

PATENT SPECIFICATION

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(54) STACKING SEISMIC TRACES WITH TIME INCREMENTS DETERMINED FROM SEISMIC MODEL

(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 the processing of field seismograms to enhance reflections thereon and more particularly relates to the use of a modeling routine to obtain arrival time curves and to the use of the signal power of reflections in seismic sections stacked along these arrival time curves to measure the fit of the seismic model to the actual subsurface layering.

In seismic exploration, seismic energy is generated at a shotpoint, is reflected from subsurface interfaces between different layers of the earth, and the reflected energy is detected at a spread of detectors, or geophones. The geophone signals provide a set of seismic traces which are commonly digitized and recorded on magnetic tape. Recently, it has been common to conduct the field exploration in such a manner that a number of traces represent the reflections of seismic energy from a common point in the earth's subsurface. Such field exploration techniques are often referred to as common surface point, or common depth point, exploration. Examples of this procedure are described by W. Harry Mayne in "Common Reflection Point Horizontal Data Stacking Techniques", Geophysics, Vol. XXVII, No. 6, Part II (December, 1962), pp. 927—938, 8 Figures.

When these seismic traces representing reflections from a common depth point are stacked, or composited, the reflection signals are added to produce enhanced reflections which are easier to interpret because the signal-to-noise ratio has been increased.

While stacked seismic sections have become an important interpretive tool for the geophysicist, the ultimate object of the geophysicist is to obtain an accurate representation of the subsurface layering. A model depicting the geometry of the subsurface layering together with the acoustic velocity characteristics of each layer is an invaluable guide in geophysical exploration.

Various techniques for generating models depicting the earth's subsurface layering from field seismograms are described in U.S. Patents Nos. 3,611,278 and 3,651,451; British Patents Nos. 1,175,700, 1,304,248 and 1,317,765, and German Offenlegungsschrift 2,110,852.

According to the present invention we provide a method of processing seismograms related to the same set of subsurface layers comprising:

(a) generating a digital seismic model of the subsurface layers producing said seismograms;

(b) calculating from said model the time shifts (Δt 's) between reflections which correspond to the same layer interfaces on one seismogram as they do on the adjacent seismogram; and (c) stacking said seismograms in accordance with the Δt 's calculated in step (b).

The method is preferably applied to estimating the earth layering and acoustic velocity of the layers from seismograms produced by detectors spaced along a line of exploration on the surface of the earth, groups of said seismograms representing the reflection of seismic energy from common depth points in the earth.

In accordance with an embodiment of this invention a modeling routine is used to obtain arrival time curves, common depth point traces are stacked along these arrival time curves, and the signal power of reflections in the stacked section produced is used as a measure of the fit of the model to the actual subsurface layering.

In carrying out embodiments of the invention, the reflection times and the acoustic velocities of the subsurface layers are first determined from the field seismograms. From these reflection times and velocities a digital seismic model of the subsurface layers is generated. From this model, the arrival times as a function of horizontal distance for reflections from common depth points are calculated. The common depth point seismograms are stacked in accordance with the arrival time-distance function calculated from the model. This produces a stacked seismic section having enhanced reflection signal power. Then, the digital seismic model is changed and the foregoing steps are repeated to produce another stacked seismic section with enhanced signal power. By iterating this procedure, a better and better model of the earth's subsurface layering is achieved with the criterion for fit being the signal power of the reflections in the stacked seismic sections.

Figures 1A and 1B depict a field exploration technique;

Figures 2A and 2B depict a field exploration technique with the resultant traveltimes curves;

Figure 3 is a flow sheet depicting the process performed by a general purpose digital computer;

Figure 4 is a seismic section;

Figure 5 is a time-distance model of the subsurface layers depicted by the seismic sections;

Figure 6 is a depth-distance model of subsurface layering depicted by the seismic section of Figure 4;

Figure 7 shows traveltime curves produced from the model of Figure 6;

Figures 8A and 8B depict a section of the earth's subsurface; and

Figure 8C depicts the generation of traveltime curves from the model.

Figures 1A and 1B depict in simplified form the field procedure for obtaining sets of common depth point (CDP) traces. Figure 1A depicts the generation of seismic energy at the source S_1 , the reflection of this seismic energy from a flat layer, and the detection of the reflected energy at the detectors R_1 , R_2 , and R_3 spaced along the line of exploration on the surface of the earth. Then, the detector spread is moved to the position indicated in Figure 1B. Again, seismic energy is produced at the source S_2 , is reflected from the interface, and is detected at the detectors R_1 , R_2 , and R_3 . Note the energy from source S_1 is reflected from the common depth point 1a and is received by the detector R_1 . Energy from the source S_2 is reflected from the same common depth point 1a and is received at the detector R_3 . The common surface point 1 corresponds to the common depth point 1a.

In this manner, sets of seismic traces are pro-

duced, each representing the reflection of seismic energy from common depth points.

Figure 2A depicts a simplified extension of this field procedure to generate sets of seismograms for the three common surface points 1, 2, and 3. For each trace in a set of CDP traces, the time of the reflection on the seismogram will vary by a time Δt from trace to trace. In Figure 2B the arrival times for the CDP set from the surface point 1 are indicated by the curve 10. This arrival time versus distance curve gives the time shift from trace to trace for each trace in the set. (In Figure 2B the time ΔT indicates the time shift between the first and last trace in the set.)

As is well known, the curve 10 generally is given by:

$$T = \sqrt{T_0^2 + X^2/V^2}$$

In the foregoing, T is the time of the reflection on a particular seismogram, T_0 is the time of that reflection on an idealized seismogram from a geophone directly under the shot, X is the spacing between the shot and the geophone producing the particular trace, and V is $V_{\text{layer}}/\cos \alpha$ where V_{layer} is the acoustic velocity characteristic of the layer through which the ray travels and α is the dip of the interface.

If the Δt 's are accurately known, the traces can be time shifted by this amount and stacked to greatly enhance the signal power of the reflections. Present practice is to assume that the Δt 's vary in the hyperbolic manner depicted in Figure 2B. As will be subsequently explained, this is not necessarily a good assumption. The problem is to accurately determine the Δt 's so that the seismograms can be stacked in a manner which best enhances the reflection signal.

Figure 3 is a flow chart of a technique performed on a general purpose digital computer in accordance with the present invention. The first step as indicated at 11 in the flow sheet is to determine the reflection times T_i on the seismograms and the acoustic velocities V_i of the subsurface layers producing each reflection. One particularly suitable technique for performing this step produces as an output the T_i 's, V_i 's, and dip of each reflecting interface. The dip can be expressed as $\Delta T/X$. This type of process is commonly referred to as VIP, an acronym for velocity by integrated power.

From these values, the conventional traveltime curves, such as the curve 10 in Figure 2B, are generated. This step is indicated at 12. The seismic traces are stacked along these traveltime curves as indicated at 13. This produces a seismic cross section of the type shown in Figure 4.

From the seismic cross section, a digitized,

layered, interpretation model is generated as indicated at 14 in the flow sheet. Such a model is depicted in Figure 6. The step 14 includes the migration of each reflecting point from its apparent position in a time section to the actual coordinates of the reflection point. Migration is described in British Patent No. 1,175,700 mentioned above.

Techniques for automatically producing the model of Figure 6 are available. One technique for automatically producing such a model is described in U.S. Patent 3,651,451 mentioned above. Such a model can be generated from the T_i 's and V_i 's of the aforementioned VIP process and from the reflection points determined in the process of U.S. Patent No. 3,614,278 mentioned above. From the distance-depth model of Figure 6, a distance-time model of the type shown in Figure 5 can be produced.

At this point, the model time section shown in Figure 5 may be compared with the seismic section of Figure 4 to determine whether the model, in the geophysicist's judgment, accurately corresponds with the seismic section. This interpretive step is indicated at 15 in the flow sheet. Provision may be made to change the model so that the model time section best corresponds with the seismic section. An even better comparison between the model and the field data can be obtained by first converting the model to a time section of zero offset traces as indicated by the step 15A.

What has been described thus far is a seismic processing technique which can be performed by the processes of the patent specifications previously referred to. While these techniques are suitable for most purposes, they are not adequate for certain critical areas and an example of such an area will be subsequently described. In order to facilitate the interpretation in these critical areas, the following steps are performed in accordance with an embodiment of the invention. The model of Figure 6 is used to calculate the arrival time curves. This step is indicated at 16 in the flow sheet. As an example of this, consider the portion of the model between shotpoint locations 17 and 29 on Figure 6. This portion of the model is used in the generation of the traveltime curves of Figure 7.

The step 16 is performed as follows. The model of Figure 6 specifies the interface coordinates and the interval velocity of each layer. Also known is the source-to-receiver geometry including the spread length and the location of the source with respect to the detectors. A modeling routine computes the arrival times for each reflecting interface.

As an example of this, consider Figure 8C. One modeling subroutine computes the time of a ray such as the ray 50 propagated

to the first interface. Another subroutine computes the traveltime over the raypath 51. The coordinates of the intersection of the ray 51 with the surface are computed together with the total traveltime. The same type of calculation is performed a large number of times as, for example, for the raypaths indicated at 52, 53, and 54. The first interface is densely sampled with raypath computations. The result is an array in memory containing traveltime and a corresponding array containing the X coordinates of the surface intersections of the rays. An output of the type shown in Figure 7 can be produced from such arrays.

For example, since the distance X for each of the receivers 55—60 is known, the reflection time for that value of X is obtained from the array computed in the modeling program. If the array does not contain a surface intersection corresponding with the X coordinate of the detector, interpolation between the two closest surface intersections in the array gives the appropriate traveltime for that detector.

Figure 7 depicts sets of seven traces in which there is a break in each line at the traveltime obtained from the traveltime array. In Figure 7 there is a trace for each of six detector locations, for example, 55—60, and in trace sets 23 to 29 there is in addition a zero offset trace corresponding to the trace obtained from the detector 61 having a zero source-to-receiver distance.

The modeling routine is repeated for all interfaces and for all source locations. The direction of ray propagation through successive layers can be determined from Snell's Law calculations since the interval velocities of each of the layers are known. Once the ray angles are known, traveltime can be computed.

The artificially generated seismic section of Figure 7 has breaks in the traces which correspond with traveltime curves. In Figure 7 the sets of traveltime curves 40—46 correspond with reflections from the interfaces 30—36, respectively. Each of the indicated traveltime curves of Figure 7 is for a reflection from a common depth point. From them, the time shifts Δt between reflections on adjacent seismograms can be easily calculated. Note that the traveltime curves 40—43 from the interfaces 30—33 are approximately hyperbolic as expected. However, the traveltime curves in the sets 44, 45, and 46 are not hyperbolic. Stacking of the traces with Δt 's specified by a hyperbolic curve would not appreciably enhance the signal power of reflection from interfaces 34—36. However, stacking with Δt 's specified by the traveltime curves 44—46 will enhance the signal power of reflections from interfaces 34—36. The step of stacking the field seismograms along

the traveltime curves of Figure 7 is indicated at the step 17 in the flow sheet.

Steps 14—17 are repeated to produce another stacked seismic section and the model is changed as indicated by the step 18. The stacked seismic sections are compared as indicated by the step 19 and the model is again changed as necessary to determine which model produces the highest signal power in the stacked section. Normally, steps 18 and 19 will be performed by an interpreter in an interactive graphics technique. Note, however, that there is no subjective interpretation involved in this procedure. It is only required that the interpreter apply objective criteria as the model is changed.

As an example, there are normally 12 traces in a CDP set. Theoretically, when these are stacked with exactly the right Δt 's, the stacked trace will have a reflection amplitude which is twelve times the amplitude of an unstacked trace. Normally, it will be possible for the interpreter to change the model until the signal power on the stacked seismic section is at least 70% of the maximum possible signal power. Given the foregoing objective criteria for changing the model, it will be appreciated that such a procedure could be automated.

At this point, one of the particular advantages of the present invention can be understood with reference to a particular interpretation example. Figure 8A depicts two layers of the earth and in which the bottom of the second layer has an anticline. Figure 8B depicts two layers of the earth and in which the second layer has a horizontal velocity gradient. For example, this section of the layer might increase from a velocity of 6,000 feet per second to 15,000 feet per second and back to 6,000 feet per second at the other edge of the gradient. Both of these types of formations will produce the same stacked seismic sections. The steps 11—15 in the flow sheet might very well produce a model in accordance with either Figure 8A or Figure 8B from a given set of field seismograms. Normally, performance of steps 11—15 will indicate that both the models of Figure 8A and Figure 8B will fit the field data. Comparison of either Figure 8A or Figure 8B with the original field seismograms would not indicate to the interpreter which particular subsurface formation produced the seismograms. However, by using both of these models in the steps 16 to 19 a selection can be made as to which model is correct on the basis of which model produces the highest reflection signal power in the stacked seismic section.

Quite often, the actual formation producing the seismograms will be a combination of an interface anomaly (Figure 8A) and a velocity anomaly (Figure 8B). This formation is generally referred to as a reef, an important

geological formation in the exploration for oil.

Given the two input models of Figure 8A and Figure 8B, the model can be changed (steps 18) between combinations of Figure 8A and Figure 8B until a maximum reflection signal power in the stacked section is obtained. When the maximum signal power is obtained, the model will accurately depict both the geometry and the velocity characteristics of the reef formation.

WHAT WE CLAIM IS:—

1. The method of processing seismograms related to the same set of subsurface layers comprising:
 - (a) generating a digital seismic model of the subsurface layers producing said seismograms;
 - (b) calculating from said model the time shifts (Δt 's) between reflections which correspond to the same layer interfaces on one seismogram as they do on the adjacent seismogram; and
 - (c) stacking said seismograms in accordance with the Δt 's calculated in step (b).
2. The method according to Claim 1, further comprising:
 - automatically determining the reflection times on said seismograms and the acoustic velocities of subsurface layers producing the reflections, the digital seismic model generated in step (a) being generated from said reflection times and velocities.
3. The method according to Claim 1 or 2, further comprising:
 - (d) changing the digital seismic model generated in step (a);
 - (e) repeating steps (b) to (d) until the stacked seismic section produced in step (c) having the highest reflection signal power is obtained, which section indicates the proper seismic model of the subsurface layers.
4. The method of estimating the earth layering and acoustic velocity of the layers from seismograms produced by detectors spaced along a line of exploration on the surface of the earth, groups of said seismograms representing the reflection of seismic energy from common depth points in the earth, said method comprising:
 - (a) automatically determining the reflection times on said seismograms and the acoustic velocities of the subsurface layers producing said reflection and generating from said reflection times and velocities a digital seismic model of said subsurface layers;
 - (b) calculating from said model, for each of several common depth points, the arrival time as a function of distance along said line of exploration of reflections from said common depth points;



the traveltime curves of Figure 7 is indicated at the step 17 in the flow sheet.

Steps 14—17 are repeated to produce another stacked seismic section and the model is changed as indicated by the step 18. The stacked seismic sections are compared as indicated by the step 19 and the model is again changed as necessary to determine which model produces the highest signal power in the stacked section. Normally, steps 18 and 19 will be performed by an interpreter in an interactive graphics technique. Note, however, that there is no subjective interpretation involved in this procedure. It is only required that the interpreter apply objective criteria as the model is changed.

As an example, there are normally 12 traces in a CDP set. Theoretically, when these are stacked with exactly the right Δt 's, the stacked trace will have a reflection amplitude which is twelve times the amplitude of an unstacked trace. Normally, it will be possible for the interpreter to change the model until the signal power on the stacked seismic section is at least 70% of the maximum possible signal power. Given the foregoing objective criteria for changing the model, it will be appreciated that such a procedure could be automated.

At this point, one of the particular advantages of the present invention can be understood with reference to a particular interpretation example. Figure 8A depicts two layers of the earth and in which the bottom of the second layer has an anticline. Figure 8B depicts two layers of the earth and in which the second layer has a horizontal velocity gradient. For example, this section of the layer might increase from a velocity of 6,000 feet per second to 15,000 feet per second and back to 6,000 feet per second at the other edge of the gradient. Both of these types of formations will produce the same stacked seismic sections. The steps 11—15 in the flow sheet might very well produce a model in accordance with either Figure 8A or Figure 8B from a given set of field seismograms. Normally, performance of steps 11—15 will indicate that both the models of Figure 8A and Figure 8B will fit the field data. Comparison of either Figure 8A or Figure 8B with the original field seismograms would not indicate to the interpreter which particular subsurface formation produced the seismograms. However, by using both of these models in the steps 16 to 19 a selection can be made as to which model is correct on the basis of which model produces the highest reflection signal power in the stacked seismic section.

Quite often, the actual formation producing the seismograms will be a combination of an interface anomaly (Figure 8A) and a velocity anomaly (Figure 8B). This formation is generally referred to as a reef, an important

geological formation in the exploration for oil.

Given the two input models of Figure 8A and Figure 8B, the model can be changed (steps 18) between combinations of Figure 8A and Figure 8B until a maximum reflection signal power in the stacked section is obtained. When the maximum signal power is obtained, the model will accurately depict both the geometry and the velocity characteristics of the reef formation.

WHAT WE CLAIM IS:—

1. The method of processing seismograms related to the same set of subsurface layers comprising:

(a) generating a digital seismic model of the subsurface layers producing said seismograms;

(b) calculating from said model the time shifts (Δt 's) between reflections which correspond to the same layer interfaces on one seismogram as they do on the adjacent seismogram; and

(c) stacking said seismograms in accordance with the Δt 's calculated in step (b).

2. The method according to Claim 1, further comprising:

automatically determining the reflection times on said seismograms and the acoustic velocities of subsurface layers producing the reflections, the digital seismic model generated in step (a) being generated from said reflection times and velocities.

3. The method according to Claim 1 or 2, further comprising:

(d) changing the digital seismic model generated in step (a);

(e) repeating steps (b) to (d) until the stacked seismic section produced in step (c) having the highest reflection signal power is obtained, which section indicates the proper seismic model of the subsurface layers.

4. The method of estimating the earth layering and acoustic velocity of the layers from seismograms produced by detectors spaced along a line of exploration on the surface of the earth, groups of said seismograms representing the reflection of seismic energy from common depth points in the earth, said method comprising:

(a) automatically determining the reflection times on said seismograms and the acoustic velocities of the subsurface layers producing said reflection and generating from said reflection times and velocities a digital seismic model of said subsurface layers;

(b) calculating from said model, for each of several common depth points, the arrival time as a function of distance along said line of exploration of reflections from said common depth points;



- (c) stacking seismograms representing reflections from common depth points in accordance with the arrival time, distance functions calculated in step (b) to produce a stacked seismic section having enhanced reflection signal power;
- (d) changing the digital seismic model generated in step (a); and
- 10 (e) repeating steps (b) to (d) until the stacked seismic section having the highest reflection signal power is obtained, which section indicates the proper seismic model of the subsurface layers.
- 15 5. The method according to Claim 3 or 4, wherein step (a) includes generating at least two models of the subsurface layers producing said seismograms, said method further comprising:
performing steps (b) to (e) for combinations of said two models until the stacked seismic section having the highest reflection signal power is obtained, which section indicates the proper combination of said two models to depict the earth layering. 20 25
6. The method according to Claim 1, substantially as described with reference to the accompanying drawings.
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