMO, and residual NMO. In order to separate the various effects, the stacking diagram shown in Figure 27 is used to help classify the traces. All traces from the "common receiver plane" contain the same receiver static, all traces from the "common source plane" contain the same source static, etc. Different surface-consistent techniques vary in their approach to estimating shot and receiver statics.

Linear traveltime inversion. The first step in this method is to apply an approximate NM0 correction so that the reflection events in each gather can be considered to be misaligned due to a source static, a receiver static, and residual moveout. Next is to obtain a time shift for all traces in each CMP gather in order to optimize the stacked trace.

Time shifts are calculated by a cross-correlation of traces (Figure 28) either by computing all pair-wise cross-correlations and picking a consistent set of delays or shifting one trace at a time until the sum of the weighted semblances or cross correlations is maximized. The window for correlation has to be selected so that the window (1) covers a time zone where primary events are dominant, (2) is long enough to cover a number of primary events, and (3) is reasonably deep.

The calculated timeshifts (T_{ijk}) are related according to

$$T_{ijk} = R_i + S_j + G_k + M_k X^2_{ij}$$

where R is receiver static, i is receiver index, S is source static, j is source index, G_k is an arbitrary time shift for kth CDP

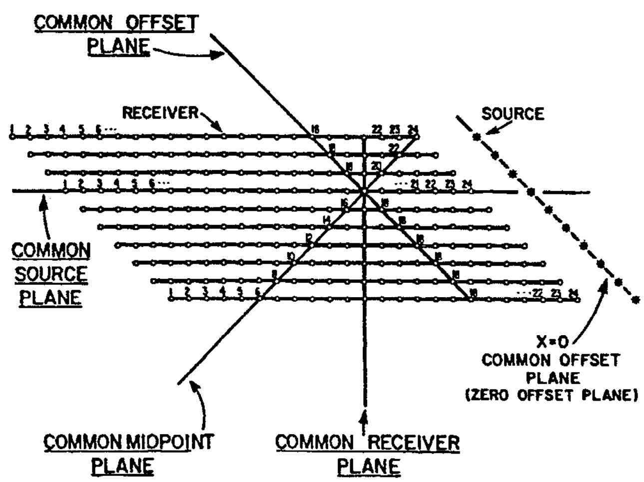


Figure 27. The four principal trace planes of the stacking diagram (from Taner et al. 1974).

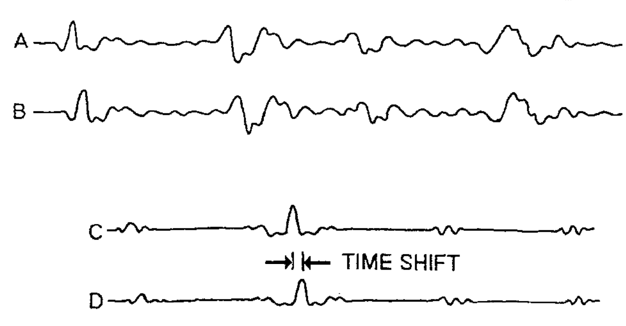


Figure 28. A and B are parts of two seismic traces showing a static shift between them. C is the autocorrelation of A and D is the cross-correlation of A with B. The time difference between the maxima on C and D is the measured time shift used to estimate the source and receiver statics.

This is the third and final part in a tutorial series on statics. Part I examined the variability of the near-surface velocity distribution and how it affects the seismic data. The types of data available, from which the near-surface velocity distribution may be determined, were considered as were datums, field statics and drift statics. Part II considered refraction statics. Part III deals with residual statics and with statics and velocity analysis. Some guidelines to the choice of method are also provided.

gather, M_k is the residual moveout at the kth CDP gather, and X_{ij} is the source-to-receiver distance.

This can be visualized in an analogous manner to Figure 26 (in Part II) for the time-term technique. The above expression gives rise to sets of simultaneous equations which have to be solved to obtain the statics for application to the data. However, it so happens that the sets of equations are overdetermined (i.e., there are more equations than unknowns) and underconstrained (i.e., there are more unknowns than there are independent equations). In Estimation *and correction of near-surface time anomalies* (GEOPHYSICS 1974), M.T. Taner et al. assume that the arbitrary time shifts G_k are zero (thus ensuring that the datum is not moved) in order to determine values for R and S. G. Saghy and A. Zelei, in *Advanced method for self-adaptive estimation of residual static corrections (Geophysical Prospecting* 1975), assume $G_k = 0$ and $M_k = 0$ but introduce limit values and weighting factors computed from the data itself. They introduce and employ an iterative process for estimating the time shifts. Wiggins et al., in their 1976 paper, use an iterative Gauss-Seidel approach to obtain a solution which results in $G_k \neq 0$, thus moving the datum in an unconstrained way.

Stack power maximization. In the linear traveltime inversion method, cross-correlation is a nonlinear operation susceptible to failure in the presence of ambiguities or noise. The ambiguities may be amplitude or phase distortions of the data due to intragroup static anomalies or variable source coupling for which Taner et al. offer a solution in *Static corrections.= Time, amplitude, and phase (SEG Expanded Abstracts,* 1991). The stack power maximization method described in *Surface-consistent residual static estimation by stack-power maximization,* J. Ronen and J.F. Claerbout (GEOPHYSICS 1985), rather than relying on the picking of a cross-correlation maxima as the most likely criterion for determining the static, hypothesizes that static shifts should be determined so that the sum of the squares of the final stack is maximized. The procedure is shown diagrammatically in Figure 29 and is explained as follows:

A supertrace is built from all the traces of the shot profile in sequence (trace F in Figure 29) which is then cross-correlated with another supertrace of all the traces in the relevant part of the stack, in sequence, without the contribution of that shot (trace G in Figure 29).

The maximum of that cross-correlation is then picked and the stack corrected, the process being repeated for each shot.

A supertrace is then similarly built from all traces in the receiver profile, in sequence, which is then cross-correlated with another supertrace of all the traces in the relevant part of the stack, in sequence, without the contribution of that receiver.

The maximum of that cross-correlation is then picked and the stack corrected, the process being repeated for every receiver.

An optional constraining routine may be included in the procedure to remove linear trends and glitches from the estimated statics.

Nonlinear inversion. In the linear traveltime inversion techniques, the residual static is estimated by linear inversion of observed traveltime deviations, a process which involves minimizing an error function. A crucial component of the approach is to pick the delay times accurately. Gross errors in picking the traveltimes are known as "cycle skipping" or

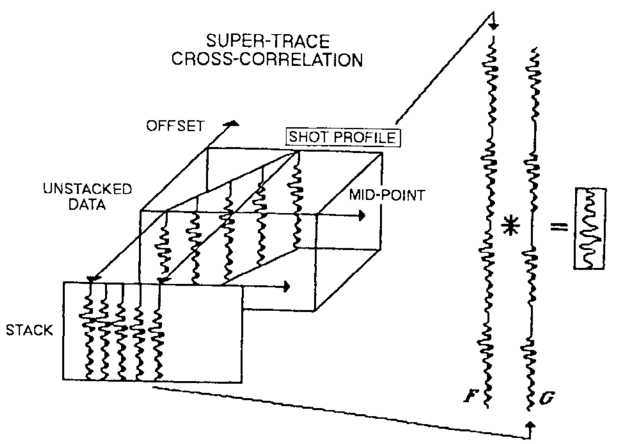


Figure 29. Supertrace cross-correlation as used in the stack-power maximization technique. The plane containing the shot profile in the unstacked data volume is moving up or down according to the static shift of the shot. The CMP stack is changing as a function of that static shift. Maximizing the power of the CMP stack as a function of that particular shot static is equivalent to maximizing the cross-correlation between two supertraces built from the shot profile (trace F) and the relevant part of the CMP stack (trace G). The procedure is repeated for every shot and geophone. Convergence is usually achieved within 5-20 iterations (from Ronen and Claerbout).

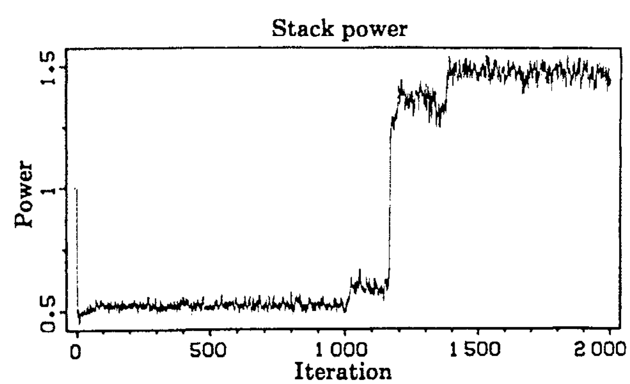


Figure 30. In the simulated annealing technique, the stack power, over a selected window of the trace, is normalized with respect to the input stack and plotted as a function of iteration. Static corrections are selected from probability distributions for the data and applied according to certain rules. It is seen that the power initially decreases very quickly, but convergence towards the solution starts to occur, in this example, at about the 1000th iteration. Each step in the function is equivalent to the method finding a local maximum while it continues to search the model space (of static corrections) for the global maximum (from Rothman).

"leg jumping" and occur through a lack of adequate data conditioning either when excessive noise is present or when the choice of maximum on the cross-correlation function is obscure. This cycle skipping causes the minimization process of the linear inversion to result in a local rather than the desired global minimum. In *Nonlinear inversion, statistical mechanics and residual statics estimation (GEOPHYSICS* 1985), D.H. Rothman showed that the estimation of large statics in noise contaminated data is better handled as a nonlinear inversion problem, at which time cycle skips appear as secondary minima.

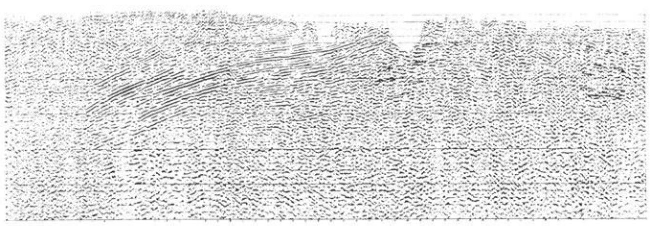
In Rothman's technique (see *Automatic estimation of large residual static corrrections*, GEOPHYSICS 1986), explicit cross-correlation of traces is determined and then, instead of picking the peaks of these functions, the method transforms them into probability distributions. A simulated annealing algorithm is then used which is in turn based on a Monte Carlo technique in which random numbers are drawn from the created probability distribution and used to iteratively update estimates of the statics until convergence to the optimal stack is achieved. The stack power described by Ronen and Claerbout (GEOPHYSICS 1985) is used as the criterion for determining the quality of the solution and a plot of stack power against iteration is used as a method of visualizing when the process has gone far enough. The. best quality solution occurs when the stack power is maximized (Figure 30).

Subsurface consistent. If the residual statics anomalies are of short enough spatial wavelength to be contained within a gather, then subsurface consistent statics (also known as trim, correlation, and CDP consistent) can be derived and applied. The method makes no attempt to apportion a time shift between source and receiver and needs to be used wisely.

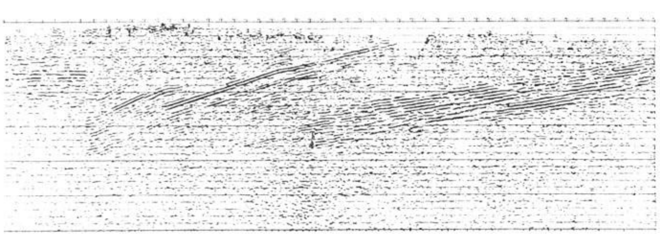
Subsurface consistent statics is a CMP process in which a model trace is built for every CMP, usually by summing together 5 or 7 stacked traces. All of the traces within the CMP are then correlated with the model trace. The traveltime difference between the model trace and all of the traces within the CMP is determined by the cross-correlation method. These time differences, when applied to the traces within the CMP, provide an optimum alignment of reflection events within the CMP for stacking purposes.

This technique should be used judiciously to remove any remaining static anomalies of very short spatial wavelength or to remove residual moveout from observed reflections for the purpose of enhancing the visual quality of the stack. It is relatively easy to abuse this technique, as illustrated in Figure *31* where a number of false reflections have been generated out of noise.

Residual statics summary. The main advantages of residual techniques are that they are automated and that supplementary information such as that provided by LVL surveys is not required. However, there are drawbacks due to the nonuniqueness of the solution. The most serious of the disadvantages is that these techniques are not capable of correcting long spatial wavelength static anomalies (anomalies of wave-



(a)



(b)

Figure 31. Surface-consistent statics applied (top). The same line (below) with nonsurface-consistent or subsurface-consistent statics applied. Note flat-lying reflectors on the west end and strongly dipping reflectors on the eastern half of the line where there were none before.

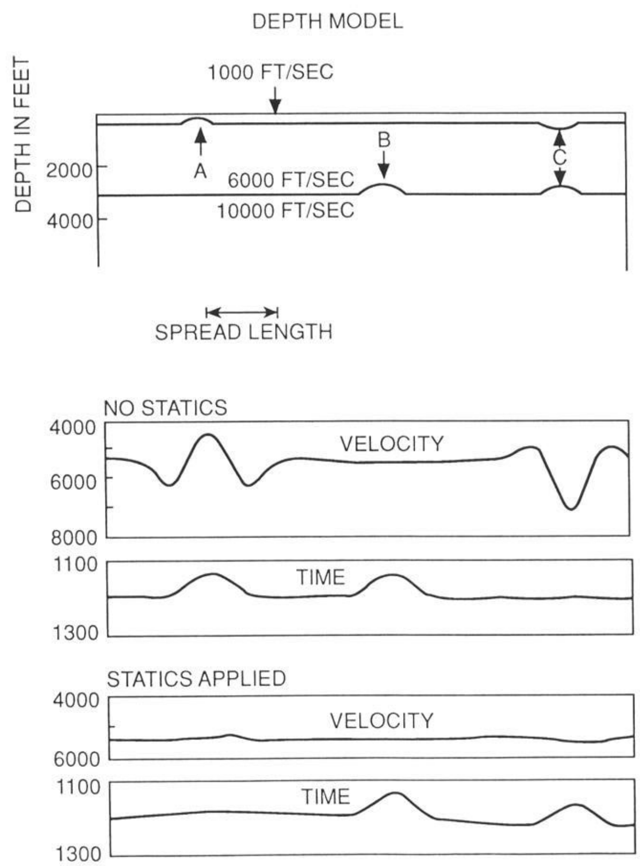


Figure 32. A.H. Booker et al. showed (in Long wavelength static estimation. GEOPHYSICS 1976) that the effects of long period statics and structure can he distinguished on the basis of the stacking velocity in the residual statics technique. Comparison of the central and lower parts of the figure demonstrate why proper static corrections are important to velocity analysis, particularly if the velocities are to he used for anything other than stacking the data.

length longer than a spread length) as illustrated in Figure 14 (in Part II). The presence of these static anomalies can be differentiated from genuine structures on the basis of the behavior of the stacking velocities which fluctuate wildly due to the presence of the static anomaly but may not change perceptibly in the presence of a structure as seen in Figure 32.

The nonuniqueness may also result in an effect known as decoupling which produces a sawtooth effect in the data (Figure 33) and is a failure of the method to detect and correct short wavelength anomalies (static anomalies whose spatial wavelength is less than the shot point interval). In their 1976 article, Wiggins et al. explain the origin of the phenomenon and show that decoupling occurs whenever every nth receiver location is occupied by a source (n being greater than 1). If shooting every group is impractical or too expensive, then by varying the sequence of shots, the system of simultaneous equations which has to be solved may be coupled; for example, if shooting every other group, it is only necessary to ensure that two shots occur on adjacent groups somewhere along the line. In 3-D acquisition, P.W. Johnson patented (1987) a novel field geometry to ensure that the problem of decoupling would not arise. When the problem is discovered in previously acquired data, many approaches are possible but probably the best way is to compute surface consistent receiver statics from the two or more decoupled systems of equations and then a single surface consistent receiver static profile is computed for the line as a running average of the various decoupled solutions.

Another problem is that serious static errors can appear in the data as faults and, in such cases, if the errors are greater than half the length of the seismic wavelet, "cycle skipping" or "leg jumping" occur; i.e., the correlation is made with the wrong cycle when residual static corrections are applied. This results in the data containing traces that are misaligned by a whole cycle of the seismic wavelet. This can be dealt with in a number of ways: (1) revise the earlier static solution, (2) low band-pass filter the data prior to residual statics, and (3) use one of the techniques not susceptible to the problem.

Yet another problem is that there is no way of ensuring with certainty that the residual technique will not introduce mis-ties into a data set, although this risk can be minimized if the data are preconditioned by scaling, filtering, etc. and if the residual static anomalies are small.

Finally, subsurface consistent statics can be misused to create coherent events and manufacture structural anomalies within the time gates used for correlation. The smaller these time gates, the more likely it is that an event will be created by aligning waveforms on the traces within a CDP. Multiple passes through the process, even with statics limited to ±4 ms on each pass, will exacerbate the process.

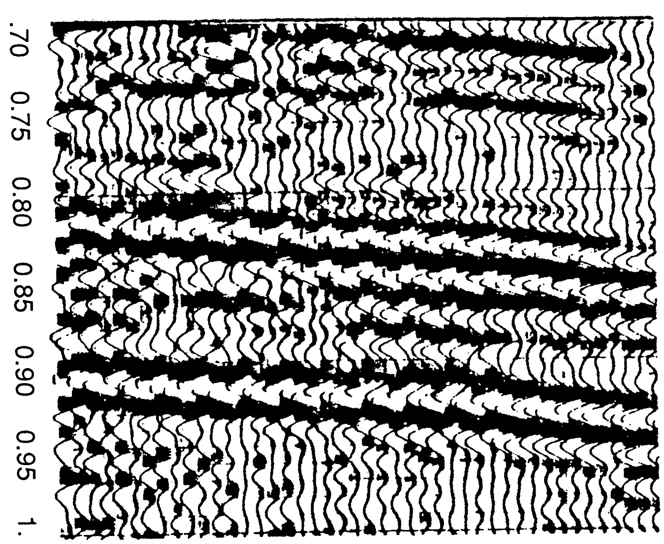


Figure 33. Effect of decoupling on data quality.

Statics and velocity analysis. The processes of static correction and velocity analysis are inextricably linked and what ought to be a single nonlinear process is treated as a set of

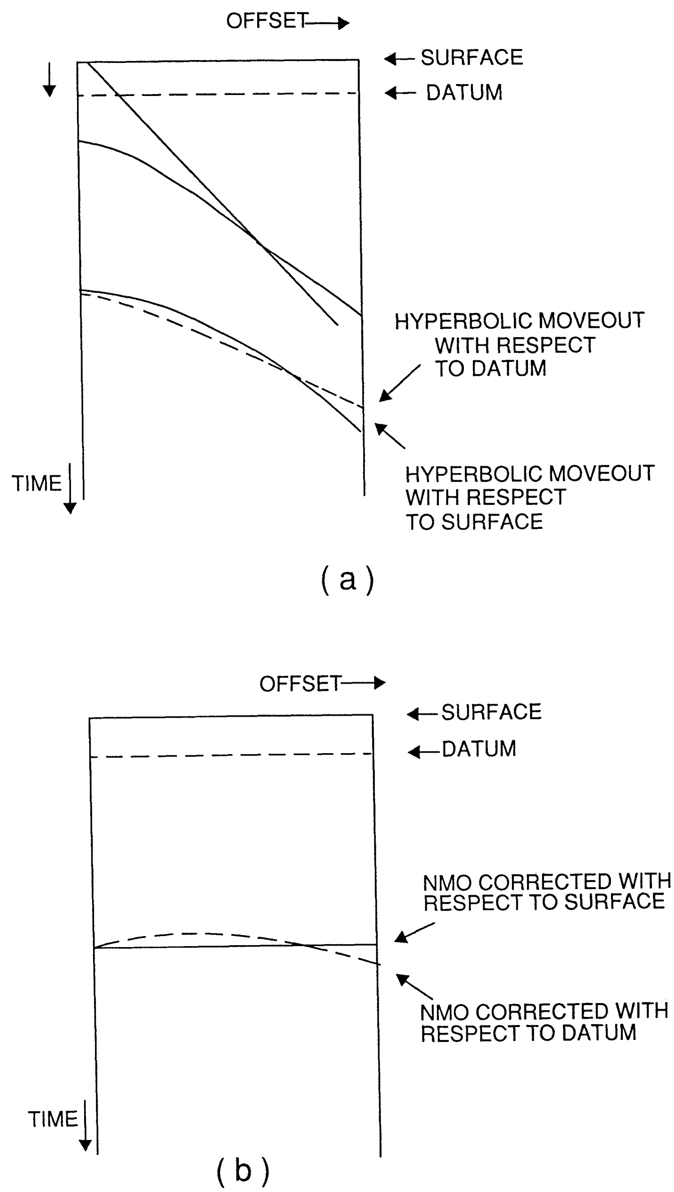


Figure 34. (a) Schematic gather before NM0 showing hyperbolic moveout curves with respect to the surface and the datum. (b) The same gather after NM0 correction showing the residual moveout which occurs when a large static shift is applied before the correction.

linear processes in an iterative manner.

The concept of stacking velocity analysis (the most common form of velocity analysis applied to seismic data) is based upon a horizontally layered earth where the NM0 can be approximated by a hyperbola. Any deviations of the topography or base of the LVL from horizontal and any variations in weathering and subweathering velocities will cause the NM0 to deviate from near hyperbolic. Erratic deviations in the moveout, due to variations of short spatial wavelength, cause the criteria by which the correctness of the velocities is judged to perform badly, thus making velocity picking (which is still an interpretive process) difficult. Longer wavelength static anomalies can have dramatic effects on the values of the velocities, as illustrated earlier in Figure 32. It is for these reasons that static corrections are applied before NM0 velocity analyses. It should be noted that static anomalies whose spatial wavelength is greater than a spread length are far less disruptive in terms of velocity analysis. Only if the anomaly ends abruptly do velocities behave as in Figure 32.

The datum of our seismic field data is the topographic surface, and it is to this surface that the NM0 correction and stacking velocity must be referenced. It can be demonstrated that application of a large static correction before the NM0 correction results in a moveout curve which deviates from the desired hyperbolic moveout curve. As shown in Figure 34, this deviation of the moveout curve is not the erratic deviation due to topography or the LVL but a systematic deviation due to a shift in the origin of the hyperbola's coordinate system. The curve is no longer hyperbolic with respect to the translated origin, even though it is still a smooth curve, and fitting hyperbolic moveout results in the familiar "gull's wing" residual moveout. The stacking velocities obtained by conventional velocity analysis deviate greatly from the root mean square velocities of the earth model which they are assumed to approximate, particularly in the shallow section, although the discrepancy between the two sets of values decreases with depth. In order to keep the residual moveout as small as possible (for residual moveout acts as a high cut filter on the data in the same way that statics do), it is necessary to keep the static corrections as small as possible before the NM0 correction and stack. This is the main justification for processing the data with the floating datum described previously,

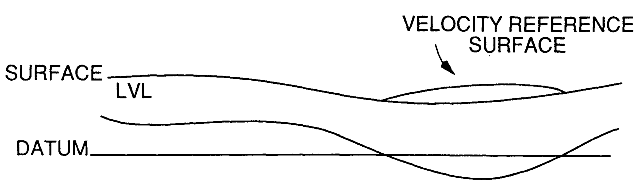


Figure 35. When the larger part of the static corrections are applied after velocity analysis, the processed seismic data will be referenced to the datum plane; the velocity functions will be referenced to the topography when the base of the LVL is above the datum plane, and to a separate reference surface (controlled by the statics) when the base of the LVL is below the datum plane. These different reference surfaces have to be taken into account when using seismically derived velocities for depth conversion,

which keeps the larger part of the elevation static separate for application after stack.

In the same way that the elevation static is split into small and large components, so shot and receiver weathering statics are often separated into two components for the same reason-the effect on the velocity analysis of shifting the origin. The large component of the weathering static is twice the mean of the shot and receiver statics at a particular location, and this is applied after the velocity analysis, often after stack, while deviations from the mean of the shot and receiver statics at a particular surface location are applied before velocity analysis.

As a result of applying the larger part of the static corrections after stack, the stacking velocities and seismic data have different reference surfaces and this difference, illustrated in Figure 35, must be taken into account if the stacking velocities are to be used for any other purpose, particularly depth conversion. The situation is exacerbated if the statics take into account low velocity section from below the reference datum.

Every time a set of static corrections is computed and applied to the data, the origin of the data (i.e., zero time) is moved for velocity analysis purposes and so for those techniques where analysis takes place after the application of an NM0 correction, it becomes necessary to reanalyze the velocities with every iteration. This reanalysis may well happen anyway since, in processing, the efficacy of a process or parameter change is judged by the effect it has on the quality of the stacked (or final) section. Thus, we see that the whole iteration process of static corrections and velocity analyses becomes an interpretational process in which the geophysicist must be involved since optimization of the data quality depends on its ultimate purpose.

Choice of techniques. While the concept of static corrections is simple enough, there are many interrelated complexities to be taken into account. In addition, there is a bewildering array of different methods which can be employed. So where does one start? At the planning stage.

It is no use waiting until the data are acquired, the tapes are at the processing center, and the crew demobilized before thinking about static corrections. Existing data may indicate the types of static problems that could be encountered; topographic maps or aerial photographs may give a clue-rock outcrops, alluvial valley, swamp, etc. If feasible, the area should be scouted. The availability of, or choice of, crew may determine the data types one can obtain and the statics techniques to be used. Consideration also has to be given to the software available for processing.

There are some general guidelines, however, to help the final selection. We have seen that the better the field statics, then the better conditioned the data will be for the next stage. In some circumstances, the statics from an LVL survey followed by residual statics may well be acceptable. Or, no LVL crew may be available so one may have to settle for field statics being no more than elevation statics, leaving the question "what next?" wide open.

Figure 36 (from F. Coppens' 1985 paper cited in Part II) shows that a deterministic approach (refraction statics) followed by a statistical approach (residual statics) produced the best result. This, however, does not mean that examples cannot be found where residual statics on their own produced the best result. The general conclusion is not surprising since we saw that the strength of the refraction based methods was an ability to correct static anomalies of spatial wavelength greater than a spread length (thus ensuring structural integrity). We see in Figure 36 that after the refraction statics, the section is still noisy; this is typical and is due to residual anomalies left by imperfections in the model.

We also saw that the strength of the surface consistent residual techniques lay in statistically adjusting the shorter wavelength anomalies which manifest themselves over a number of gathers and that the subsurface consistent techniques provide a cosmetic finish, taking care of the shortest wavelength anomalies remaining in the individual gathers after the other techniques had been applied. Figure 36 shows how much improved the data are when refraction statics are followed by residual statics. This approach should ensure the structural integrity of the data, enable the data set to be processed with no internal misties, and optimize the image quality for stratigraphic information.

Beyond conventional statics. Conventional static corrections are part of a continuum of corrections, really dynamic in nature, stretching from spatial wavelengths of less than a geophone group length to those whose wavelength is several spreadlengths and which range in magnitude from a fraction of a millisecond upwards in magnitude. As we encounter static anomalies at the extremes of the continuums, new problems are encountered which conventional static corrections do not or cannot handle well or because the static anomalies manifest themselves in other ways.

Static anomalies whose spatial wavelengths are less than that of the geophone group length are generated in the top 10 ft or so of the earth's surface. The resulting intragroup statics cause variations in the amplitude and phase of the seismic data from trace to trace in the field records. In his 1991 article, Taner suggests how variations in the amplitude and phase of the data can be treated in ways similar to the way he treats

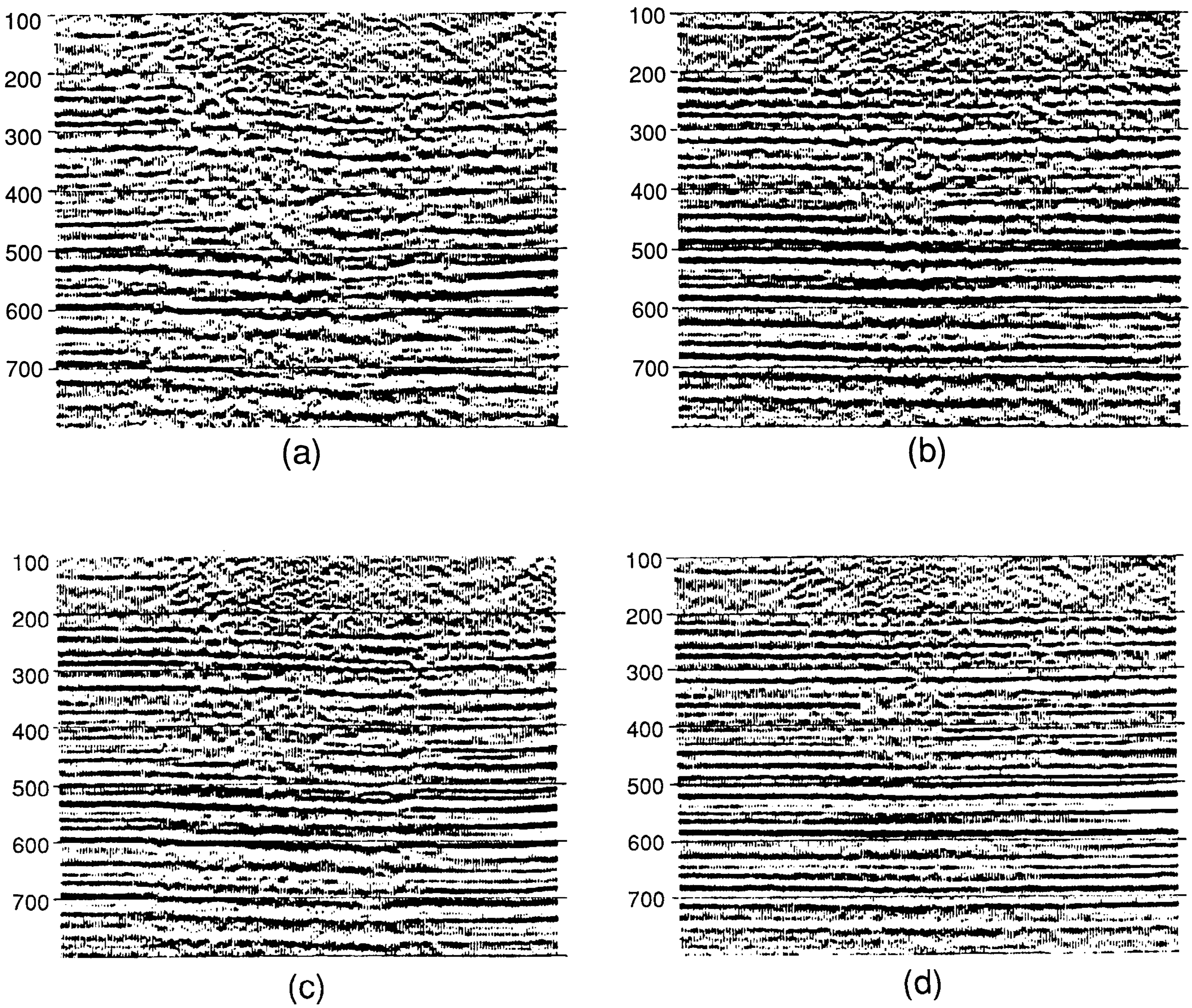


Figure 36. (a) Seismic line with only elevation statics applied. (b) Same line with elevation and refraction statics, (c) with elevation and residual statics, and (d) with elevation, refraction, and residual statics (from Coppens).

residual statics. Such an approach may not restore the attenuated high frequencies (Figure 6) which at the moment are best captured by single geophone (rather than extended array) recording. Such a solution poses new problems, however.

The 1979 paper by Ziolkowski and Lawill, cited in Part I, showed that the termination of a thin high velocity bed within the low velocity layer (which is equivalent to a very small static time correction) gave rise to an apparent phase change in the seismic data (which they explained as being due to trapped reverberations). Whatever the cause, if such phase changes occur on an intragroup basis, they will give rise to even more variability in the phase and amplitude of the signal than that caused by intragroup statics alone. When such phase changes occur spasmodically in seismic data, they are often considered to be, and treated as, a residual statics problem and are compensated for by a time shift rather than phase rotation of the data.

In the marine environment, rugged seafloor topography will induce effects in the seismic data not unlike severe statics. J.A. Berryhill, in *Submarine canyons: Velocity replacement by wave equation datuming before stack*, and O.Yilmaz and D. Lucas, in *Prestack layer replacement (wave-equation da-*turning)--both in GEOPHYSICS 1986-use prestack layer replacement and wave equation datuming (downward continuation of the wavefield) to correct the data.

A similar approach was used by C. Beasley and W. Lynn in The zero-veloc*ity layer: Migration from irregular surfaces (SEG Expanded Abstracts, 1989)* to do prestack depth migration from a datum above all topography and infilling with a zero velocity layer, to image data from extremely rugged topography where conventional statics and processing fail. Such an approach, however, needs a more detailed velocity field than is usually available in areas of complex shwture which are usually associated with rugged topography.

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