

PATENT SPECIFICATION

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DRAWINGS ATTACHED

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(54) CONTINUOUS VELOCITY ESTIMATION

(71) We, MOBIL OIL CORPORATION, a corporation organised 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:—

The invention relates to the estimation of acoustic velocity from a set of seismic traces and more particularly to producing an index set of travel time curves for use in the estimation of acoustic velocity.

In seismic exploration, the measurement of velocity is generally considered the major parameter in the processing and interpretation of seismograms. The determination of the acoustic velocity characteristics of seismograms is described in "Seismic Velocities From Subsurface Measurements", C. H. Dix, *Geophysics*, Vol. 20, pages 68—86, 1955. In general, acoustic velocity is determined from seismograms by the following relationship:

$$\Delta T^2 = \frac{x^2}{V^2} - 2T_0 \Delta T$$

wherein x is the horizontal offset distance from a given detection point to the seismic source, T_0 is the reflection time at the detection point when x is zero, i.e. the zero offset time, ΔT is the time difference between T_0 and the reflection time detected at distance x , and V is the acoustic velocity of the earth. We call the curve which expresses this relationship a travel time curve.

One type of field technique which produces sets of traces in which the reflection times follow the above relationship is commonly referred to as common depth point, or common reflection point, seismic exploration.

The acoustic velocity characteristic of the earth is an important parameter used in geophysical interpretation. It is also necessary to know acoustic velocity as accurately as possible

in order to make normal move-out corrections of the seismic traces. U.S. patent 3,417,370, Brey, shows a typical system in which signal detection techniques are used to estimate acoustic velocity from seismic traces. In techniques such as this velocity is computed for each trace for each time of interest, typically for equally spaced zero offset times. These computations of velocity consume a great amount of computer time.

In its broadest aspect the invention provides a method of processing of seismic traces representing reflections of seismic energy produced from a plurality of spaced sources and reflected from subsurface interfaces, utilizing automatic computing apparatus, comprising detecting signals in each of a plurality of said seismic traces along several travel time curves, as hereinbefore defined, each computed for one of a range of assumed acoustic velocities, selecting the acoustic velocity corresponding to maximum detected signal and plotting the alpha numeric representation of the selected acoustic velocity upon a chart of horizontal earth surface distance *versus* record time.

In a preferred embodiment of the method according to the invention, curves expressing the relationship:

$$\Delta T^2 = \frac{x^2}{V^2} - 2T_0 \Delta T$$

wherein T represents reflection signal time on a particular trace, T_0 being zero offset time and ΔT being the time shift of the same reflection from trace to trace, x represents horizontal offset distance associated with the particular trace and V is the acoustic velocity of the earth, are computed for a particular zero offset sampling time in a set of seismic traces to constitute an index set of travel time curves, said signal values are detected in said traces along the travel time curves for a plurality of iterated zero offset sampling times to which the same index set is applied, and the velocity respectively satisfying each

curve in the index set is computed for each zero offset sampling time.

According to further features of the preferred embodiment, the method comprises
 5 summing the signal values detected in each of the seismic traces at periodic sampling times specified by one of said travel time curves, to form a sum representing the signal power of said traces along said travel time
 10 curve, and iterating the summation for each travel time curve in the index set to form respective sums each indicating the signal power of reflections along a different travel time curve. Said sums are compared to
 15 identify the travel time curve associated with maximum reflection signal power, and the acoustic velocity is selected which satisfies the identified travel time curve. The selected acoustic velocity is plotted at a plot position
 20 representing the zero offset time for which it was selected. The foregoing summation, selection and plotting steps are iterated for different zero offset times and for different sets of seismic traces from a spread of sources, and
 25 a line segment is plotted to represent a reflection with continuity across a space representing the distance between two adjacent sources, if a reflection is detected from one said source which falls within a predetermined record
 30 time of a reflection detected from the other.

According to the preferred mode of performing the present invention, an index set of travel time curves is arrived at which
 35 specifies ΔT versus x for a set of velocities such that the travel time curves pass through sample points on the outermost trace of a set of traces from an expanding spread. This index set is computed only once and it can
 40 be used to obtain velocity for every trace with a minimum of computation time.

Initially, an apriori estimate of velocity is made to determine the range of velocities over which travel time curves will be computed.
 45 Then the index set of travel time curves is computed in this bracketed range.

At the first sampling time on the first trace in the set of traces, a set of travel time curves is generated relating the horizontal distance x to each source, the time
 50 shift of a given event from trace to trace ΔT , the acoustic velocity V , and the zero offset time T_0 . For succeeding zero offset times, the velocity which respectively satisfies each curve in the set is recomputed, x and ΔT being the same.
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Seismic reflections in the traces are identified by detecting the signal across the traces along the travel time curves. In one particular signal detection technique, the traces are
 60 summed along each of the travel time curves in the set. The maximum signal power identifies the proper velocity.

The selected acoustic velocity is then plotted at the zero offset time and at the
 65 horizontal position for which it was selected.

A determination is made as to whether selected reflections have continuity between sets of seismic traces. If continuity is detected, a continuous line segment is plotted with the associated acoustic velocity.

In the accompanying drawings,

Fig. 1 depicts a set of seismic traces;

Fig. 2 is a block diagram of a system making use of the invention;

Fig. 3 is a flow sheet depicting the process of the present invention;

Fig. 4 shows a plot of velocities; and

Fig. 5 shows a plot with continuity indicated between reflections.

Referring to Fig. 1, there is shown a set of seismograms, $S_1, S_2 \dots S_1 \dots S_n$. As is the usual practice, these seismograms are digitized so that values at periodic sample times, indicated by the vertically spaced dots, represent reflections of seismic energy. The seismic energy is produced from a plurality of spaced sources and reflected from subsurface interfaces. The abscissa in Fig. 1 represents horizontal distance x along a line of exploration. Sources of seismic energy and detectors for detecting the reflected seismic energy are spaced along the line of exploration. In Fig. 1, x_1 is the horizontal distance of the detector producing seismogram 1, x_i is the horizontal distance of the seismometer producing the trace S_i and so on.

The zero offset times for this set of traces are the theoretical times of reflections for a trace from a detector directly beneath the source, at the location denoted x_0 . The zero offset times of T_1 and T_2 have been denoted in Fig. 1. As previously mentioned, the times of reflections across this set of traces are described by:

$$\Delta T^2 = \frac{x^2}{V^2} - 2T_0 \Delta T \quad 105$$

where V is acoustic velocity, T_0 is the zero offset time, T is the time of a reflection signal on a particular trace, x is the horizontal offset distance associated with that trace and ΔT is the time shift of the same reflection from trace to trace. Stated another way, the times of reflections across the set of traces are specified by a hyperbolic curve, the shape of which depends upon the acoustic velocity of the earth, and which we refer to as a travel time curve. Two hyperbolic curves have been drawn across the set of traces in Fig. 1 to show the expected time of arrival of a particular reflection for two different assumed values of velocity V_1 and V_2 .
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Before describing the process by which the present invention estimates velocity, reference is made to Fig. 2 which depicts the type of processing in which the present invention is useful. The technique of this invention can
 125 be used to determine the reflection times and

the time shifts as indicated at 11. These reflection times and time shifts can be used for normal moveout correction as indicated at 12. After normal moveout correction, the traces can be conventionally stacked to enhance the reflections. It is important to note that in this normal moveout correction no intermediate computations of velocity are required. The traces are merely composited along those ΔT , x curves which yield the maximum composite signal.

The stacked traces are again applied to the technique of this invention as indicated at 13. The output is reflection times, time shifts and velocity. The amplitude of the reflections are determined and a determination is made as to whether there is continuity between reflections as indicated at 14. The output is a matrix 15 indicating time, distance, velocity and amplitude of each reflection. This time-distance-velocity-amplitude matrix can be used in a number of ways.

The traces can be restacked as indicated at 16 to further enhance signal reflections. The information can be used in a velocity modeling routine 17. Alternatively, the information can be used in a migration and mapping technique, or the information can be used to compute and sort multiple reflections. The flow sheet of the process of an embodiment of this invention is shown in Fig. 3. The inputs to the system include sets of common depth point traces, each set including traces S_1-S_n . Also applied as inputs to the system are the limits of the range of expected velocities, the range being defined by the limits V_1 and V_2 . Another input to the system is the threshold α against which the signal power of reflections is compared to determine whether a reflection exists along a particular expected T versus x travel time curve.

The first two indicated steps are used to start the computation of travel curves from particular samples on the last trace S_n . As indicated at 20, the expected time shift ΔT to the far traces S_n is computed for the velocity V_2 . As shown in Fig. 1, this ΔT occurs at the point 21 on the trace S_n . That is, the travel time curve does not fall on a sample point of the far trace S_n . Therefore, the routine selects the ΔT corresponding with the sample point occurring at 22 in Fig. 1. The selection of this ΔT that falls on the sample 22 is indicated at 23 in the flow sheet. Using this ΔT , the actual velocity for that travel time curve can be computed. Then, the expected ΔT for each of the other traces $S_1 \dots S_{n-1}$ can be computed. This specifies a travel time curve:

$$\Delta T^2 = \frac{x^2}{V^2} - 2T_0\Delta T$$

Then, other travel time curves are computed for other samples on the trace S_n . For example, the travel time curves which intersect S_n at the sample times 24, 25, and so on, are each computed. The computations of these travel time curves are indicated at 26 in the flow sheet. As indicated at 27, the computation of travel time curves is iterated for assumed velocities in the range V_1 to V_2 . For example, there may be 100 travel time curves in the resulting index set.

This index set of travel time curves is now applied to a larger value of T_0 , but the curvature of each respective curve as characterized by ΔT remains the same as before. The respective assumed velocities appropriate to the new position of each curve are then computed. This process is repeated for different iterated zero offset times as indicated at 28. At each successive zero offset time, the associated value of velocity is smaller. This approach permits the calculation of an index set for signal detection once, or at most a limited number of times, for each record. This is to be contrasted with prior art techniques wherein an index is computed for each velocity for each time of interest thereby consuming a great deal more computer time. For example, there are normally approximately 2000 sample times on each trace for which determination of velocity must be made. The calculation of velocity on each trace for each sample time requires a great lead of computation. On the other hand, by the procedure adopted in the present invention, the ΔT values for the index set of curves are computed only once and serve for all the traces. For each one of the 2000 sample times on one trace we in principle compute only the velocity for each curve.

It should be noted however that it will probably not be possible to use the same index set of travel times curves over the full length of the records. The range of velocities will change for each sample time. For example, assume that the range for zero offset time T_1 was $V_1=12,000$ feet per second and $V_2=5,000$ feet per second. For the zero offset time T_2 , the range might become 4,751 to 9,275 feet per second. At some later record time, the range of velocities associated with the index set may not encompass the range of actual velocities expected in that area. Therefore, at this point, there must be a recomputation of the travel time curves. Three or more index sets of travel time curves should be used over the full record length. In practice, an index set is computed for each 25 samples.

In carrying out the present invention, reflections in the traces are detected along the curved lines of the index set. One particular signal detection technique which can be used is to sum the samples from each trace along one of the curved lines. For example, refer-

ring to Fig. 1, the sum is formed of the value at the sampling time 29 on the first place, the sampling time 30 on the second trace, the sampling time 31 on the *i*th trace, the sampling time 32 on the *n*th trace, and the values at the sampling times on intermediate traces specified by the same travel time curve. This sum indicates the signal power of reflections along that line. A similar sum is formed along each of the curves in the index set. This summation of the traces along the travel time curves is indicated at 33 in Fig. 3.

The sums are compared to determine the travel time curve associated with the maximum reflection signal power. The acoustic velocity associated with the travel time curve so identified is selected as the acoustic velocity at that time. Next, a determination of whether an actual reflection exists at this record time is made. This is done by comparing the sum of the threshold α . The search for sums exceeding α is indicated at 34 in the flow sheet. Where the sum exceeds the threshold α , the value of velocity is plotted as indicated at 35.

A portion of a plot produced by the subroutine indicated at 35 is shown in Fig. 4. In this plot, the abscissa is horizontal distance between common depth point sets and the ordinate is record time. For example, at the record time t_1 , the velocity 4900 feet per second is plotted for the CDP set at the extreme right. At the time t_2 , the velocity 4700 is plotted for this CDP set. At the time t_3 , the velocity 4800 is plotted for this CDP set.

For the next CDP set to the left, the velocity 4800 is plotted at time t_1 , the velocity 4700 is plotted at the time t_2 , and the velocity 4800 is plotted at the time t_3 .

The next set of instructions in the process determines whether there is reflection continuity, that is, whether the same reflection has been detected between adjacent CDP sets. This set of instructions is indicated at 36 in the flow sheet.

Continuity is determined by looking for a reflection which, for example, falls within 20 milliseconds on either side of a reflection detected for an adjacent CDP set. If there is continuity, a line segment is plotted with continuity across a space representing the distance between adjacent sources. The plotting of these line segments is indicated at 37.

A portion of a plot produced in accordance with this technique is shown in Fig. 5. Fig. 5 shows the plotting of velocities for twelve adjacent CDP sets. (This plot is derived from the same area as the plots between the points 38 and 39 in Fig. 4. Note that Figs. 4 and 5 have different scales). At 1.0 seconds record time in Fig. 5, there is a line segment indicating the detection of a continuous reflection across all twelve CDP

sets. Other continuous reflections have been plotted in Fig. 5.

A plot, such as that shown in Fig. 5, is a useful tool for the geophysicist. It indicates continuous reflections, and it also indicates the acoustic velocity characteristics of the earth associated with that continuous reflection.

While 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.

WHAT WE CLAIM IS:—

1. A method of processing seismic traces representing reflections of seismic energy produced from a plurality of spaced sources and reflected from subsurface interfaces, utilizing automatic computing apparatus, comprising detecting signals in each of a plurality of said seismic traces along several travel time curves, as hereinbefore defined, each computed for one of a range of assumed acoustic velocities, selecting the acoustic velocity corresponding to maximum detected signal and plotting the alpha numeric representation of the selected acoustic velocity upon a chart of horizontal earth surface distance *versus* record time.

2. A method according to claim 1 wherein curves expressing the relationship:

$$\Delta T^2 = \frac{x^2}{V^2} - 2T_0 \Delta T$$

wherein T represents reflection signal time on a particular trace, T_0 being zero offset time and ΔT being the time shift of the same reflection from trace to trace, x represents horizontal offset distance associated with the particular trace and V is the acoustic velocity of the earth, are computed for a particular zero offset sampling time in a set of seismic traces to constitute an index set of travel time curves, said signals are detected in said traces along the travel time curves for a plurality of iterated zero offset sampling times to which the same index set is applied, and the velocity respectively satisfying each curve in the index set is computed for each zero offset sampling time.

3. A method according to claim 2 which comprises summing the signals detected in each of the seismic traces at periodic sampling times specified by one of said travel time curves, to form a sum representing the signal power of said traces along said travel time curve, and iterating the summation for each travel time curve in the index set to form respective sums each indicating the signal power of reflections along a different travel time curve.

4. A method according to claim 3 further



ring to Fig. 1, the sum is formed of the value at the sampling time 29 on the first place, the sampling time 30 on the second trace, the sampling time 31 on the *i*th trace, the sampling time 32 on the *n*th trace, and the values at the sampling times on intermediate traces specified by the same travel time curve. This sum indicates the signal power of reflections along that line. A similar sum is formed along each of the curves in the index set. This summation of the traces along the travel time curves is indicated at 33 in Fig. 3.

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The next set of instructions in the process determines whether there is reflection continuity, that is, whether the same reflection has been detected between adjacent CDP sets. This set of instructions is indicated at 36 in the flow sheet.

Continuity is determined by looking for a reflection which, for example, falls within 20 milliseconds on either side of a reflection detected for an adjacent CDP set. If there is continuity, a line segment is plotted with continuity across a space representing the distance between adjacent sources. The plotting of these line segments is indicated at 37.

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sets. Other continuous reflections have been plotted in Fig. 5.

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2. A method according to claim 1 wherein curves expressing the relationship:

$$\Delta T^2 = \frac{x^2}{V^2} - 2T_0 \Delta T$$

wherein T represents reflection signal time on a particular trace, T_0 being zero offset time and ΔT being the time shift of the same reflection from trace to trace, x represents horizontal offset distance associated with the particular trace and V is the acoustic velocity of the earth, are computed for a particular zero offset sampling time in a set of seismic traces to constitute an index set of travel time curves, said signals are detected in said traces along the travel time curves for a plurality of iterated zero offset sampling times to which the same index set is applied, and the velocity respectively satisfying each curve in the index set is computed for each zero offset sampling time.

3. A method according to claim 2 which comprises summing the signals detected in each of the seismic traces at periodic sampling times specified by one of said travel time curves, to form a sum representing the signal power of said traces along said travel time curve, and iterating the summation for each travel time curve in the index set to form respective sums each indicating the signal power of reflections along a different travel time curve.

4. A method according to claim 3 further



comprising comparing said sums to identify the travel time curve associated with maximum deflection signal power, and selecting the acoustic velocity satisfying the identified travel time curve.

5 5. A method according to claim 4 further comprising plotting the selected acoustic velocity at a plot position representing the zero offset time for which it was selected.

10 6. A method according to claim 5 comprising iterating the steps defined in claims 3, 4 and 5 for different zero offset times and for different sets of seismic traces from a spread of sources and plotting a line segment to
15 represent a reflection with continuity across a space representing the distance between two adjacent sources if a reflection is detected from one said source which falls within a predetermined record time of a reflection
20 detected from the other.

7. A method of processing seismic traces substantially as herein described with reference to the accompanying drawings.

8. An array of computer signals representing a velocity section of the earth's subsurface indicating subsurface reflections, said array being obtained by the method of any preceding claim, in which array alpha numeric representations of acoustic velocity obtained from a seismic survey are stored as a function of horizontal earth surface distance and record time.

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