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(54) CONVERTING SEISMIC TRACES TO A SEISMIC DEPTH SECTION AND THEN CONVERTING THE SEISMIC DEPTH SECTION TO A SEISMIC TIME SECTION

(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:—

This invention relates to seismic exploration and more particularly to generating a seismic time section which can be compared to the original field data.

Seismic modeling provides the geophysicist with knowledge of the manner in which seismic waves are reflected from various configurations of subsurface formations. Time sections generated in modeling studies simulate a miniaturized exploration program carried out on metal and plastic plates. U.S. patents 2,834,422—Angona, and 3,246,290—McClure, are directed to analog type modeling studies. These investigations greatly increase the understanding of wave propagation phenomena associated with exploration seismology. However, analog model studies pose a number of problems which are not easily solved. Modeling parameters are limited. That is, plate materials have a limited range of velocity and density. The time required to construct any but the simplest models is prohibitive. Also, analog models produce many wave phenomena which are of no consequence in exploration seismology, such as converted waves, shear waves and reflections from model edges.

The use of a digital computer to generate seismic models provides an attractive alternative to analog models. Copending application No. 37594/70 (Specification 1347765) is directed to the use of a digital computer to determine interval velocity by an iteration process which fits an arbitrarily dipping Snell's Law layered model to the field data.

In the performance of the present inven-

tion, the principles of seismic modelling with a digital computer may be extended to produce a seismic time section depicting travel time versus distance curves which can be compared to the original field data.

In an embodiment of the invention, the arrival times of seismic energy reflected from a fault are generated by the same process used to generate the arrival time curve for other reflecting interfaces.

In another embodiment of the invention, the coordinates of a point on a seismic depth section are automatically translated by means of a ray tracing algorithm into the coordinates of the corresponding point on a seismic time section.

According to the present invention, there is provided a method of producing a seismic record from seismic traces representing the arrival time of seismic reflections at detectors spaced along lines of exploration, which comprises carrying out in an automatic computing system and plotting means the steps of:

- (A) converting the seismic traces to a seismic depth section representing the interval velocity, depth, and dip of the reflecting zones of a subsurface formation, and
- (B) converting the seismic depth section to a plotted seismic time section representing the travel times to the reflecting zones as functions of the subsurface coordinates along the lines of exploration.

In accordance with a specific embodiment of the invention, the velocity, thickness and depth of each reflecting zone of subsurface formations are automatically determined from seismic field data representing the arrival time and time dip of the seismic reflections. For a particular reflecting zone, the coordinates of sampling points along the interface are generated. The ray path at each sampling point, normal to the interface, is generated

to determine the surface coordinates where the ray strikes the surface. From this ray path, and the velocity and thickness of each zone, the time for seismic energy to travel between the sampling point and the surface coordinate point is determined. The times are generated for all sampling points on the interface and these times are plotted in the form of a travel versus horizontal distance curve. Repeating the process for succeeding reflecting zones generates a time section which can be compared to the original seismic data.

The invention can be performed in a batch type process with all steps automatically performed to generate a seismic time section which is produced by an automatic plotter. Alternatively, computer graphics type equipment can be used in which there is a display generated at succeeding stages of the process. The coordinates of a point on a seismic depth section are generated by the application of an interactive device such as a light pen to the point. These coordinates are converted by ray tracing to the coordinates of the corresponding point on the seismic time section. The seismic time section is displayed on another display device.

By using computer graphics techniques, the interpreter can enter the configuration of a suspected fault on the seismic depth section. The travel times for seismic energy reflected from this fault are automatically generated by the same procedure used to generate travel times from other reflecting interfaces.

Fig. 1 is a block diagram of an embodiment of the invention;

Fig. 2 shows ray paths in a multilayered model in which the source and the receiver are at the same location;

Fig. 3 shows the ray paths generated for a single interface and the travel time curve computed from these ray paths;

Fig. 4 is a flow sheet depicting the manner in which the seismic time section is generated in a digital computer;

Fig. 5 shows the ray paths of the diffractions from a faulted interface;

Fig. 6 shows a seismic depth section as generated during a batch type process;

Fig. 7 shows a seismic time section as generated during a batch type process;

Fig. 8 shows a seismic depth section generated during a computer graphics type process; and

Fig. 9 shows a seismic time section generated during a computer graphics type process.

Referring to Fig. 1, the initial step in the process of this embodiment of the invention is the estimation of the acoustic velocity characteristics of the earth in the various reflecting zones of the subsurface formation. There are many suitable procedures for determining the acoustic velocity characteristics of the

earth from seismic records. As indicated at 1a, one particularly suitable procedure is that described in the copending application No. 50471/70 (Specification 1304248).

Briefly, this process provides a continuous estimation of the velocity characteristics of the earth by determining the signal power in seismic traces along an index set of travel time versus horizontal distance curves. An assumed acoustic velocity characteristic is associated with each travel time curve. The curve having the maximum signal power is taken as indicative of the actual acoustic velocity. In this manner, acoustic velocity is estimated for each reflection.

The output of the velocity estimation process is a plot of reflections occurring at various record times together with the acoustic velocity associated with each reflection. Such a plot can be displayed on the display device of a computer graphics system. The display step is indicated at 2a in Fig. 1.

Such a display includes plots of numerous, unconnected, reflections in the reflecting interfaces in the subsurface which have been detected during the signal detection process. In order to generate a time section suitable for further processing, it is necessary to interconnect these various unconnected reflection strings. Normally, it will be apparent to a geophysicist observing such a display as to which strings should be interconnected. By using an interactive device such as a light pen on the face of the display device, these strings can be automatically interconnected. Other interactive devices such as a stylus can be used. Programs for interconnecting the reflections in the manner are available with most computer graphics systems. The process may be referred to as interconnecting "polystrings". This step is indicated at 3a in Fig. 1.

After the polystrings have been interconnected, the display indicated at 3a will be of the form shown in Fig. 5 of the aforementioned application No. 50471/70 (Specification No. 1304248). The signals represented by this display are made the input to a modeling process indicated at 4a. The signals, representing continuous reflections on a time versus horizontal distance plot, are converted to a depth section by the modeling routine 4a. More specifically, one suitable routine is the stratigraphic velocity modeling routine disclosed in application No. 37594/70 (Specification No. 1347765). Briefly, the velocity modeling process determines interval velocity by iteration which fits an arbitrarily dipping Snell's Law layered model to the field data. Reflections on the seismogram are characterized by three parameters, their zero offset arrival time T_0 , their apparent average velocity V_a , and their time dip ΔT . That is, a set of reflections 1, 2, 3 . . . i can be characterized by the set of arrival times $T_i(X)$ and

dips ΔT_1 . These parameters can be determined directly from the field seismograms by several processes but the aforementioned continuous velocity estimation technique is particularly suitable for this purpose.

The stratigraphic velocity modeling routine 4a generates the interval velocity by fitting dipping layered model to this data. In addition, the migrated subsurface attitude of the reflector is obtained. The use of the velocity model permits the migration of the original data into its true spatial position. The output of the stratigraphic velocity modeling routine represents the spatial position of each reflecting point together with the interval velocity of the layers between the reflecting points.

This output is displayed as indicated at 5a. At each estimate of interval velocity, and each indicated reflector, a model of the reflecting zone is generated by merely interconnecting the indicated reflecting points. Again, this step is easily performed with a computer graphics type of system. At the same time, suspected faults in the subsurface layering can be entered with an interactive device. This step is indicated at 6a in Fig. 1.

The resultant output indicates the interval velocity, thickness, depth and dip of each reflecting zone of a subsurface formation. From this output, a seismic time section is automatically generated, in the computer, and in a form which can be compared to the original seismic traces. The generation of the time section, in accordance with this invention, is indicated at 7a. The resultant output is utilized by plotting means for the production of the seismic time section as indicated at 8a. The plotting means may be a cathode ray tube type of display device on which the seismic time section is displayed. Alternatively, the plotting means may be an automatic plotter, one example of which is the "Calcomp" (registered Trade Mark) plotter available from California Computer Products Company.

Before describing in detail the operation of the digital computer in generating the seismic time section, there will be described the general principles involved in generating this time section.

In one embodiment, the invention takes advantage of the fact that a perfectly corrected time section is one in which each trace after correction has the same form as one in which the source and receiver occupy the same position. In such a system, the downgoing and upgoing ray paths to a reflector overlap, and are normal to the reflector. Fig. 2 shows such a ray path between a source and receiver at the same location.

The model seismic depth section which is the input to the process at 7a is in the form of data representing the continuous interfaces 1 to 6 in Fig. 2. These interfaces define the depth and dip of reflecting zones

and the interval velocity of each reflecting zone is specified. For a particular reflecting zone, the coordinates of sampling points along the interface are generated. In Fig. 2, the x, y coordinates of the sampling points 7 to 11 on the interface 1 are generated by the system shown in Fig. 1. As will be subsequently explained, the sampling points must be much more dense than is indicated in Fig. 2.

For each of these sampling points, the ray path normal to the interface and extending to a surface coordinate point is generated.

This can be better seen with reference to Fig. 3. Fig. 3 shows, at the bottom, a single reflecting interface 12 with ray paths 13 to 16 extending respectively from the sampling points 17 to 20 to the surface coordinate points 21—24. The ray path 13 is normal to the interface 12 at the sampling point 17 and extends through the first earth layer to the surface coordinate points 21.

From the thickness of the reflecting layer and from the interval velocity of this layer, the travel time along this ray path is computed. The computed travel time forms one point on the travel time curve 25. In this case, the computed travel time forms the point 26 at the horizontal distance corresponding with the horizontal distance of the surface coordinate point 21. Similarly, the travel times along the ray paths 14, 15 and 16 are computed and plotted as the points 27, 28 and 29 on the travel time curve 25.

Fig. 3 demonstrates the requirement for greater density of sampling points than is depicted. Because of the presence of the anomaly in the reflecting interface, the surface coordinate points 23 and 24 are widely separated and a linear interpolation (time curve 25) between these points is not a proper representation of the true time curve. Therefore, additional sample points are added to the interface 12 to determine the proper shape of the travel time curve 25. For the case shown in Fig. 3, it has been found that the use of approximately 500 sampling points for each interface produces satisfactory results.

The generation of the ray path and the computation of travel times through successive layers can be explained in more detail with reference to Fig. 2. Assume that the generation of the ray path begins at the sampling point 38 on the interface 6. The equation defining the line between the sampling points 39 and 40 is:

$$y=mx+b$$

In the foregoing, m is the slope of the straight line and it is equal to tangent α where α is the dip of the interface 6, y is the vertical coordinate, x is the horizontal coordinate, and b is the zero intercept. This is one of the

inputs to the system. The line which is perpendicular to the interface at the point 38 has a slope equal to

$$-\frac{1}{m}$$

- 5 The coordinates x_2, y_2 at the sampling point 38 are known. Therefore, the equation of the line 41, extending perpendicularly to the interface at the point 38, is determined. The intersection of this line with the interface 5 is determined as follows. A search is conducted for the intersection of the line 41 with the line joining two sampling points. For example, the equation of the line joining points 42 and 43 is known. A determination can be made as to whether there is an intersection of the line 41 with this line. Then, a determination is made as to whether there is an intersection of the line between the points 43 and 44 with the line 41. The coordinates of this intersection are determined and are denoted x_2', y_2' . The length of the ray path 41 between the interfaces 5 and 6 is:

$$\sqrt{(x_2 - x_2')^2 + (y_2 - y_2')^2}$$

- 25 The travel time over this distance is the distance divided by the velocity in that layer. Interval velocity is an input to the system. Note that the angle of incidence of the ray path segment 41 with the interface 5 can be determined. As previously noted, the equation for the segment 41 is known and the equation of the line between the points 43 and 44 is known. Therefore, the angle of intersection between these two lines can be determined. From this, the angle of refraction of the ray path segment 45 can be determined from Snell's Law:

$$\frac{\sin \alpha_R}{\sin \alpha_1} = \frac{V_2}{V_1}$$

where

- 40 α_R is the angle of refraction,
 α_1 is the angle of incidence,
 V_2 is the interval velocity of the layer through which the ray path segment 45 extends, and
 45 V_1 is the velocity of the layer through which the ray path segment 41 extends.

- The equation of the line segment 45 is determined from this angle and, the intersection of this line segment with the interface 4 is determined as previously explained. The same calculation of travel time is performed. This process is repeated for succeeding layers until the travel time over each of the layers has been calculated. This is plotted as previously described.

The foregoing can be summarized with respect to the operation of the digital computer in performance of the invention by referring to Fig. 4. Fig. 4 is a flow sheet depicting the digital computer performance of part of the invention.

As indicated at 30, the input to the process is a seismic depth section specifying the interval velocity, thickness, depth and dip of each reflecting zone of a subsurfaces formation. The first step, 31, is the generation of the x, y coordinates of each of the sampling points. For example, the x, y coordinates of the sampling points 17 to 20 on the interface 12 in Fig. 3 are generated.

The next step, 32, is the determination of the ray path from the coordinates, designated generally X_M, Y_M to the surface. From the depth and dip of the subsurface reflector, the length of the ray path 13, for example, is determined. From respective values of velocity V_N for successive layers, the travel time T_n to the surface coordinate point is computed as indicated at 33. As indicated at 34, the computation of the travel times is iterated for each of the other sampling points on the first interface.

At 35, the travel times are plotted as a function of horizontal distance X to produce a travel time curve for the first interface. Then, the procedure is iterated for successive interfaces as indicated at 36. In making the computation of travel times for successive layers, the ray path at each interface between the surface and the reflector of interest is specified by Snell's Law. In making the determination of travel time, the interval velocity of each layer through which the ray path travels is used over the particular layer.

The invention preferably also takes account of diffractions at faults. Studies of arrival time curves of diffractions show that the point source located at the break in the interface caused by faulting accounts for the shape of the travel time curve. Fig. 5 shows a ray emanating from a point source located at a faulted interface.

In applying this aspect of the present invention, the periphery 37 around the point source is sampled with the same number of sampling points as are employed on an interface. For example, 500 sampling points are used along the periphery 37 and the ray paths from each of these sampling points are traced. Because of this, the same process previously described with respect to an interface is used for determining a set of ray paths emanating from a fault.

As previously mentioned, the invention may be performed in a batch type process in which all parameters are coded on cards and the output is in the form of a plot. In this type of processing, Fig. 6 is representative of the input. That is, Fig. 6 is a plot of

the data which is the output of step 6a in Fig. 1. In Fig. 6, the interval velocities indicated by the numbers along the interface lines as determined by the aforementioned stratigraphic velocity estimation technique in the previously mentioned application No. 50471/70 (Specification No. 1304248), appear as printouts at the appropriate places on the interfaces. Fig. 7 is a plot of the output of the process of the present invention. That is, it is a seismic time section which can be compared to the field data.

In another form of the process of this invention, a computer graphics process is employed. In this process, the parameters are entered with an interactive device through a cathode ray tube display. In this process, the parameters can be altered as is required or desired. The output of the computer graphics type of process is in the form of a display on a display device. Fig. 8 is an example of a display of the input and Fig. 9 is a display of the output, that is, a display of the seismic time section.

The process in the computer graphics form has another important aspect. This is that ray paths from any desired point on any interface to the surface can be traced and corresponding points on the travel time curves of the time section can be determined. For example, assume that the geophysicist wishes to study reflections from particular points on an interface, for example, from the points 50 to 52 on the sixth interface in Fig. 8. The coordinates of these points are entered into the computer by the interactive device. By this form of the process of this invention, the ray paths, shown by dashed lines in Fig. 8, are automatically determined and the ray paths are used to compute travel times. The travel times along the ray paths appear as times on the time curves displayed in Fig. 9. The times 53 to 55 in Fig. 9 correspond to the points 50 to 52 on Fig. 8.

The method of the present invention is particularly well suited to be practised on a general purpose digital computer. Many different programmes can be derived to carry out this method.

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:—

55	6604	Central Computer, 65K Memory
	6608	Disc System
	6602	Console Display
	6681	Data Channel Converter
	3228	Magnetic Tape Controller
60	607	Magnetic Tape Transport
	3447	Card Reader Controller
	405	Card Reader
	3256	Line Printer Controller
	501	Line Printer.

WHAT WE CLAIM IS:—

1. A method of producing a seismic record from seismic traces representing the arrival time of seismic reflections at detectors spaced along lines of exploration, which comprises carrying out in an automatic computing system and plotting means the steps of:—

converting the seismic traces to a seismic depth section representing the interval velocity, depth, and dip of the reflecting zones of a subsurface formation, and

converting the seismic depth section to a plotted seismic time section representing the travel times to the reflecting zones as functions of the subsurface coordinates along the lines of exploration.

2. A method according to claim 1 in which the plotted seismic time section is obtained by:—

(a) generating, for a particular reflecting zone, the coordinates of sampling points along the interface of the reflecting zone;

(b) generating at each sampling point the respective ray path extending through successive layers to a surface coordinate point representing the surface of the earth;

(c) computing, from the interval velocity and thickness of each zone, the travel time for seismic energy to travel between the sampling point and the surface coordinate point;

(d) plotting the said travel time as a function of the surface point coordinates to generate a travel time curve for the particular reflecting zone, and

(e) repeating the foregoing steps (a) to (d) for succeeding sampling points and reflecting zones to generate a time section representing travel time to the reflecting zones as a function of the surface point coordinates along a line of exploration.

3. A method according to claim 2 in which the reflecting zones are displayed in the form of a seismic depth section on a display device in a computer graphics system, the method including the steps of:—

(a) generating, in response to the selection of a point on the seismic depth section by the use of an interactive device, the coordinates of the selected point on the seismic depth section,

(b) generating the ray path and computing the travel time between the point thus selected and the corresponding surface coordinate point, and

(c) displaying on a display device the seismic time section with an indication of the travel time computed in the pre-



the data which is the output of step 6a in Fig. 1. In Fig. 6, the interval velocities indicated by the numbers along the interface lines as determined by the aforementioned stratigraphic velocity estimation technique in the previously mentioned application No. 50471/70 (Specification No. 1304248), appear as printouts at the appropriate places on the interfaces. Fig. 7 is a plot of the output of the process of the present invention. That is, it is a seismic time section which can be compared to the field data.

In another form of the process of this invention, a computer graphics process is employed. In this process, the parameters are entered with an interactive device through a cathode ray tube display. In this process, the parameters can be altered as is required or desired. The output of the computer graphics type of process is in the form of a display on a display device. Fig. 8 is an example of a display of the input and Fig. 9 is a display of the output, that is, a display of the seismic time section.

The process in the computer graphics form has another important aspect. This is that ray paths from any desired point on any interface to the surface can be traced and corresponding points on the travel time curves of the time section can be determined. For example, assume that the geophysicist wishes to study reflections from particular points on an interface, for example, from the points 50 to 52 on the sixth interface in Fig. 8. The coordinates of these points are entered into the computer by the interactive device. By this form of the process of this invention, the ray paths, shown by dashed lines in Fig. 8, are automatically determined and the ray paths are used to compute travel times. The travel times along the ray paths appear as times on the time curves displayed in Fig. 9. The times 53 to 55 in Fig. 9 correspond to the points 50 to 52 on Fig. 8.

The method of the present invention is particularly well suited to be practised on a general purpose digital computer. Many different programmes can be derived to carry out this method.

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:—

- 6604 Central Computer, 65K Memory
- 6608 Disc System
- 6602 Console Display
- 6681 Data Channel Converter
- 3228 Magnetic Tape Controller
- 607 Magnetic Tape Transport
- 3447 Card Reader Controller
- 405 Card Reader
- 3256 Line Printer Controller
- 501 Line Printer.

WHAT WE CLAIM IS:—

1. A method of producing a seismic record from seismic traces representing the arrival time of seismic reflections at detectors spaced along lines of exploration, which comprises carrying out in an automatic computing system and plotting means the steps of:—

converting the seismic traces to a seismic depth section representing the interval velocity, depth, and dip of the reflecting zones of a subsurface formation, and

converting the seismic depth section to a plotted seismic time section representing the travel times to the reflecting zones as functions of the subsurface coordinates along the lines of exploration.

2. A method according to claim 1 in which the plotted seismic time section is obtained by:—

- (a) generating, for a particular reflecting zone, the coordinates of sampling points along the interface of the reflecting zone;
- (b) generating at each sampling point the respective ray path extending through successive layers to a surface coordinate point representing the surface of the earth;
- (c) computing, from the interval velocity and thickness of each zone, the travel time for seismic energy to travel between the sampling point and the surface coordinate point;
- (d) plotting the said travel time as a function of the surface point coordinates to generate a travel time curve for the particular reflecting zone, and
- (e) repeating the foregoing steps (a) to (d) for succeeding sampling points and reflecting zones to generate a time section representing travel time to the reflecting zones as a function of the surface point coordinates along a line of exploration.

3. A method according to claim 2 in which the reflecting zones are displayed in the form of a seismic depth section on a display device in a computer graphics system, the method including the steps of:—

- (a) generating, in response to the selection of a point on the seismic depth section by the use of an interactive device, the coordinates of the selected point on the seismic depth section,
- (b) generating the ray path and computing the travel time between the point thus selected and the corresponding surface coordinate point, and
- (c) displaying on a display device the seismic time section with an indication of the travel time computed in the pre-



coding step, the indication corresponding to the point on the seismic depth section selected by the interactive device.

4. A method according to claim 2 or 3
5 in which the subsurface formation includes a fault, the method including the steps of:

- (a) taking the periphery around the fault
as an interface, generating the coordinates of sampling points around the fault,
10 (b) repeating steps (b) and (c) of claim 2 for each sampling point around the fault, and
(c) plotting the travel times computed in the preceding step to generate a travel
15 time curve for the fault.

5. A method according to claim 2 or 3 which is performed on a computer graphics system in which the reflecting zones are displayed in the form of a seismic depth model
20 on a display device, a fault being traced on the seismic depth section with an interactive device as a preliminary step, the method including the steps of:—

- (a) taking the periphery around the fault
25 as an interface, generating the coordinates of sample points around the fault, and
(b) repeating steps (b) and (c) of claim 2 to generate the arrival time of seismic energy reflected from the fault and received at the surface of the earth.
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6. A method according to any of claims 2 to 5 in which the step of generating the ray path includes:—

- (a) generating a ray path from the sampling point normal to the interface and at an angle, relative to the depth section, specified by the dip of the reflecting zone, and
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(b) at successive layers, generating a ray path specified by Snell's Law at each interface.
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7. A method according to any of claims 2 to 6 in which the step of plotting the time section is performed on an automatic plotter producing a hard copy output of the time section.
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8. A method according to any of claims 2 to 6 in which the step of plotting the time section is performed on a cathode ray tube display device producing a visible display of the time section on the face of the display device.
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9. A method of producing a seismic time section substantially as herein described with reference to the accompanying drawings.
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10. An automatic computing system and plotting means programmed to perform a method claimed in any of claims 1 to 9.

11. Programming means in physical form adapted to control an automatic computing system and plotting means to perform a method as claimed in any of claims 1 to 9.
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