

Description

This invention relates to a method for determining subsurface structure using vertical seismic profiling (VSP).

VSP is a measurement procedure in which a seismic source on or near the the earth's surface transmits energy to a geophone secured at a desired depth to the wall of a borehole. This type of seismic recording differs from ordinary surface seismic reflection shooting primarily in the manner in which the geophones are positioned. In common midpoint shooting performed on land or in the sea, receivers are distributed laterally on the surface of the earth along the direction of profile. In VSP, geophones are positioned vertically to depths of sometimes several thousand feet and no receivers are generally positioned on the surface. Thus, the direction of geophone deployment differs by 90° degrees in the two types of seismic recording.

In VSP, the seismic source is generally located as close to the borehole as possible. The idea is to send energy vertically downwards to reflecting interfaces so that the reflected energy will return vertically upwards to the borehole geophone located in the well. Data shot in this manner can be utilized to correlate sonic log data with conventional surface seismic data shot in the area of the well. However, this type of data has very little use in determining subsurface structure at any distance from the well since the energy travels substantially vertically.

The GB—A— 15 69 581 discloses a method of processing seismic signals in which both direct and reflected seismic signals are detected by a borehole geophone. The downgoing signal is used to deconvolute the upcoming signal and a system of stacking borehole signals by common depth-point is employed.

The conference contribution "Determination of subsurface structural information using the vertical seismic profile" by K. Dautenhahn Wyatt and S. B. Wyatt, SEG Convention, 1981, pp. 1915—1949 describes the results of a common depth point stacking procedure, in which reflection event times on VSP traces are correlated with the corresponding reflection point locations in the subsurface.

There are a number of advantages in using VSP to determine subsurface structure. Since the receivers are buried within the earth rather than on the surface, the receivers are less affected by distortion and noise which are generally present in surface seismic data. Also, since the receivers are so close to the reflectors of interest, the receivers have a greater ability to resolve the structure in the immediate vicinity of the borehole.

It is thus an object of this invention to provide a method for determining subsurface structure using VSP.

In accordance with the present invention, a method for stacking vertical seismic profiling data traces is provided as defined in claim 1. VSP is conducted by locating the seismic source at a substantial distance from the well. Seismic data thus obtained is then transformed into seismic data which has the appearance of seismic data which would be obtained using conventional seismic exploration techniques which employ surface receivers (referred to hereinafter as "surface seismic data"). The surface seismic data can be interpreted by standard techniques to determine subsurface structure with, in some cases, more precision than could be obtained using only the conventional surface seismic data obtained using surface receivers.

The basic steps performed in making the transformation from VSP seismic data to surface seismic data are as follows:

1. Select a VSP data trace from the VSP seismic data.
2. Map a segment of the selected VSP data trace at its VSP time into a segment of surface seismic data at its appropriate surface seismic time and lateral offset from the borehold. Since the surface seismic data is a plot of surface seismic time as a function of distance from the borehole, the mapping may also be considered as mapping segments of VSP data into the correct location on such a slot.
3. Repeat steps 1—2 for all desired VSP data traces.
4. Sum samples which accumulate at the same surface seismic data time and at the same distance from the borehold on the surface seismic data being produced from the VSP seismic data.

The term "moveout" is a well recognized term in the art of exploration geophysics. The term generally refers to the difference in arrival time of waves at different geophone positions even though the waves were reflected from the same point on a reflector. To stack the data for a common point on the reflector in order to enhance the subsurface structure information, it is necessary to apply what is referred to as a moveout correction. For surface seismic data this is typically accomplished by correlating all arrival times to the time which would be required for a wave to travel from a source, located directly above the reflection point, to the reflector and back to a receiver located directly above the reflection point.

The same problem is present in transforming VSP seismic data to surface seismic data. The waves received by various geophones may be from the same reflection point and thus the output from the geophones should be stacked. However, the waves will again have different arrival times and it has not been known in the past how a correction could be applied to VSP seismic data such that stacking could be performed. The procedure used in the present invention is a mapping of a segment of a VSP data trace into a segment of surface seismic data to place the data in a form that can be stacked to produce surface seismic data from VSP seismic data.

Other objects and advantages of the invention will be apparent from the foregoing brief description of

the invention and the claims as well as the detailed description of the drawings which are briefly described as follows:

FIGURE 1 is a typical field geometry for the acquisition of the VSP seismic data;

FIGURE 2 is an illustration of actual VSP seismic data;

FIGURES 3, 4 and 5 are geometric illustrations utilized to derive the equations required to transform VSP seismic data into surface seismic data;

FIGURE 6 is an illustration of a synthetic VSP response;

FIGURE 7 is an illustration of surface seismic data obtained by transforming the synthetic VSP response illustrated in FIGURE 6 in accordance with the present invention;

FIGURES 8 and 9 are illustrations of applying the transformation technique of the present invention to single VSP data traces in the synthetic VSP response illustrated in FIGURE 6; and

FIGURES 10 and 11 are geometric representations utilized to derive the equations required for applying the transformation of the present invention where dipping reflectors are present.

Referring now to FIGURE 1, there is illustrated a typical VSP configuration. The Vibroseis® source 11 is illustrated as imparting energy into the earth. It is noted that any other suitable seismic source such as explosives could be utilized if desired.

A geophone 12 is shown located at a desired depth in the borehole 14. For the location of the geophone 12, energy would be reflected from the subsurface strata 15 at point 16. The output produced from geophone 12 is recorded by the recording truck 17.

In VSP, the geophone 12 would typically be moved to a new location for each shot with the distance between geophone locations being some constant distance such as 15 m (50 feet). If desired, a string of geophones spaced apart by some desired distance could be utilized or a plurality of sources spaced apart could be used.

The offset of the source 11 from the well 14 is one of the most critical parameters to be selected if the VSP data is to be used to determine the subsurface structure. In general, the amount of subsurface imaged increases with source offset. For the simple case of a single horizontal interface, the interface is imaged out to 152 m (500 feet) for a source offset of 305 m (1000 feet). For an offset of 152 m (500 feet), only 76.2 m (250 feet) of the interface is imaged. Some structural features quite near the well may not be imaged at all if the source offset is too small. On the other hand, if the offset is too large, there may be a problem of deterioration of the VSP data due to compressional-to-shear mode conversions. A source offset in the range of about 91 m (300 feet) to about 915 m (3000 feet) is generally preferred.

The source should be placed so that the subsurface reflection points lie, in general, in the plane containing the borehole and the source location. For example, if there is general subsurface dip, the source should be offset along the dip direction rather than along the strike direction in order to avoid out-of-profile reflections.

The proper source location will also depend on the specific subsurface structure to be imaged. A much broader region of the subsurface is imaged if the source is placed updip rather than downdip.

In general, the number of reflection points along an interface is equal to the number of borehole geophone stations above it. The stacking fold in the data transformation of the present invention depends on the density of reflection points. The stacking fold can therefore be controlled by changing the geophone station spacing. If the spacing is decreased the stacking fold is increased and, conversely, if the spacing is increased the fold decreases. The geophone spacing also influences aliasing in the VSP data. The preferred geophone spacing is in the range of about 7.6 m (25 feet) to about 30.5 m (100 feet).

Data obtained by VSP has the appearance of that illustrated in FIGURE 2. The data illustrated in FIGURE 2 was obtained using a Vibroseis® source located 1000 feet from the well. The Vibroseis® source provided a 14 second sweep from 10 to 80 hz. The borehole geophone was located at stations every 15 m (50 feet) between depths of 366 m (1200 feet) and 3400 m (11,150 feet).

It is very difficult to determine subsurface structure from the VSP data illustrated in FIGURE 2 because the data is not stacked and is not in the format generally worked with by exploration geophysicists who are typically knowledgeable in interpreting surface seismic data. The following mapping and stacking procedure is utilized to convert the VSP data illustrated in FIGURE 2 to surface seismic data which has the appearance of conventional seismic data obtained using surface geophones and which can be more easily interpreted with respect to determining subsurface structure because the data is stacked and because the data is in a more conventional form. FIGURES 3, 4 and 5 will be utilized to illustrate the manner in which this conversion can be achieved.

Referring now to FIGURE 3, three rays 21—23 are shown propagating from the source at offset X from the well down to a horizontal interface at a depth h and back up to the three borehole geophone stations 26—28. For the geophone 28, the signal recorded comes from a reflection point on the interface at a distance X/2 from the well. For the geophone 26, the signal received is from a reflection point which is considered essentially 0 distance from the well. For intermediate borehole geophone stations such as the station of geophone 27, the reflection points on the interface fall between distances of 0 and X/2 from the well.

For the configuration illustrated in FIGURE 3, a number of locations could be located on the interface between 0 and X/2 which are referred to hereinafter as vertical seismic profile common depth points (VSPCDP). The number of VSPCDP locations is arbitrary as are their mutual distance from each other. For

simplicity, a constant separation of 6.1 m (20 feet) will be assumed between adjacent VSPCDP locations. For any one of the VSPCDP locations such as the location 55 m (180 feet) from the well, those pieces of the recorded VSP data which correspond to signals which had reflection points lying on the interface at depth h between 52 m (170 feet) and 58 m (190 feet) from the well (within half the VSPCDP spacing to either side of the VSPCDP location at 55 m (180 feet) from the well) can be picked out. The times at which these pieces appear on their respective VSP traces (VSP time) can all be mapped into the two-way vertical travel time for this particular interface at depth h (surface seismic time). Once the proper mapping has been applied to the pieces, the pieces can be stacked together. The result is placed on a VSPCDP stack trace associated with the VSPCDP location at 55 m (180 feet) from the well and at a time equal to the two-way vertical travel time to the reflector at depth h (surface seismic time for that reflector). Again, the stacking is made possible by the fact that the number of reflection points will be greater than the number of VSPCDP locations. As an example, for a source at offset 305 m (1000 feet), an interface at a depth of 1525 m (5000 feet) and a distance of 15 m (50 feet) between adjacent borehole geophone locations, there will be more than 100 reflection points along the interface from the well out to a distance of 152 m (5000 feet) in the direction of the source. However, for the assumed 6 m (20 foot) spacing, there will be only 25 VSPCDP locations.

FIGURE 4 shows the VSP reflection geometry for the case of a horizontal layer located at a depth h . A downgoing straight ray 31 extends from the source at offset x to a reflection point at depth h and lateral distance q from the borehole 33. The pathlength along this straight ray is L . The upgoing reflected ray passes through the borehole geophone 34 located at depth d and strikes the surface at lateral distance p . Simple geometry gives the equation

$$(1) \quad L^2 = h^2 + \left(\frac{x+p}{2} \right)^2$$

If $T_{o,r}$ is defined as the surface seismic time or two-way vertical traveltime from the surface to the reflection point, $V(T_{o,r})$ is defined as the average velocity from the surface down to the reflection point and t_r is defined as the two-way traveltime along the straight raypath 31 shown in FIGURE 4, then

$$(2) \quad L = \frac{t_r V(T_{o,r})}{2}$$

and

$$(3) \quad h = \frac{T_{o,r} V(T_{o,r})}{2}$$

Substituting equations (2) and (3) into equation (1) and rearranging gives the familiar hyperbolic moveout equation,

$$(4) \quad t_r^2 = T_{o,r}^2 + \left(\frac{x+p}{V(T_{o,r})} \right)^2$$

Similar triangles give

$$(5) \quad \frac{p}{d} = \frac{x+p}{T_{o,r} V(T_{o,r})}$$

Equation 5 can be rearranged to give

$$(6) \quad p = \frac{xd}{T_{o,r} V(T_{o,r}) - d}$$

Substituting equation (6) into equation (4) and taking the square root gives

$$(7) \quad t_r = T_{o,r} \left[1 + \left(\frac{x}{T_{o,r} V(T_{o,r}) - d} \right)^2 \right]^{\frac{1}{2}}$$

which is the total traveltime from the source to the reflection point and back up to the surface along the straight raypath 31 shown. The VSP reflection event time (t_{vsp}) which is generally referred to herein as VSP time will be the difference between t_r and the traveltime from the borehole geophone location up to the surface along the raypath 31.

In FIGURE 5, a straight raypath 36, which could correspond to a reflection if a source were at lateral distance p from the well and if there were a horizontal interface at the depth d , is illustrated. The pathlength along the upgoing part of the raypath is 1. The traveltime along this upgoing portion is the time we need to subtract from t_r to get t_{vsp} .

Simple geometry gives the equation

$$(8) \quad \ell^2 = d^2 + p^2$$

If $T_{o,d}$ is defined as the two-way vertical traveltime from the surface to the geophone depth (d), $V(T_{o,d})$ is defined as the average velocity from the surface down to the borehole geophone 34 location, and t_d is defined as the two-way traveltime along the raypath 36, then

$$(9) \quad \ell = \frac{t_d V(T_{o,d})}{2}$$

and

$$(10) \quad d = \frac{T_{o,d} V(T_{o,d})}{2}$$

Substituting equations (9) and (10) into equation (8) gives

$$(11) \quad t_d^2 = T_{o,d}^2 + \left(\frac{2p}{V(T_{o,d})} \right)^2$$

Substituting for p from equation (6) and using equation (10) gives

$$(12) \quad t_d = T_{o,d} \left[1 + \left(\frac{x}{T_{o,r} V(T_{o,r}) - d} \right)^2 \right]^{\frac{1}{2}}$$

Since $t_d/2$ is the traveltime along the upgoing part of the raypath 36, the VSP time (t_{vsp}) becomes

$$(13) \quad t_{vsp} = t_r - t_d/2 = (T_{o,r} - \frac{1}{2}T_{o,d}) \left[1 + \left(\frac{x}{T_{o,r} V(T_{o,r}) - d} \right)^2 \right]^{\frac{1}{2}}$$

Using equation (10) again, equation (13) can be rewritten as

$$(14) \quad t_{vsp} = (T_{o,r} - \frac{1}{2}T_{o,d}) \left[1 + \left(\frac{x}{T_{o,r} V(T_{o,r}) - \frac{1}{2}T_{o,d} V(T_{o,d})} \right)^2 \right]^{\frac{1}{2}}$$

Equations (13) and (14) map t_{vsp} , the VSP time on the VSP trace recorded by the borehole geophone located at depth d , to the surface seismic time or the two-way vertical traveltime $T_{o,r}$ for the corresponding reflector which produced the event.

The lateral position of the reflection point for this event (q) can be determined from the relationship

$$(15) \quad p + q = \frac{x+p}{2}$$

Using equation (6) and solving for q gives

$$(16) \quad q = x \frac{T_{o,r} V(T_{o,r}) - 2d}{2T_{o,r} V(T_{o,r}) - 2d}$$

or substituting for d from equation (10) gives

$$(17) \quad q = x \frac{T_{o,r} V(T_{o,r}) - T_{o,d} V(T_{o,d})}{2T_{o,r} V(T_{o,r}) - T_{o,d} V(T_{o,d})}$$

Using the above equations, the VSPCDP stack can be performed on VSP data such as that illustrated in FIGURE 2. However, in order to better illustrate the present invention, the VSPCDP stack will be described in terms of the synthetic VSP data illustrated in FIGURE 6.

The synthetic VSP data illustrated in FIGURE 6 was derived for four horizontal homogeneous layers with each deeper layer having a higher velocity. The layers were located at 610 m (2000 feet), 915 m (3000 feet), 1220 m (4000 feet) and 1525 m (5000 feet). The velocity between the surface and 610 m (2000 feet) was 1525 m/s (5000 feet per second), the velocity between 610 m (2000 feet) and 915 m (3000 feet) was 3050 m/s (10,000 feet per second), the velocity between 915 m (3000 feet) and 1220 m (4000 feet) was 4575 m/s (15,000 feet per second), the velocity between 1200 m (4000 feet) and 1525 m (5000 feet) was 5490 m/s (18,000 feet per second) and the velocity below 1525 m (5000 feet) was 6100 m/s (20,000 feet per second). The source was offset 305 m (1000 feet) from the well and the borehole geophone is located at stations every 15 m (50 feet) between 45.7 m (150 feet) and 1510 m (4950 feet). Random noise has been added to the synthetic data.

The following steps are utilized to convert the synthetic VSP response, illustrated in FIGURE 6, to the VSPCDP stack illustrated in FIGURE 7 which presents the seismic data in a conventional stacked form:

1. Specify a number of VSPCDP locations between the well and the lateral distance $X/2$ along the direction towards the source. These locations would typically be separated from each other by a constant lateral spacing of D . A VSPCDP stack trace is associated with each location as has been previously stated. For the VSPCDP stack illustrated in FIGURE 7, the spacing (D) was 7.6 m (25 feet), the first trace is at 3.8 m (12.5 feet) and the last trace is at 149 m (487.5 feet) from the well.

2. Choose a VSP data trace from the VSP data illustrated in FIGURE 6. This is accomplished by choosing a depth where a geophone was located such as 152 m (500 feet), 305 m (1000 feet), 366 m (1200 feet), etc. This choice determines the value of d which will correspond to the depth of the geophone. $T_{o,d}$ can be calculated based on the first break time (t_f) taken from the VSP response illustrated in FIGURE 6. As an example, for the VSP trace at 610 m (2000 feet), the first break time is approximately .4 seconds. This time is related to $T_{o,d}$ by the equation

$$(18) \quad \frac{T_{o,d}}{d} = \frac{t_f}{y}$$

and y is the direct distance between the source and the geophone. Since d , y and t_f are known, equation (18) can be solved for $T_{o,d}$.

Once $T_{o,d}$ is known, equation (10) can be solved for $V(T_{o,d})$.

3. Choose a value for $T_{o,r}$. This gives a location on the VSPCDP stack illustrated in FIGURE 7. Also, $V(T_{o,r})$ can be determined based on the chosen value of $T_{o,r}$. This is generally accomplished by calculating a plurality of values for $T_{o,d}$ and $V(T_{o,d})$ from the VSP response illustrated in FIGURE 6. Since $T_{o,d}$ and $T_{o,r}$ would be equal for the same depth, the value of $V(T_{o,r})$ for any particular $T_{o,r}$ can be determined by finding the value of $T_{o,d}$ which corresponds to the chosen value of $T_{o,r}$ and $V(T_{o,r})$ will be equal to $V(T_{o,d})$ for that particular value.

4. Calculate a value of T_{vsp} using equation (14) and a value for q using equation (17).

5. Take the data sample at time t_{vsp} on the VSP data trace chosen and place it at time $T_{o,r}$ on the VSPCDP stack trace associated with the location K for which equation (19) is satisfied.

$$(19) \quad q - \text{VSPCDP}_K < \frac{D}{2}$$

As an example, the calculated q might be 32.3 m (106 feet). For a D of 6.1 m (20 feet), the VSPCDP location which satisfies equation (19) would be 30.5 m (100 feet) assuming a constant lateral spacing of the VSPCDP locations.

6. Sum together samples which accumulate at the same value of $T_{o,r}$ on a given VSPCDP stack trace.

7. Repeat steps 3—6 for all desired values of $T_{o,r}$ for the VSPCDP stack illustrated in FIGURE 7. A typical increment for $T_{o,r}$ is 1 millisecond.

8. Repeat steps 2—7 for all VSP traces illustrated in FIGURE 6.

Essentially, steps 3, 4 and 5 are a mapping of VSP data at a VSP time (t_{vsp}) into surface seismic data at the surface seismic time ($T_{o,r}$) chosen in step 3 such that a data sample or segment of the VSP data at the VSP time is moved onto a position on the surface seismic data illustrated in FIGURE 7 which position is determined by the surface seismic time ($T_{o,r}$) and the distance between the reflection point and the borehole (q). Step 7 is a repeat of this mapping function for different surface seismic times. Step 6 is a

summing or a stacking of samples or sections which accumulate at the same location in FIGURE 7. Step 8 is a repeat of the mapping and stacking for the remaining VSP traces to form the complete surface seismic data illustrated in FIGURE 7.

Again, FIGURE 7 may be considered a plot of surface seismic time as a function of distance from the borehole. The data samples or sections in step 5 are thus placed on a plot of surface seismic time as a function of distance from the borehole. When the procedure is completed, the plot is the total surface seismic data.

FIGURE 8 illustrates the result of applying steps 1—7 to the single VSP trace recorded at 458 m (1500 feet). FIGURE 9 shows the results of applying steps 1—7 to the single VSP trace recorded at 763 m (2500 feet). As can be seen, the data on a single VSP trace is distributed to a number of VSPCDP traces by the VSPCDP stacking procedure. Again, FIGURE 7 is a result of stacking all individual traces.

The description of the invention to this point has centered around the simple case where the borehole is vertical and the reflecting interface is horizontal. Modifications must be made if the borehole is not vertical or if the horizontal reflector is not horizontal. For the case of a deviated well, the changes are simple and do not make the mapping and stacking procedure any more difficult.

Considering the case where the deviated well forms a two-dimensional curve and the source is in the plane of the curve, the geophone locations along the deviated well will no longer have the same lateral position. In this case, it is preferred to measure the lateral distances from the constant source position rather than from the variable geophone locations. Equations (13), (14), (16) and (17) can be modified to reflect this change in origin from well to source by replacing the constant x by the variable $y(d)$, where $y(d)$ is the lateral distance from the source to the borehole geophone at depth d . The modified versions of equations (13), (14), (16) and (17) are given by

$$(20) \quad t_{vsp} = (T_{o,r} - \frac{1}{2}T_{o,d}) \left[1 + \left(\frac{y(d)}{T_{o,r}V(T_{o,r}) - d} \right)^2 \right]^{\frac{1}{2}},$$

$$(21) \quad t_{vsp} = (T_{o,r} - \frac{1}{2}T_{o,d}) \left[1 + \left(\frac{y(d)}{T_{o,r}V(T_{o,r}) - \frac{1}{2}T_{o,d}V(T_{o,d})} \right)^2 \right]^{\frac{1}{2}}$$

$$(22) \quad q = y(d) \cdot \frac{T_{o,r}V(T_{o,r}) - 2d}{2T_{o,r}V(T_{o,r}) - 2d},$$

and

$$(23) \quad q = y(d) \cdot \frac{T_{o,r}V(T_{o,r}) - T_{o,d}V(T_{o,d})}{2T_{o,r}V(T_{o,r}) - T_{o,d}V(T_{o,d})} \text{ respectively.}$$

The modified versions of equations (16) and (17) still give the lateral distance between the borehole geophone at depth d and the reflection points. If s is the lateral distance from the source to the reflection points, then

$$(24) \quad s = y(d) - q.$$

Substituting equation (22) for q in equation (24) gives

$$(25) \quad s = y(d) \cdot \frac{T_{o,r}V(T_{o,r})}{2T_{o,r}V(T_{o,r}) - 2d}.$$

Substituting equation (23) for q in equation (24) gives

$$(26) \quad s = y(d) \cdot \frac{T_{o,r}V(T_{o,r})}{2T_{o,r}V(T_{o,r}) - T_{o,d}V(T_{o,d})}.$$

If the borehole has been surveyed, either equations (20) and (25) or equations (21) and (26) can be used to perform the VSPCDP stack by the method described above for a vertical borehole.

When dipping beds are present, the reflection points will not occur in the same locations as they would horizontal reflectors. In fact, the location of the reflection points may not even lie between the borehole and half the distance out to the source as in the usual VSPCDP stack. Therefore, in the case of dipping reflectors, it is necessary to migrate the reflection points to their actual lateral positions with respect to the borehole.

For example, FIGURE 10 shows a reflector 51 which dips at an angle of θ degrees and intercepts the well 52 at depth h . The source is offset a distance x feet from the well 52 and the borehole geophone 34 is at depth d . As in the VSPCDP stack previously described, the objective is to calculate the actual location of the reflection point, the time that the reflection arrives at the borehole geophone 34, and the two-way vertical traveltime to the actual reflection point. Then the event on the VSP trace can be mapped into the migrated VSPCDP stack at both the correct time and the correct lateral position with respect to the well 52.

FIGURE 11 shows the parameters needed to derive the VSPCDP migration equations. Using geometry, the angle ϕ between the reflector 51 and incident ray 56, the vertical distance h' to the reflection point 57, and the lateral distance q from the borehole 52 to reflection point 57 can be written, respectively, as

$$(27) \quad \phi = \arctan \left[\frac{2h - x \tan \theta - d}{x + d \tan \theta} \right]$$

$$(28) \quad h' = h - q \tan \theta,$$

and

$$(29) \quad q = \frac{-h + x \tan(\phi + \theta)}{\tan(\phi + \theta) - \tan \theta}$$

If the reflected ray is extended past the borehole 52 to a point on the surface which is a distance p from the well, then p can be written as

$$(30) \quad p = d \cot(\phi - \theta).$$

The length L of the downgoing raypath between the source and the reflection point 57 can be written as

$$(31) \quad L = h'^2 + (x - q)^2.$$

The length L' of the upgoing raypath between the reflection point 57 and the surface can be written as

$$(32) \quad L' = h'^2 + (q + p)^2.$$

The length l of the portion of the upgoing raypath between the borehole geophone and the surface can be written as

$$(33) \quad l = p^2 + d^2.$$

If $T_{o,r}$ is again the two-way vertical traveltime and $V(T_{o,r})$ is again the average velocity down to the reflection point 57, then

$$(34) \quad h' = \frac{T_{o,r} V(T_{o,r})}{2}.$$

If t_r is the traveltime along the entire raypath from source to reflection point and back up to the surface, then the total pathlength can be approximated by

$$(35) \quad L + L' \approx t_r V(T_{o,r})$$

from which

$$(36) \quad t_r \approx \frac{L + L'}{V(T_{o,r})}.$$

The VSP reflection time (t_{VSP}) will again be the difference between t_r and the traveltime from the borehole geophone location up to the surface. If t_d is the two-way traveltime along the raypath from the geophone 34 to the surface then

$$(37) \quad \ell \approx \frac{t_d V(T_{o,d})}{2}$$

from which

$$(38) \quad t_d \approx \frac{2\ell}{V(T_{o,d})}$$

where $V(T_{o,d})$ is again the average velocity down to the borehole geophone location. The VSP reflection event is given by

$$(39) \quad t_{VSP} = t_r - \frac{t_d}{2}$$

Substituting equations (36) and (38) into (39) gives

$$(40) \quad t_{VSP} = \frac{L + L'}{V(T_{o,r})} - \frac{1}{V(T_{o,d})}$$

Then substituting equations (31), (32), and (33) into (40) gives

$$(41) \quad t_{VSP} = \frac{h'^2 + (x-q)^2 + h'^2 + (q+p)^2}{V(T_{o,r})} - \frac{p^2 + d^2}{V(T_{o,d})}$$

Using equations (27)–(41), a VSPCDP stack can be performed according to the following procedure:

1. Estimate the dip angle (Θ) by the technique described in Balch, A. H., Lee, M. W., and Muller, D. "A Vertical Seismic Profiling experiment to determine the depth and dip of the Paleozoic surface at drill hole U10bd, Nevada Test Site: U.S. Geological Survey Open-File Report No. 80–847, 25pp, 1980.

2. Specify a number of VSPCDP locations. These locations should extend over a broader region than just between the well and half the source offset. These locations would again typically be separated from each other by a constant lateral spacing of D . A VSPCDP stack trace is associated with each location as has been previously stated.

3. Choose a VSP data trace. This is again accomplished by choosing a depth where a geophone was located such as 152 m (500 feet), 305 m (1000 feet), 366 m (1200 feet), etc. This choice determines the value of d which will correspond to the depth of the geophone. $T_{o,d}$ can again be calculated based on the first break time taken from the VSP response. Once $T_{o,d}$ is known, equation (10) can again be solved for $V(T_{o,d})$.

4. Choose a value for h which is greater than the chosen d . Essentially, a false assumption is being made that reflectors are located at periodic distances below d but this assumption allows the mapping to be accomplished by varying h . The choice of h determines an approximate value for $V(T_{o,r})$ since $V(T_{o,r})$ will be equal to $V(T_{o,d})$ where $d = h$ and $V(T_{o,d})$ will be known for a plurality of depths (d) from the calculation of a plurality of values of $V(T_{o,d})$ as previously described.

5. Calculate a value of ϕ using equation (27), a value for g using equation (29) and a value of p using equation (30). Then calculate a value of h' using equation (28), a value of $T_{o,r}$ using equation (34) and finally a value for t_{VSP} using equation (41).

6. Take the data sample at time t_{VSP} on the VSP data trace chosen and place it at time $T_{o,r}$ on the VSPCDP stack trace associated with the location K for which equation (19) is satisfied as previously described.

7. Sum together samples which accumulate at the same value of $T_{o,r}$ on a given VSPCDP stack trace.

8. Repeat steps 4–7 for all desired values of h . A typical increment for h is 5 feet.

9. Repeat steps 3–8 for all VSP data traces.

Again, steps 4, 5 and 6 are the mapping of a segment of the chosen VSP data trace for the calculated VSP time (t_{VSP}) into the surface seismic data at the calculated surface seismic time ($T_{o,r}$). Step 8 accomplishes the mapping for a plurality of segments of the chosen VSP data trace. Step 9 accomplishes the mapping for all VSP data traces. Step 7 accomplishes the stacking which results in the production of the surface seismic data from the VSP seismic data.

The preferred computer program for accomplishing steps 1–8 which transform VSP seismic data into surface seismic data for the case of a horizontal reflector which is substantially parallel to the surface is set forth in Appendix I. The preferred computer program for accomplishing steps 1–9 which convert VSP seismic data into surface seismic data for the case of a dipping horizontal layer is set forth in Appendix II.

EP 0 117 280 B1

Both computer programs are written for the 2100 Series computer manufactured by Hewlett-Packard and are self-explanatory to one skilled in the use of the 2100 Series computer. The input required into the computer programs is VSP seismic data such as that illustrated in FIGURE 2 and the first break time for each geophone trace.

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APPENDIX I

FTN4.L
\$EMA(KAY,O)
PROGRAM STACK

<04-B1, KDW>

PROGRAM TO CALCULATE THE "VSPCDP STACK" SECTION FROM THE
UNALIGNED UPGOING EVENTS OF THE VSP.

VARIABLES USED IN PROGRAM "STACK"

LIST	LOGICAL UNIT OF DEVICE TO LIST DATA TO
MAGIN	MAG TAPE LU TO READ VSP UPGOING TRACES FROM
G1	DEPTH OF THE SHALLOWEST GEOPHONE TRACE
G2	DEPTH OF THE DEEPEST GEOPHONE TRACE
GI	DISTANCE BETWEEN GEOPHONES
NG	TOTAL NUMBER OF GEOPHONES
ISP1	SHOTPOINT NUMBER OF GEOPHONE TRACE AT "G1"
ISP2	SHOTPOINT NUMBER OF GEOPHONE TRACE AT "G2"
IDSH	SHOTPOINT INCREMENT BETWEEN GEOPHONE TRACES
IMC	DASH NUMBER FOR VSP UPGOING TRACES
IMTS	MULT CODE NUMBER FOR VSP UPGOING TRACES
ISR	NUMBER OF POINTS FOR VSP UPGOING TRACES
NGE	SAMPLE RATE (MS) FOR VSP UPGOING TRACES
NOPHON	NUMBER OF GEOPHONES TRACES TO ELIMINATE. (NOISY)
IFILE	ARRAY WHICH CONTAINS WHICH GEOPHONES TO ELIMINATE
IBLK	FILE LOCATION CONTAINING FIRST BREAKS
GF	BLOCK NUMBER IN IFILE WHERE FIRST BREAKS ARE LOCATED
IFB	DEPTH OF THE FIRST GEOPHONE LOCATION IN "IFILE"
IFBC	ARRAY CONTAINING THE FIRST BREAKS FOR GEOPHONES STARTING AT G1FB
VEL	ARRAY CONTAINING THE FIRST BREAKS THAT ARE CORRECTED FOR ZERO OFFSET FOR GEOPHONES STARTING AT G1FG
DVEL	AVERAGE VELOCITY
XS	DATUM VELOCITY
MAGOT	SOURCE OFFSET
NTR	MAG TAPE LU TO WRITE "VSPCDP" TRACES TO "VSPCDP" TRACES TO OUTPUT TO TAPE
LSR	NUMBER OF "VSPCDP" TRACES
KPTS	SAMPLE RATE OF "VSPCDP" TRACES
ISPD	NUMBER OF POINTS IN "VSPCDP" TRACES
BOUND	OUTPUT SHOTPOINT FOR "VSPCDP" TRACES
ISVD	ARRAY CONTAINING DISTANCE FROM WELL FOR EACH "VSPCDP" TR
ISV	ARRAY CONTAINING THE BOUNDS OVER WHICH ALL REFLECTIONS ARE STACKED FOR EACH "VSPCDP" TRACE
	ARRAY CONTAINING THE STACKING VELOCITY AT EACH GEOPHONE TRACE LOCATION (1 TO NG)
	ARRAY CONTAINING THE STACKING VELOCITY AT EACH TIME INCREMENT (1 TO KPTS)

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ID - ARRAY CONTAINING THE DEPTH AT EACH TIME INCREMENT (1 TO
*****
DIMENSION ID(2000), ISV(2000), BOUND(20,2), X(2000)
DIMENSION IFBC(256), ISVD(256), IDC8(144), IFILE(5)
DIMENSION NOPHON(100), IFB(256), GG(3), CDP(20)
COMMON /KAY/ BUF(2000,20), IDUM(1000,20)
CALL RMPAR(ID)
LOUT=ID(2)
WRITE(1,4)

4 FORMAT("LIST DEVICE? ")
READ(1,*) LIST
WRITE(1,5)
5 FORMAT("MAG TAPE INPUT FOR UPGOING EVENTS? ")
READ(1,*) MAGIN
WRITE(1,8)
8 FORMAT("GEOPHONE START, STOP, INCREMENT? ")
READ(1,*) G1,G2,GI
ISP1=G1
ISP2=G2
ISP1=G1
WRITE(1,10)
10 FORMAT("SHOT POINT START, STOP, INCREMENT? ")
READ(1,*) ISP1,ISP2,ISPI
WRITE(1,11)
11 FORMAT("NO OF GEOPHONES TO ELIMINATE? ")
READ(1,*) NGE
CALL VINIT(NOPHON,0,100)
IF(NGE.EQ.0) GO TO 13
WRITE(1,12)
12 FORMAT("GEOPHONES TO ELIMINATE? ")
READ(1,*) I(I=1,NGE)
13 WRITE(1,14)
14 FORMAT("DASH NO. AND MULT CODE OF VSP UPGOING TRACES? ")
READ(1,*) IDSH,IMC
WRITE(1,114)
114 FORMAT("TRACE NUMBER? ")
READ(1,*) ITR
15 WRITE(1,20)
20 FORMAT("NUMBER OF POINTS IN VSP UPGOING TRACES? ")
READ(1,*) NPPTS
IF(NPPTS.GT.2000) GO TO 15
WRITE(1,30)
30 FORMAT("SAMPLE RATE OF VSP UPGOING TRACES (IN MILLISECONDS)? ")
READ(1,*) ISR
WRITE(1,40)
40 FORMAT("FOR FIRST BREAK TIMES, ENTER ")
CALL GETFI(IFILE,1)
WRITE(1,45)

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45 FORMAT("BLOCK NUMBER FOR FIRST BREAK TIMES? ")
   READ(1,*) IBLK
46 FORMAT("FIRST AND LAST PHONE FOR FIRST BREAKS? ")
   READ(1,*) G1FB,G2FB
   G1FB=G1
   IF(G1.LT.G1FB) GO TO 9999
   IF(G2.GT.G2FB) GO TO 9999
   NG=(G2-G1)/G1+1
   NGG=(G2FB-G1FB)/G1FB+1
   CALL GETD(IDC8,IER,IFILE,IFILE(4),IFB,NGG,IBLK,1,1)
   WRITE(1,60) G2FB
60 FORMAT("AVERAGE VELOCITY OF EARTH BELOW PHONE AT",F5.0,"? ")
   READ(1,*) VEL
   WRITE(1,61)
61 FORMAT("NEAR SURFACE VELOCITY? ")
   READ(1,*) DVEL
   WRITE(1,70)
70 FORMAT("SOURCE OFFSET? ")
   READ(1,*) XS
75 WRITE(1,80)
80 FORMAT("FOR OUTPUT VSPCDP TRACES, ENTER START POSITION"
+ " STOP POSITION, AND INCREMENT"/
+ " (ALL POSITIONS ARE RELATIVE TO WELL. NEGATIVE POSITION"/
+ " IS DOWNDIP FROM WELL, AND POSITIVE POSITION IS UPDIP) ")
   READ(1,*) CDP1,CDP2,CDP1+1
   NTR=(CDP2-CDP1)/CDP1+1
   IF(NTR.GT.20) GO TO 75
   IF(NTR.GT.20) GO TO 75
   WRITE(1,84)
84 FORMAT("SAMPLE RATE OF OUTPUT DATA? ")
85 READ(1,*) LSR
90 FORMAT("NO. OF OUTPUT PTS? ")
   READ(1,*) KPTS
   IF(KPTS.GT.2000) GO TO 85
   WRITE(1,95)
95 FORMAT("MAG TAPE LU OUT? ")
   READ(1,*) MAGOT
   WRITE(1,96)
96 FORMAT("OUTPUT SHOTPOINT? ")
   READ(1,*) ISPO

   WRITE PROGRAM PARAMETERS ON PRINTER
   WRITE(LIST,1010) G1,G2,G1,NPTS,ISR,VEL,DVEL,XS,NTR,KPTS,
+ LSR,ISPO

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C C

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1010 FORMAT(" GEOPHONE START", F10.1, /
+ " GEOPHONE STOP", F10.1, /
+ " GEOPHONE INCREMENT", F10.1, /
+ " NO. INPUT PTS", I10, /
+ " INPUT SAMPLE RATE", F10.1, /
+ " AVERAGE VELOCITY BELOW TD", F10.1, /
+ " NEAR SURFACE VELOCITY", F10.1, /
+ " SOURCE OFFSET", F10.1, /
+ " NUMBER OF VSPCDP TRACES", I10, /
+ " NO. OUTPUT PTS", I10, /
+ " OUTPUT SAMPLE RATE", F10.1, /
+ " OUTPUT SHOT POINT", F10.1, /
+ " IF(NGE.GT.0) WRITE(LIST,1020) NGE
1020 FORMAT(" THE FOLLOWING", I5, " GEOPHONES WERE ELIMINATED:")
1030 FORMAT(20X,I6)
C-----CALCULATE STACKING VELOCITIES AND DEPTHS
C-----
C-----IFB(256) ARE FIRST BREAKS FOR EVERY PHONE LOCATION WITH SOURCE OFF
C-----IFBC(256) ARE FIRST BREAKS FOR EVERY PHONE CORRECTED TO ZERO OFFSE
C-----ID(2000) IS DEPTH AS A FUNCTION OF VSPCDP REFLECTION TIME
C-----ISV(2000) STACKING VELOCITY AS A FUNCTION OF VSPCDP REFLECTION TIM
C-----ISVD(256) STACKING VELOCITIES FOR EVERY PHONE LOCATION
C-----
DO 110 I=1,NGG
D=GIFB+(I-1)*GIFB
DD=SQRT(D*D+XS*XS)
ISVD(I)=DD*1000./IFB(I)
110 IFBC(I)=D*1000./ISVD(I)
DEPTH=VEL*LSR/2000.
DO 140 I=1,KPTS
ITIME=I*LSR/2.
DO 115 J=1,NGG
IF(ITIME.LE. IFBC(J)) GO TO 116
115 CONTINUE
GO TO 130
116 T1=IFBC(J-1)
T2=IFBC(J)
D1=GIFB+(J-2)*GIFB
D2=GIFB+(J-1)*GIFB
V1=ISVD(J-1)
V2=ISVD(J)
IF(J.GT.1) GO TO 120
T1=0.
D1=0.
V1=DVEL

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120 ID(I)=D1+(D2-D1)*(ITIME-T1)/(T2-T1)
    ISV(I)=V1+(V2-V1)*(ITIME-T1)/(T2-T1)
    GO TO 135
130 ID(I)=ID(I-1)+DEPTH
    SAVE=ID(I)*1000./ITIME
    ISV(I)=SAVE
135 CONTINUE
140 CONTINUE
C-----CALCULATE BOUNDS (XP1 AND XP2) FOR EACH OUTPUT TRACE
C
    BINC=CDP1/2
    DO 250 I=1,NTR
      BMID=CDP1+(I-1)*CDP1
      CDP(I)=BMID
      BOUND(I,1)=BMID-BINC
      BOUND(I,2)=BMID+BINC
250 CONTINUE
C
C    LIST BOUNDS, TIMES, DEPTHS, AND STACKING VELOCITIES.
C
    WRITE(LIST,1110)
    + " TRACE NUMBER          CDP BOUND ONE BOUND TWO"
1110 WRITE(LIST,1120) ((I,CDP(I),BOUND(I,1),BOUND(I,2)),I=1,NTR)
1120 FORMAT(6X,13.6X,F8.2,5X,F8.2,5X,F8.2)
1130 WRITE(LIST,1130)
    + " TIME ",10(" DEPTH STACK")
1130 WRITE(LIST,1140)
    + " (MS) ",10(" (FT) VEL ")
1140 FORMAT(" (MS) ",10(" (FT) VEL ")
    DO 260 I=1,KPTS,10
      II=I+LSR
      WRITE(LIST,9030) II,((ID(K),ISV(K)),K=I,I+9)
9030 FORMAT(2116)
260 CONTINUE
9020 FORMAT(2016)
    WRITE(LIST,1150)
    + " DEPTH 1ST BRK CORRECTED STACKING "
1150 FORMAT(/3(" DEPTH 1ST BRK CORRECTED STACKING "
    + " TIMES VELOCITY",5X))
1155 FORMAT(3(22X,"TIMES VELOCITY",5X))
    DO 9040 I=1,NGG,3
      GG(1)=G1FB+(I-1)*G1FB
      GG(2)=GG(1)+G1FB
      GG(3)=GG(2)+G1FB
1156 WRITE(LIST,1156) (GG(K),IFB(I+K-1),IFBC(I+K-1),ISVD(I+K-1),K=1,3)
9040 FORMAT(3(F9.1,2X,15.5X,15.5X,15.7X))
    CONTINUE
C-----ZERO OUT OUTPUT TRACES
C

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C      DO 300 I=1,NTR
C      DO 300 J=1,KPTS
C      BUF(J,I)=0.
C      DO 301 I=1,NTR
C      DO 301 J=1,1000
C      IDUM(J,I)=0
C
C-----START STACKING
C
C      D    - DEPTH OF GEOPHONE TRACE
C      TO   - TIME OF ARRIVAL ON "VSPCDP" TRACES FOR CURRENT REFLECTION
C      H    - DEPTH TO CURRENT REFLECTION
C      R    - HORIZONTAL DISTANCE FROM WELL TO REFLECTION POINT
C      T    - TIME OF ARRIVAL ON VSP UPGOING TRACES FOR CURRENT
C              REFLECTION (THE EVENT AT THIS TIME WILL BE MAPPED
C              INTO TIME TO ON THE "VSPCDP" SECTION)
C      BUF  - ARRAY CONTAINING "VSPCDP" TRACES
C      X    - ARRAY CONTAINING VSP UPGOING TRACE
C
C      INC=1
C      IMIN=(G1-GIFB)/GIFB
C      DO 1000 I=1,NG
C      D =G1+(I-1)*GI
C      ISP=ISP1+(I-1)*ISPI
C      KD=D
C      IF(NGE.NE.O.AND.KD.EQ.NOPHON(INC)) GO TO 900
C      WRITE(1,9000) ISP
C      FORMAT(" PROCESSING SHOTPOINT ",IS)
C      CALL RDAP(NPTS,ISP,IDSH,INC,ITR,2,X,MAGIN,1)
C      DO 500 J=1,KPTS
C      TO=J*LSR
C      H=ID(J)
C      IF(H.LT.D) GO TO 500
C      R=X*(H-D)/(2*H-D)
C      DO 400 K=1,NTR
C      IF(R.GE.BOUND(K,1).AND.R.LT.BOUND(K,2)) GO TO 410
C      CONTINUE
C      DO 500
C      ARG1=(XS-R)/ISV(J)*1000.
C      ARG2=(XS-2*R)
C      II=I+IMIN
C      T=2.*SQRT(TO*TO/4.+ARG1*ARG1)-SQRT(ARG2*ARG2+D*D)/ISVD(II)*1000.
C      PT=T/ISR
C      IPT=PT
C      PT=PT-IPT
C      IF(IPT.LT.1.OR.IPT.GE.NPTS) GO TO 500
C      BUF(J,K)=BUF(J,K)+X(IPT)+PT*(X(IPT+1)-X(IPT))
C      IF(LOUT.NE.O) WRITE(LOUT,420) I,D,J,TO,H,R,K,T,IPT,PT

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420 FORMAT(15,F7.0,15,F10.4,F7.0,F10.4,15,F10.4,15,F10.4)
111=256*(J-(J/2)*2)
IF(111.EQ.0) 111=1
122=(J+1)/2
IDUM(I22,K)=IDUM(I22,K)+111
500 CONTINUE
GO TO 990
900 INC=INC+1
990 CONTINUE
1000 CONTINUE
C-----WRITE OUTPUT TRACES TO TAPE
C
DO 2000 I=1,NTR
DO 1990 J=1,KPTS
122=(J+1)/2
111=J-(J/2)*2
ISAV=IDUM(I22,I)
IF(111.EQ.1) IAA=ISAV/256
IF(111.EQ.0) IAA=IAND(377B,ISAV)
IF(IAA.EQ.0) IAA=1
1990 X(J)=BUF(J,I)/IAA
2000 CALL RDTAP(KPTS,ISPD,IDSH,IMC,I,6,X,MAGDT,1)
9999 END
END$

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APPENDIX II

FTN4.L
\$EMA(KAY,Q)
PROGRAM MIGRT

<06-B1, KDW>

PROGRAM TO CALCULATE THE "VSPCDP STACK" SECTION FROM THE
UNALIGNED UPGOING EVENTS OF THE VSP
THIS IS A MODIFIED VERSION OF THE PROGRAM "STACK" SINCE IT
ASSUMES THAT ALL BEDS ARE DIPPING WITH ANGLE "PHI" RATHER
THAN HAVING HORIZONTAL BEDS.

VARIABLES USED IN PROGRAM "STACK"

LIST	LOGICAL UNIT OF DEVICE TO LIST DATA TO
MAGIN	MAG TAPE LU TO READ VSP UPGOING TRACES FROM
G1	DEPTH OF THE SHALLOWEST GEOPHONE TRACE
G2	DEPTH OF THE DEEPEST GEOPHONE TRACE
G1	DISTANCE BETWEEN GEOPHONES
NG	TOTAL NUMBER OF GEOPHONES
ISP1	SHOTPOINT NUMBER OF GEOPHONE TRACE AT "G1"
ISP2	SHOTPOINT NUMBER OF GEOPHONE TRACE AT "G2"
ISP1	SHOTPOINT INCREMENT BETWEEN GEOPHONE TRACES
IDSH	DASH NUMBER FOR VSP UPGOING TRACES
IMC	MULT CODE NUMBER FOR VSP UPGOING TRACES
NPTS	NUMBER OF POINTS FOR VSP UPGOING TRACES
ISR	SAMPLE RATE (MS) FOR VSP UPGOING TRACES
NGE	NUMBER OF GEOPHONES TRACES TO ELIMINATE (NOISY)
NOPHON	ARRAY WHICH CONTAINS WHICH GEOPHONES TO ELIMINATE
IFILE	FILE LOCATION CONTAINING FIRST BREAKS
IBLK	BLOCK NUMBER IN IFILE WHERE FIRST BREAKS ARE LOCATED
GF	DEPTH OF THE FIRST GEOPHONE LOCATION IN "IFILE"
IFB	ARRAY CONTAINING THE FIRST BREAKS FOR GEOPHONES
	STARTING AT G1FB
IFBC	ARRAY CONTAINING THE FIRST BREAKS CORRECTED FOR
	ZERO SOURCE OFFSET FOR GEOPHONES STARTING AT G1FB
VEL	AVERAGE VELOCITY
DVEL	DATUM VELOCITY
XS	SOURCE OFFSET
	(+ MEANS SOURCE IS UPDIP)
	(- MEANS SOURCE IS DOWNDIP)
PHI	DIP ANGLE IN DEGREES
MAGOT	MAG TAPE LU TO WRITE "VSPCDP" TRACES TO
NTR	NUMBER OF "VSPCDP" TRACES TO OUTPUT TO TAPE
LSR	SAMPLE RATE OF "VSPCDP" TRACES
KPTS	NUMBER OF POINTS IN "VSPCDP" TRACES
ISPO	OUTPUT SHOTPOINT FOR "VSPCDP" TRACES
CDP	ARRAY CONTAINING DISTANCE FROM WELL FOR EACH "VSPCDP" TRACE

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CC
CC
CC
CC
CC
CC
BOUND - ARRAY CONTAINING THE BOUNDS OVER WHICH ALL REFLECTIONS
        ARE STACKED FOR EACH "VSPCDP" TRACE
ISVD - ARRAY CONTAINING THE STACKING VELOCITY AT EACH GEOPHONE
        TRACE LOCATION (1 TO NG)
ISV - ARRAY CONTAINING THE STACKING VELOCITY AT EACH TIME
        INCREMENT (1 TO KPTS)
ID - ARRAY CONTAINING THE DEPTH AT EACH TIME INCREMENT (1 TO KPTS)

DIMENSION ID(2000), ISV(2000), BOUND(20,2), X(2000)
DIMENSION IFBC(256), ISVD(256), IDC(144), IFILE(5)
DIMENSION NOPHON(100), IFB(256), GG(3), CDP(20)
COMMON /KAY/ BUF(2000,20), IDUM(1000,20)
CALL RMPAR(ID)
WRITE(1,4)
4 FORMAT("LIST DEVICE? ")
READ(1,*) LIST
WRITE(1,5)
5 FORMAT("MAG TAPE INPUT FOR UPGOING EVENTS? ")
READ(1,*) MAGIN
WRITE(1,8)
8 FORMAT("GEOPHONE START, STOP, INCREMENT? ")
READ(1,*) G1,G2,GI
ISP1=G1
ISP2=G2
ISP1=GI
ISP1=GI
WRITE(1,10)
10 FORMAT("SHOT POINT START, STOP, INCREMENT? ")
READ(1,*) ISP1,ISP2,ISP1
WRITE(1,11)
11 FORMAT("NO. OF GEOPHONES TO ELIMINATE? ")
READ(1,*) NGE
CALL VINIT(NOPHON,0,100)
IF(NGE.EQ.0) GO TO 13
WRITE(1,12)
12 FORMAT("GEOPHONES TO ELIMINATE? ")
READ(1,*) (NOPHON(I),I=1,NGE)
13 WRITE(1,14)
14 FORMAT("DASH NO. AND MULT CODE OF VSP UPGOING TRACES? ")
READ(1,*) IDSH,IMC
WRITE(1,14)
114 FORMAT("TRACE NUMBER? ")
READ(1,*) ITR
15 WRITE(1,20)
20 FORMAT("NUMBER OF POINTS IN VSP UPGOING TRACES? ")
READ(1,*) NPTS
IF(NPTS.GT.2000) GO TO 15
WRITE(1,30)
30 FORMAT("SAMPLE RATE OF VSP UPGOING TRACES (IN MILLISECONDS)? ")
READ(1,*) ISR
WRITE(1,40)

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40 FORMAT("FOR FIRST BREAK TIMES, ENTER _")
   CALL GETFI(IFILE,1)
   WRITE(1,45)
45 FORMAT("BLOCK NUMBER FOR FIRST BREAK TIMES? _")
   READ(1,*) IBLK
   WRITE(1,46)
46 FORMAT("FIRST AND LAST PHONE FOR FIRST BREAKS? _")
   READ(1,*) G1FB,G2FB
   G1FB=G1
   IF(G1.LT.G1FB) GO TO 9999
   IF(G2.GT.G2FB) GO TO 9999
   NG=(G2-G1)/G1+1
   NGG=(G2FB-G1FB)/G1FB+1
   CALL GETD(IDCBI,IER,IFILE,IFILE(4),IFILE(5),IFB,NGG,IBLK,1,1)
   WRITE(1,60) G2FB
60 FORMAT("AVERAGE VELOCITY OF EARTH BELOW PHONE AT ",F5.0,"? _")
   READ(1,*) VEL
   WRITE(1,61)
61 FORMAT("NEAR SURFACE VELOCITY? _")
   READ(1,*) DVEL
   WRITE(1,70)
70 FORMAT("SOURCE OFFSET? _")
   READ(1,*) XS
   XS=ABS(XS)
   WRITE(1,71)
71 FORMAT("IS SOURCE UPDIP--1, OR SOURCE DOWNDIP--2? _")
   READ(1,*) IANS
   IF(IANS.EQ.2) XS=-XS
72 WRITE(1,73)
73 FORMAT("DIP ANGLE (IN DEGREES)? _")
   READ(1,*) PHI
   IF(PHI.LT.0.0) OR PHI.GT.90.) GO TO 72
75 WRITE(1,80)
80 FORMAT("FOR OUTPUT VSPCDP TRACES, ENTER START POSITION"
  +" STOP POSITION, AND INCREMENT"/
  +" (ALL POSITIONS ARE RELATIVE TO WELL. NEGATIVE POSITION"/
  +" IS DOWNDIP FROM WELL, AND POSITIVE POSITION IS UPDIP) _")
   READ(1,*) CDP1,CDP2,CDPI
   NTR=(CDP2-CDP1)/CDPI+1
   IF(NTR.GT.20) GO TO 75
   WRITE(1,84)
84 FORMAT("SAMPLE RATE OF OUTPUT DATA? _")
85 READ(1,*) LSR
90 WRITE(1,90)
90 FORMAT("NO. OF OUTPUT PTS? _")
   READ(1,*) KPTS
   IF(KPTS.GT.2000) GO TO 85
   WRITE(1,95)
95 FORMAT("MAG TAPE LU OUT? _")

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      READ(1,*) MAGOT
      WRITE(1,96)
96  FORMAT("OUTPUT SHOTPOINT?  ")
      READ(1,*) ISPO
C
C  WRITE PROGRAM PARAMETERS ON PRINTER
C
      WRITE(LIST,1010) G1,G2,G1.NPTS,ISR,VEL,DVEL,XS,PHI,NTR,KPTS,
+ LSR,ISPO
1010 FORMAT("  GEOPHONE START",F10.1/,
+ "  GEOPHONE STOP",F10.1/,
+ "  GEOPHONE INCREMENT",F10.1/,
+ "  NO. INPUT PTS",I10/,
+ "  INPUT SAMPLE RATE",F10.1/,
+ "  AVERAGE VELOCITY BELOW TD",F10.1/,
+ "  NEAR SURFACE VELOCITY",F10.1/,
+ "  SOURCE OFFSET",F10.1/,
+ "  (POS. SOURCE IS UPDIP)"/,
+ "  (NEG. SOURCE IS DOWNDIP)"/,
+ "  DIP ANGLE (DEGREES)",F10.1/,
+ "  NUMBER OF VSPCDP TRACES",I10/,
+ "  NO. OUTPUT PTS",I10/,
+ "  OUTPUT SAMPLE RATE",F10.1/,
+ "  OUTPUT SHOT POINT",F10.1/,
+ "  PHI=3.14159*PHI/180.",
+ "  TANPHI=TAN(PHI)",
+ "  IF(NGE.GT.0) WRITE(LIST,1020) NGE
1020 FORMAT("  THE FOLLOWING",IS," GEOPHONES WERE ELIMINATED: ")
      IF(NGE.GT.0) WRITE(LIST,1030) (NOPHON(I),I=1,NGE)
1030 FORMAT(20X,16)
C-----CALCULATE STACKING VELOCITIES AND DEPTHS
C
C-----IFB(256) ARE FIRST BREAKS FOR EVERY PHONE LOCATION WITH SOURCE OFFSET
C-----IFBC(256) ARE FIRST BREAKS FOR EVERY PHONE CORRECTED TO ZERO OFFSET
C-----ID(2000) IS DEPTH AS A FUNCTION OF VSPCDP REFLECTION TIME
C-----ISV(2000) STACKING VELOCITY AS A FUNCTION OF VSPCDP REFLECTION TIME
C-----ISVD(256) STACKING VELOCITIES FOR EVERY PHONE LOCATION
C
      DO 110 I=1,NGG
      D=G1FB+(I-1)*G1FB
      DD=SQRT(D*D+XS*XS)
      ISVD(I)=DD*1000./IFB(I)
110  IFBC(I)=D*1000./ISVD(I)
      DEPTH=VEL*LSR/2000.
      DO 140 I=1,KPTS
      ITIME=I*LSR/2.
      DO 115 J=1,NGG
      IF(ITIME.LE. IFBC(J)) GO TO 116

```



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1155 WRITE(LIST,1155)
      FORMAT(3(22X,"TIMES VELOCITY",5X))
      DO 9040 I=1,NGG,3
        GG(1)=G1FB+(I-1)*G1FB
        GG(2)=GG(1)+G1FB
        GG(3)=GG(2)+G1FB
        WRITE(LIST,1156)(GG(K), IFB(I+K-1), IFBC(I+K-1), ISVD(I+K-1), K=1,3)
      9040 CONTINUE
      1156 FORMAT(3(F9.1,2X,15.5X,15.7X))

C-----ZERO OUT OUTPUT TRACES
C
      DO 300 I=1,NTR
        DO 300 J=1,KPTS
          300 BUF(J,I)=0.
          DO 301 I=1,20
            DO 301 J=1,1000
              301 IDUM(J,I)=0
          C-----START STACKING
          C
          D - DEPTH OF GEOPHONE TRACE
          H - DEPTH TO THE POINT THAT THE REFLECTION INTERSECTS THE WELL
          THETA - THE ANGLE BETWEEN THE INCIDENT WAVE AND DIPPING REFLECTOR
          XP - HORIZONTAL DISTANCE FROM WELL TO REFLECTION POINT
          YP - HORIZONTAL DISTANCE FROM SURFACE TO REFLECTION POINT
          R - SAME AS XP
          TO - TIME OF ARRIVAL ON "VSPCDP" TRACES FOR CURRENT REFLECTION
          ED - DISTANCE BETWEEN SOURCE AND REFLECTION POINT
          DF - DISTANCE BETWEEN REFLECTION POINT AND SURFACE IMAGE POINT
          BF - DISTANCE BETWEEN GEOPHONE (RECEIVER) AND SURFACE IMAGE PT
          T - TIME OF ARRIVAL ON VSP UPGOING TRACES FOR CURRENT REFLECTION (THE EVENT AT THIS TIME WILL BE MAPPED INTO TIME TO ON THE "VSPCDP" SECTION)
          BUF - ARRAY CONTAINING "VSPCDP" TRACES

          INC=1
          IMIN=(G1-G1FB)/G1FB
          DO 1000 I=1,NG
            D =G1+(I-1)*G1
            ISP=ISP1+(I-1)*ISP1
            KD=D
            IF(NGE.NE.O.AND.KD.EQ.NDPHON(INC)) GO TO 900
            WRITE(1,9000) ISP
            9000 FORMAT(" PROCESSING SHOTPOINT ",I5)
            CALL RDTAP(NPTS,ISP,IDSH,IMC,ITR,2,X,MAGIN,1)
            DO 500 J=1,KPTS
              H=ID(J)

```

```

ARG1=2.*H-D-XS*TANPHI
ARG2=XS+D*TANPHI
THETA=ATAN2(ARG1,ARG2)
ARG1=TAN(THETA+PHI)
XP=(-H+XS*ARG1)/(ARG1-TANPHI)
YP=-XP*TANPHI+H
XI=-D/TAN(THETA-PHI)
R=XP
IF(YP.LT.D) GO TO 500
TO=2.*YP/ISV(J)*1000.
JJ=(TO+LSR/2.)/LSR
IF(JJ.LT.1.OR.JJ.GT.KPTS) GO TO 500
DO 400 K=1,NTR
IF(R.GT.BOUND(K,1).AND.R.LE.BOUND(K,2)) GO TO 410
400 CONTINUE
GO TO 500
410 ED=SGRT(YP*YP+(XS-XP)**2)
BF=SGRT(XI*XI+D*D)
T=(ED+BF)/ISV(J) - BF/ISVD(I-IMIN)
PT=T/ISR
IPT=PT
PT=PT-IPT
IF(IPT.LT.1.OR.IPT.GE.NPTS) GO TO 500
BUF(JJ,K)=BUF(JJ,K)+X(IPT)+PT*(X(IPT+1)-X(IPT))
I11=256*(JJ-(JJ/2)*2)
IF(I11.EQ.0) I11=1
I22=(JJ+1)/2
IDUM(I22,K)=IDUM(I22,K)+I11
500 CONTINUE
GO TO 990
900 INC=INC+1
990 CONTINUE
1000 CONTINUE

C-----WRITE OUTPUT TRACES TO TAPE
C
DO 2000 I=1,NTR
DO 1990 J=1,KPTS
I22=(J+1)/2
I11=J-(J/2)*2
ISAV=IDUM(I22,I)
IF(I11.EQ.1)IAA=ISAV/256
IF(I11.EQ.0)IAA=IAND(377B,ISAV)
IF(IAA.EQ.0)IAA=1
1990 X(J)=BUF(J,I)/IAA
CALL RDTAP(KPTS,ISPO,IDSH,IMC,I,6,X,MAGOT,1)
2000 CONTINUE
9999 END
END$

```



Claims

1. A method for stacking vertical seismic profiling data traces each data trace comprising seismic wave signals generated by a surface source at one offset distance from a borehole and received at different arrival times by a borehole geophone locatable at various depths in a well, comprising the steps of:
 - a) specifying a number of common depth point locations laterally positioned at a distance from the borehole, laterally separated from each other by a lateral spacing D, and located at various depths, each depth corresponding to a two-way vertical travel time being the time required for a wave to travel vertically from the surface to a subsurface reflector at said depth and back to the surface;
 - b) selecting a data trace comprising signals received at a certain geophone depth d;
 - c) choosing a two-way vertical travel time $T_{0,r}$ corresponding to a subsurface reflector at a depth h;
 - d) calculating a reflection event time t_{vsp} being the time required for the wave to travel from said source to a reflection point on said subsurface reflector at said depth h and then to said geophone at said depth d;
 - e) calculating a lateral distance q of said reflection point from said borehole;
 - f) taking a wave signal from said selected data trace for an arrival time equal to said reflection event time and placing it at a location K corresponding to said time $T_{0,r}$ and laterally positioned at a distance $VSPCDP_K$ from the borehole which is related to said distance q by the inequality

$$q - VSPCDP_K < D/2,$$

whereby signals having reflection points within half of said spacing D to either side of said common depth point location are stacked at said common depth point location K and whereby signals which accumulate at said location K are summed together;

- g) repeating steps c) to f) for a plurality of values of said two-way vertical travel time;
- h) selecting further data traces and repeating steps b) to g).
2. A method in accordance with claim 1 wherein $T_{0,r}$ is chosen in increments of about 1 millisecond.
3. A method in accordance with claim 1 wherein said subsurface reflector dips with respect to the surface and wherein said method further comprises the initial steps of estimating a dip angle Θ for said reflector and said choosing of a two-way vertical travel time $T_{0,r}$ of step c) comprises the substeps of
 - c1) choosing a depth at which said reflector intercepts said borehole, and
 - c2) calculating the two-way vertical travel time $T_{0,r}$ based on said interception depth and on said dip angle.
4. A method in accordance with claim 3, wherein said interception depth is incremented by values of about 1.5 meters.
5. A method in accordance with any of the claims 1—4, wherein said surface source is offset from said borehole a distance in the range of 91 to 915 m.

Patentansprüche

1. Verfahren zum Bereichszusammenfassen vertikaler, seismischer Profildatenspur, wobei jede Datenspur seismische Wellensignale aufweist, die von einer Oberflächenquelle mit einem versetzten Abstand von einem Bohrloch erzeugt werden und zu unterschiedlichen Ankunftszeiten von einem Bohrloch-Geophon empfangen werden, das in verschiedenen Tiefen in einem Schacht positioniert werden kann, wobei das Verfahren aufweist die folgenden Schritte:
 - a) Spezifizieren einer Anzahl von gemeinsamen Tiefenpunkten, die lateral in einem Abstand von dem Bohrloch positioniert sind und seitlich voneinander durch einen seitlichen Abstand D getrennt sind und in verschiedenen Tiefen lokalisiert sind, wobei jede Tiefe einer zweiwegigen, vertikalen Wanderzeit entspricht, die die erforderliche Zeit für eine Welle ist, um vertikal von der Oberfläche zu einem unterirdischen Reflektor in dieser Tiefe und wieder zurück zur Oberfläche zu wandern;
 - b) Auswählen einer Datenspur, die Signale aufweist, die in einer gewissen Geophontiefe d empfangen werden;
 - c) Auswählen einer zweiwegigen, vertikalen Wanderzeit $T_{0,r}$, die einem unterirdischen Reflektor in einer Tiefe h entspricht;
 - d) Berechnen einer Reflexionsereigniszeit t_{vsp} , die die erforderliche Zeit für die Welle ist, um von der Quelle zu einem Reflexionspunkt auf diesem unterirdischen Reflektor in der Tiefe h und dann zu dem Geophon in der Tiefe d zu wandern;
 - e) Berechnen eines seitlichen Abstands q des Reflexionspunktes von dem Bohrloch;
 - f) Herausnehmen eines Wellensignals aus der selektierten Datenspur für eine Ankunftszeit, die gleich ist der Reflexionsereigniszeit und Plazieren desselben an einem Ort K, der der Zeit $T_{0,r}$ entspricht und der seitlich in einem Abstand $VSPCDP_K$ von dem Bohrloch positioniert ist, der dem Abstand q zugeordnet ist durch die Ungleichung

$$q - VSPCDP_K < D/2,$$

wobei Signale mit Reflexionspunkten innerhalb des halben Abstandes D auf beiden Seiten des



gemeinsamen Tiefenpunktores in dem gemeinsamen Tiefenprodukt K bereichszusammengefaßt werden und wobei Signale, die sich an diesem Ort K akkumulieren, miteinander summiert werden;

g) Wiederholen der Schritte c) bis f) für eine Vielzahl von Werten der zweiwegigen, vertikalen Wanderzeit;

h) Auswählen weiterer Datenspuren und Wiederholen der Schritte b) bis g).

2. Verfahren nach Anspruch 1, dadurch gekennzeichnet, daß $T_{0,r}$ in Inkrementen von ungefähr 1 msec. ausgewählt wird.

3. Verfahren nach Anspruch 1, dadurch gekennzeichnet, daß der unterirdische Reflektor bezüglich der Oberfläche geneigt ist und daß das Verfahren weiterhin aufweist den Anfangsschritt des Einschätzens eines Neigungswinkels für den Reflektor und das Auswählen einer zweiwegigen, vertikalen Wanderzeit $T_{0,r}$ von Schritt c), der die Unterschritte aufweist

c1) Auswählen einer Tiefe, in der der Reflektor das Bohrloch schneidet und

c2) Berechnen einer zweiwegigen, vertikalen Wanderzeit $T_{0,r}$ auf der Basis der Schnittiefe und des geneigten Winkels.

4. Verfahren nach Anspruch 3, dadurch gekennzeichnet, daß die Schnittiefe um Werte von ungefähr 1,5m inkrementiert wird.

5. Verfahren nach einem der Ansprüche 1 bis 4 dadurch gekennzeichnet, daß die Oberflächenquelle von dem Bohrloch mit einem Abstand im Bereich von 91 bis 915m versetzt ist.

20 Revendications

1. Procédé pour l'exploration sismique verticale d'addition des traces de données, chaque trace de donnée comprenant des signaux d'onde sismique produits par une source de surface à une distance déportée d'un trou de sondage et reçus à différents temps d'arrivée par un géophone de trou de sondage pouvant être situé à diverses profondeurs dans un puits, comprenant les étapes consistant à:

a) spécifier un nombre d'emplacements de point de profondeur commun positionnés latéralement à une distance du trou de sondage, séparés latéralement l'un de l'autre par un espacement latéral D, et situé à diverses profondeurs, chaque profondeur correspondant à un temps de trajet vertical à deux voies étant le temps nécessaire pour une onde de traverser verticalement de la surface à un réflecteur de la couche sous la surface à ladite profondeur et en retour vers la surface;

b) sélectionner une trace de donnée comprenant des signaux reçus à une certaine profondeur d de géophone;

c) choisir un temps de trajet à deux voies $T_{0,r}$ correspondant à un réflecteur de la couche sous la surface à une profondeur de h;

d) calculer un temps d'occurrence de réflexion t_{sv} qui est le temps nécessaire pour l'onde de traverser de la source à un point de réflexion sur le réflecteur de la couche sous la surface à la profondeur h et ensuite vers le géophone à la profondeur d;

e) calculer une distance latérale q du point de réflexion à partir du trou de sondage;

f) prélever un signal d'onde de la trace de donnée sélectionnée pour un temps d'arrivée égal au temps d'occurrence de réflexion et placer celui-ci en un emplacement K correspondant au temps $T_{0,r}$ et positionné latéralement à une distance $PPCESV_K$ du trou de sondage qui est en rapport avec la distance q par l'inégalité:

$$q - VSPCDP_K < D/2,$$

où des signaux ayant des points de réflexion compris dans la moitié de l'espacement D de l'un ou l'autre côté de l'emplacement de points de profondeur commun sont additionnés à l'emplacement de point de profondeur commun K et permettant que les signaux qui s'accumulent en cet emplacement K sont sommés ensemble;

g) répéter les étapes c) à f) pour une multitude de valeurs du temps de trajet vertical à deux voies;

h) sélectionner de nouvelles traces de données et répéter les étapes b) à g).

2. Procédé selon la revendication 1, dans laquelle $T_{0,r}$ est choisi en incréments d'environ 1 milliseconde.

3. Procédé selon la revendication 1, dans laquelle le réflecteur de la couche sous la surface présente un pendage par rapport à la surface et dans laquelle le procédé comprend en outre l'étape initiale d'estimation d'un angle θ de pendage pour le réflecteur et le choix d'un temps de trajet vertical à deux voies $T_{0,r}$ de l'étape c) comprend les sous étapes de:

c1) choisir une profondeur à laquelle le réflecteur intercepte le trou de sondage, et

c2) calculer le temps de trajet vertical à deux voies $T_{0,r}$ sur la base de la profondeur d'interception et sur l'angle de pendage.

4. Procédé selon la revendication 3, dans laquelle la profondeur d'interception est incrémentée par des valeurs d'environ 1,5 mètres.

5. Procédé selon l'une quelconque des revendications 1 à 4, dans laquelle la source de surface est déportée latéralement du trou de sondage d'une distance dans la plage de 91 à 915 m.