

PATENT SPECIFICATION

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(54) MEAN LINEAR ESTIMATION OF VELOCITY

(71) We, MOBILE OIL CORPORATION, a corporation organized under the laws of the State of New York, United States of America, of 150 East 42nd Street, New York, New York 10017, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the determination of velocity from seismic traces and more particularly to a technique for determining interval velocity from seismograms.

The measurement of velocity is generally considered the most important parameter in seismic exploration. The determination of the acoustic velocity characteristics from seismograms is described in "Seismic Velocities From Subsurface Measurements", C.H.Dix, *Geophysics*, Volume 20, pages 868—886, 1955.

When, in the prior art, the RMS value of velocity as a function of time is determined from the seismograms, and the interval velocity is computed from the RMS velocity, small errors in the estimation of time or RMS velocity cause successive values of interval velocity to oscillate between exceedingly high and exceedingly low values.

This causes errors in the calculation of average velocity to depth which is the integral of interval velocity. Average velocity to depth is used in the search for pressure changes and in making maps.

Obtaining velocity curves by conventional methods requires the hand fitting of curves to data points. From these the slopes of curves fitted to an x^2-t^2 plot are used to obtain acoustic velocity. In an x^2-t^2 plot, the square of the horizontal shot-to-receiver distance or offset (x^2) is plotted against the square of the reflection time (t^2); the slope gives the inverse of the average velocity squared and the intercept gives four times the depth squared. For example, refer to "The Interpretive Significance of Automatic Velocity Determinations", John F. Bradshaw, a

paper presented at a symposium sponsored by the Pacific Coast Section of the Society of Exploration Geophysicists, Los Angeles, California, November 15, 1968. This paper describes curve fitting techniques for obtaining velocity.

One velocity determination technique obtains numeric values of velocity at each reflection for each set of seismic traces. For example, our Specification 1,304,248 describes a technique in which sets of traces, commonly referred to as common depth point or common surface point traces, are processed to obtain numeric representations of velocity at each reflection. In Figure 4 of that application there are shown numeric representations of velocity which are positioned on a plot having an abscissa representing horizontal distance along a line of exploration and an ordinate representing seismogram record time, directly related to depth. The positions of the numeric representations of velocity depict the subsurface reflecting layers.

If each vertical column or series of velocity values is converted to interval velocity, there is produced a number of interval velocity curves which do not necessarily have continuity between them. It is desirable to produce interval velocity curves which can be compared with each other from layer to layer.

While techniques such as the foregoing are useful in obtaining velocity values applicable to single separate horizontal locations each assigned to a common depth point set of traces, it is desirable to interpolate between common depth point sets to obtain velocity values for other horizontal positions.

It is an object of this invention to obtain interval velocity automatically from field seismograms without the necessity of tedious curve fitting operations performed by the operator. In carrying out the invention, mean linear estimates of velocity and time are formed from a series of ordered data points. By computing interval velocity from these mean linear estimates, the problem is avoided of having successive values of interval velocity oscillate between exceedingly high and

low values because of small errors in estimates of time or RMS velocity.

According to the invention we provide a method of seismic exploration, wherein sets of seismic traces are derived which represent the reflections of seismic energy as a function of record time, a respective set for each of a plurality of locations on a line of exploration, and wherein automatic computing apparatus is used to determine the interval velocity of the subsurface layers, the method comprising: applying a signal detection operation to said traces to detect reflections represented in said traces, computing the RMS velocity of each reflection, storing the computed values of RMS velocity and associated record times as series of consecutive data points, a respective series for each set of seismic traces, forming the mean linear estimates of RMS velocity and time from series of said consecutive data points, and computing interval velocity from said mean linear estimates.

In the preferred embodiment the step of forming the mean linear estimates comprises: fitting straight line segments to a curve of velocity as a function of time, each segment having a slope β_m , between consecutive data points of a said series, where m is an index denoting a point in the series; separating the curves of adjacent sets into time intervals in which there is only one respective straight line segment for each set; summing the slopes of said straight line segments of adjacent sets in an interval to obtain an average value

of slope $\bar{\beta}$; and repeating the summing operation for different intervals to obtain an average value of slope as a function of record time $\bar{\beta}(T)$.

In accordance with a preferred feature of the invention, the mean linear estimates of velocity are interpolated between sets of seismic traces to obtain a uniformly sampled curve of velocity as a function of time. Velocities are picked from the uniformly sampled curve at the reflection times on adjacent sets. This produces a series of data points, depicting velocity at reflection time for additional locations on the line of exploration.

Interpolation may be performed on the smoothed RMS value of velocity, on the smoothed interval velocity, or on average velocity to depth obtained by integrating interval velocity.

In accordance with another preferred feature of the invention, the data points for which interval velocity lies outside a given range are stripped from the stored array in order to eliminate multiple reflections and data points which represent the second legs of primary reflections.

The invention will now be described in

more detail and by way of illustration with reference to the accompanying drawings, in which:—

Figures 1A and 1B together form a flow chart depicting the performance of the invention on a general purpose digital computer;

Fig. 2 shows a plot of series of data points, one series for each set of common depth point traces, and in which detected reflections are depicted by numeric representations of velocity on the plot;

Fig. 3 is a plot similar to Fig. 2 made after the continuity and smoothing operations;

Fig. 4 shows line segments fitted to three pairs of data points;

Fig. 5 shows line segments for a number of sets of traces fitted between data points in difference series;

Fig. 6 shows velocity as a function of record time and particularly shows interval velocity, mean linear estimate of velocity, and smoothed mean linear estimate of velocity; and

Fig. 7 shows the interpolation to obtain smoothly sampled curves at additional points on the line of exploration.

Referring to Fig. 1 the input to the process includes sets of common depth point (CDP) or common surface point (CSP) traces. From each set of traces there can be obtained an indication of the acoustic velocity of the earth at reflecting beds which produce the seismic reflections on the traces. The first step in the process is the detection of reflections as indicated by the step 11. While many signal detection techniques can be used to pick seismic reflections and to determine the velocities of the reflectors, the process which is the subject of our Specification 1 304 248 is particularly advantageous.

The RMS velocity-to-depth of each detected reflection is computed as indicated by the step 12 in Fig. 1. The computed velocity is stored with the associated record time on the seismic traces as indicated by the step 13. The result is a stored array of data points, a respective series of data points for each set of common depth point traces. Each data point includes acoustic velocity at a detected reflection and associated record time T . These values may be plotted as indicated by the step 14. The result is a plot of the type shown in Fig. 2. The abscissa in Fig. 2 represents horizontal distance along the line of exploration. The reference numerals 15, 16 and 17 indicate the locations on this line of exploration for each of which a set of common depth point traces has been obtained. Other locations for which sets have been obtained are not indicated by reference numerals. The ordinate in Fig. 2 depicts record time on the seismograms. The numeric values on the plot indicate the acoustic velo-

city of the detected reflection. For example, below the horizontal location 15, the first numeric value is 47 indicating that the process has detected a reflection at a record time of approximately .15 seconds and that the acoustic velocity of this reflector is 4,700 feet per second. One process for obtaining a plot of the type shown in Fig. 2 is described in Specification 1 304 248, as also is the step of determining continuity of reflections between sets of CDP traces. This step is indicated at 18 in Fig. 1. That is, if the preceding process has picked an isolated event on a CDP set as a reflection, but this event has not been picked on adjacent CDP sets, the pick will be rejected. As part of the determination of continuity there is a smoothing operation as indicated at 19. This smoothing takes place over both time and velocity. As an example of the determination of continuity and smoothing, consider the following velocity picks which might appear on a plot of the type shown in Fig. 2.

73 75 76
74 77
75

A moving operator of six points is moved across these picks and the average value of the six points in the operator is selected at each point. Also, there is smoothing in the time direction. After smoothing and the continuity determination, the foregoing velocity picks might appear on the plot of Fig. 3 as follows:

73 73 74 74 75 75

After determination of continuity and smoothing along the reflections, the averaged

time $\hat{T}$, and averaged velocity $\hat{V}$ are plotted in a plot of the type shown in Fig. 3. This step is indicated at 20 in Fig. 1.

In the actual computer programme employed in this connection, the criteria for establishing continuity and for smoothing are as follows. All single and double velocity picks are deleted from the stored array. Where there are three velocity picks in a line the mean of these three points is taken. Similarly, where there are four, five or six picks in a line the mean is taken of these. Where there are above six a mixing operator of six points is used.

The next step in the process, indicated at 21 in Figure 1, is to delete the multiple reflections and the secondary legs of primary

reflections. Columns of reflection picks are deleted from the stored array and each mean value of RMS velocity is converted to interval velocity. This conversion to interval velocity is in accordance with:

$$V_{I_i} = \sqrt{\frac{\left\{v_{rms_i}\right\}^2 t_i - \left\{v_{rms_{(i-1)}}\right\}^2 t_{i-1}}{t_i - t_{(i-1)}}} \quad 60$$

where V_{I_i} represents interval velocity at the i^{th} interval, V_{rms} is RMS velocity and t is record time.

Those values of interval velocity lying outside a given range are identified as multiples, or as secondary legs of a primary reflection. For example, one may adopt limits of 4,000 to 30,000 feet per second for interval velocity values. When a value of interval velocity outside this range is detected, the corresponding value of RMS velocity in the array is deleted from the array.

The next portion of the process includes the formation of the mean linear estimate (as hereinafter explained) of velocity and time. This includes the steps 22, 23 and 24. In making a mean linear estimate of velocity and time, vertical series of data points are operated upon. For example, referring to the right hand column of Fig. 3, the data points 51 (5,100 feet per second at .45 second) 69, (6,900 feet per second at .68 second) and (7,000 feet per second at .77 second) may be considered a series. The process finds a mean curve which fits this series. This may be explained with reference to Figs. 4 wherein the three points are plotted on velocity-time scales. That is, the point T_1, V_1 is the time .45 seconds and the velocity 5,100 feet per second; the point T_2, V_2 is the time .68 seconds and the velocity 6,900 feet per second; and the point T_3, V_3 is the time .77 seconds and the velocity 7,000 feet per second. For each series, a curve comprising straight line segments having slope β_m between consecutive data points is given. This continuous curve between data points is defined by the equation

$$v_m = \beta_m t + V_{0m}$$

where m is an index, V_m is the r.m.s. velocity of the m^{th} point in the series. The slope of each line and the velocity of each point are given by:

$$\beta_m = \frac{V_{m+1} - V_m}{T_{m+1} - T_m}; \quad V_{0m} = \frac{V_m + V_{m+1}}{2} - \frac{\beta_m}{2} (T_m + T_{m+1})$$

The step of curve fitting line segments between consecutive data points is indicated at 22 in Fig. 1.

Whereas Fig. 4 shows one set (series) of points from a vertical column, Fig. 5 shows several series from adjacent columns. These series are divided into intervals in which there are no breaks in the slopes of any of the curves. That is, in each interval there is only one respective straight line segment for each set. For example, the interval between the times 25 and 26 is the first interval. The slopes of all of the lines over this interval are

averaged to obtain an averaged value of $\bar{\beta}$. Similarly, the second interval between the times 26 and 27 in Fig. 5 has no breaks in the slopes of any of the curves. The slopes of all of the lines over this interval are averaged to obtain an averaged value of slope. The step of separating the curves into intervals having only one respective straight line segment for each set is indicated at 23. The step of summing the slopes of the line segments over each interval is indicated at 24.

It is important to average these slopes over intervals which do not have breaks in the slopes of the curves. Otherwise, these breaks will distort the mean value of slope. In actual practice, between 12 and 24 sets (vertical columns) are averaged to obtain the mean value of slope. Up to 48 sets have been used. In obtaining the average value of slope an index is always carried along to indicate how many sets are in each interval. Note that the number of sets will vary from interval to interval.

From the mean values of slope, estimates of average velocity $\hat{V}$ and times $\hat{T}$ are derived which we refer to as mean linear estimates of velocity and time. The average values of velocity are smoothed again as indicated at 28 in the flow chart of Figure 1. These mean linear estimates of velocity as a function of time are plotted in Figure 6 as the plot 30 and the smoothed mean linear estimates are the plot 29. The step of plotting these functions is indicated at 31 in Figure 1.

The mean value of all of the slopes in each interval is used in the computation of interval velocity from the following equation:

$$V_i(T) = \sqrt{2V\bar{\beta}(T)T + V^2}.$$

In the foregoing $V_i(T)$ is interval velocity as a function of time, V is mean linear estimate

of the RMS velocity as a function of time, $\bar{\beta}$ is average slope and T is seismic record time. The step of computing interval velocity is indicated at 32 and the plotting of these

functions is indicated at 33 in Figure 1. The values of interval velocity obtained in this manner are plotted as shown by the dashed plot 34 in Figure 6.

The smoothed RMS velocity $\hat{V}_{RMS}$, the smoothed interval velocity $\hat{V}_i$, or the average velocity $\hat{V}_{AVE}$ may be interpolated for locations on the line of exploration between those for which the CPD sets are applicable. The average velocity is obtained by integrating the interval velocity as indicated by the step 35.

One of the three velocities, $\hat{V}_{RMS}$, $\hat{V}_i$ or $\hat{V}_{AVE}$ is interpolated between sets. Referring to Figure 7, assume that a velocity curve has been obtained for each of the points 36, 37 and 38 along the line of exploration. Interpolation of the curves 39 and 40 produces the uniformly sampled curve 41. From this curve 41 values of velocity at the times T are picked. The interpolation step is indicated at 42 in Fig. 1 and the picking of velocity values at reflection times is indicated at 43.

From the foregoing it will be apparent that the method of the present invention can be practiced with the use of several well known types of computing apparatus. The method is particularly suitable for use with a general purpose digital computer.

One particular computing system which is suitable for use is supplied by the Control Data Corporation under the general model designation 6600, and includes the following components

Central Computer, 65K Memory	
6608 Disc System	
6602 Console Display	
6681 Data Channel Converter	
3228 Magnetic Tape Controller	95
607 Magnetic Tape Transport	
3447 Card Reader Controller	
405 Card Reader	
3256 Line Printer Controller, and	
501 Line Printer	100

WHAT WE CLAIM IS:—

1. A method of seismic exploration, wherein sets of seismic traces are derived which represent the reflections of seismic energy as a function of record time, a respective set for each of a plurality of locations on a line of exploration, and wherein automatic computing apparatus is used to determine the interval velocity of the subsurface layers, the method comprising: applying a signal detection operation to said traces to detect reflections represented in said traces; computing the RMS velocity of each reflection; storing the



The step of curve fitting line segments between consecutive data points is indicated at 22 in Fig. 1.

Whereas Fig. 4 shows one set (series) of points from a vertical column, Fig. 5 shows several series from adjacent columns. These series are divided into intervals in which there are no breaks in the slopes of any of the curves. That is, in each interval there is only one respective straight line segment for each set. For example, the interval between the times 25 and 26 is the first interval. The slopes of all of the lines over this interval are

averaged to obtain an averaged value of $\bar{\beta}$. Similarly, the second interval between the times 26 and 27 in Fig. 5 has no breaks in the slopes of any of the curves. The slopes of all of the lines over this interval are averaged to obtain an averaged value of slope. The step of separating the curves into intervals having only one respective straight line segment for each set is indicated at 23. The step of summing the slopes of the line segments over each interval is indicated at 24.

It is important to average these slopes over intervals which do not have breaks in the slopes of the curves. Otherwise, these breaks will distort the mean value of slope. In actual practice, between 12 and 24 sets (vertical columns) are averaged to obtain the mean value of slope. Up to 48 sets have been used. In obtaining the average value of slope an index is always carried along to indicate how many sets are in each interval. Note that the number of sets will vary from interval to interval.

From the mean values of slope, estimates of average velocity $\hat{V}$ and times $\hat{T}$ are derived which we refer to as mean linear estimates of velocity and time. The average values of velocity are smoothed again as indicated at 28 in the flow chart of Figure 1. These mean linear estimates of velocity as a function of time are plotted in Figure 6 as the plot 30 and the smoothed mean linear estimates are the plot 29. The step of plotting these functions is indicated at 31 in Figure 1.

The mean value of all of the slopes in each interval is used in the computation of interval velocity from the following equation:

$$V_i(\tau) = \sqrt{2V\bar{\beta}(\tau)\tau + V^2}.$$

In the foregoing $V_i(T)$ is interval velocity as a function of time, V is mean linear estimate of the RMS velocity as a function of time, $\bar{\beta}$ is average slope and T is seismic record time. The step of computing interval velocity is indicated at 32 and the plotting of these

functions is indicated at 33 in Figure 1. The values of interval velocity obtained in this manner are plotted as shown by the dashed plot 34 in Figure 6.

The smoothed RMS velocity $\hat{V}_{RMS}$, the smoothed interval velocity $\hat{V}_i$, or the average velocity $\hat{V}_{AVE}$ may be interpolated for locations on the line of exploration between those for which the CPD sets are applicable. The average velocity is obtained by integrating the interval velocity as indicated by the step 35.

One of the three velocities, $\hat{V}_{RMS}$, $\hat{V}_i$ or $\hat{V}_{AVE}$ is interpolated between sets. Referring to Figure 7, assume that a velocity curve has been obtained for each of the points 36, 37 and 38 along the line of exploration. Interpolation of the curves 39 and 40 produces the uniformly sampled curve 41. From this

curve 41 values of velocity at the times $\hat{T}$ are picked. The interpolation step is indicated at 42 in Fig. 1 and the picking of velocity values at reflection times is indicated at 43.

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3256 Line Printer Controller, and
501 Line Printer

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1. A method of seismic exploration, wherein sets of seismic traces are derived which represent the reflections of seismic energy as a function of record time, a respective set for each of a plurality of locations on a line of exploration, and wherein automatic computing apparatus is used to determine the interval velocity of the subsurface layers, the method comprising: applying a signal detection operation to said traces to detect reflections represented in said traces; computing the RMS velocity of each reflection; storing the



computed values of RMS velocity and associated record times as series of consecutive data points, a respective series for each set of seismic traces; forming mean linear estimates of RMS velocity and time from series of said consecutive data points; and computing interval velocity from said mean linear estimates.

2. The method according to Claim 1, wherein the step of forming the mean linear estimates comprises: fitting straight line segments to a curve of velocity as a function of time, each segment having a slope β_m , between consecutive data points of a said series, where m is an index denoting a point in the series; separating the curves of adjacent sets into time intervals in which there is only one respective straight line segment for each set; summing the slopes of said straight line segments of adjacent sets in an interval

to obtain an average value of slope $\bar{\beta}$; and repeating the summing operation for different intervals to obtain an average value of slope

as a function of record time $\bar{\beta}(T)$.

3. The method according to Claim 1 or 2, wherein the step of computing interval velocity is performed in accordance with:

$$V_i(T) = \sqrt{2V \bar{\beta}(T) \cdot T + V^2}$$

where $V_i(T)$ is interval velocity as a function

of time, $\bar{\beta}(T)$ is the average value of slope at the record time T and V is the RMS velocity at the record time T.

4. The method according to any preceding Claim comprising: smoothing the mean linear estimates of velocity and time to obtain a smoothed mean linear estimate of velocity and time.

5. The method according to any preceding Claim, further comprising detecting continuity between data points of adjacent sets, and deleting from storage the data points for which continuity is not detected.

6. The method according to any preceding Claim further comprising deleting from storage data points for which the interval velocity lies outside a given range to eliminate multiple reflections.

7. The method according to any preceding Claim further comprising integrating said interval velocity to obtain true average velocity.

8. The method according to any preceding claim further comprising interpolating said mean linear estimates of velocity between sets to obtain uniformly sampled values of velocity as a function of time for an intervening location on said line of exploration, and picking velocities from said uniformly sampled values at the record time of reflections of sets adjacent to said location to produce a series of data points relating to said location.

9. Method of seismic exploration according to claim 1 and substantially as hereinbefore described.

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