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(54) SEISMIC DELINEATION OF OIL AND GAS RESERVOIRS USING BOREHOLE GEOPHONES

(71) I, NIGEL ALLISTER ANSTEY BM Box 7064 London WC1V 6XX, a British citizen, do hereby declare the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:-

This invention is concerned with a method of processing seismic signals, particularly in the delineating of an oil or gas reservoir when at least one borehole exists close to or penetrating the reservoir. In its preferred form it employs several novel adaptations of the seismic check-shooting technique. Both direct and reflected seismic signals are detected by a borehole geophone; the downgoing signal is used to deconvolve the upcoming signal; the properties of the reflected signal are mapped over the reservoir locality; and a system of stacking borehole signals by common depth-point is employed.

After a hydrocarbon discovery has been made, it is common practice to delineate the extent of the reservoir by drilling additional boreholes toward (and sometimes beyond) its boundaries. This is very expensive, and there is a major need for a technique to reduce the number of boreholes necessary.

Occasionally it happens that, once the target is specified by the discovery well, the extent of the reservoir can be seen, as a variation of seismic reflection characteristics, after very careful processing of the normal seismic sections through the well. More often, however, the resolution afforded by the seismic reflection technique is inadequate for this purpose; an inadequacy of vertical resolution is imposed by the limited bandwidth of the reflection pulse after two-way transmission through the earth, and an inadequacy of horizontal resolution is imposed by the large area of the reservoir reflectors which contributes to the reflection pulse. The present method reduces these problems by the use of a geophone deployed in the borehole. The method is also of value when a dry hole is believed to be dry because it has just missed (vertically or horizontally) what is actually an entirely satisfactory reservoir, and it is desired to do further drilling.

The present invention is concerned not only with the direct downgoing signal from source to geophone, as in the check-shooting techniques of the prior art, but also with the upcoming signals reflected from reservoir boundaries below the geophone. Specifically, it seeks to investigate the reservoir material, and the lateral or vertical variations in its properties, by means of the reflection characteristics of these boundary interfaces, particularly as the reflection characteristics are observed to change with angle of incidence and with wave type. In order to study these variations and changes, the method may provide one or more horizontal profiles of source positions along the surface.

When such horizontal source profiles are associated with each of several positions of the geophone in the borehole, it becomes possible to gather groups of reflection signals representing the same depth-point; such gathered groups may be used both for analysis of incidence-angle effects and for stacking.

The use of a borehole geophone, rather than a surface geophone, immediately improves the resolution of the seismic reflections from the reservoir; this is so because only one path through the absorptive near-surface is involved, and because the zone of insonification of the reflecting interfaces is reduced in extent. An additional improvement is provided by the present invention, in that the downgoing signal is used to deconvolve the reflected upcoming signal; by this means the absorptive effects of the shallower materials above the geophone are further compensated. The deconvolution is accomplished by isolating the direct downgoing arrival, by calculating a deconvolution operator to transform the pulse form of the downgoing arrival into a more desirable pulse form, and by applying this operator to the reflected arrivals.

The techniques used to achieve these objectives are set out in the following description with reference to the attached drawings, in which:

Figure 1 illustrates the present practice of seismic check-shooting;

Figure 2 shows the signals typically obtained by such practice, before and after the application of the deconvolution disclosed in the specification;

Figure 3 illustrates a vertical profile of geophone positions above a reservoir;

Figure 4 illustrates the concept of down-stacking the outputs from a vertical seismic profile;

Figure 5 depicts a horizontal profile of seismic sources whose signals are recorded at a borehole geophone by both the direct path and by reflection from a hydrocarbon reservoir;

Figure 6a illustrates the seismic signals obtained by the arrangement of Figure 5, after deconvolution using the direct downgoing signal observed at the geophone, and

Figure 6b illustrates the effect of applying normal-moveout corrections to obtain a sectional display;

Figure 7a shows the surface-to-surface ray-path geometry for common-depth-point stacking, and Figures 7b and 7c show the surface-to borehole ray-path geometry for common-depth-point stacking of borehole signals.

Figure 1 shows a standard arrangement, known in the prior art, for the operation of check-shooting a borehole 1. A borehole geophone 2, usually adapted to lock into the wall of the hole by the arm 3, is lowered down the hole by means of an armoured conducting cable 6. A seismic source 7 at or near the wellhead (typically an air gun in the mudpit 8, or in the sea) initiates a seismic signal in the earth. The output produced by the borehole geophone in response to this signal is recorded by .the recording instruments 9. The outgoing signal is monitored by a geophone or hydrophone 10 close to the seismic source 7, and this monitor output is also recorded by the instruments 9.

The object of the conventional check-shooting operation is to obtain a measure of the time taken by the seismic pulse to travel from the source 7 to the geophone 2, as a function of the depth of the geophone in the borehole. This time-depth relation is then used to calibrate the acoustic log observed in the borehold, and further used for the conversion of seismic reflection times to depth.

Figure 2 shows the type of recording obtained conventionally. The signal 11 displayed on trace 12 is the record of the outgoing pulse as obtained from the hydrophone 10, close to the source. The signal 13 displayed on trace 14 is the record of the "direct" arrival as obtained from the borehole geophone 2, deep in the earth. The conventional objective is then achieved by measuring the time between some suitable part (normally the first trough) or pulse 11 and the "corresponding" part of pulse 13, for different depths of the geophone 2.

The present invention requires an understanding of the factors influencing the form of the borehole trace 14.

The first such factor is obviously the form of the pulse 11 generated by the source 7. To this basic pulse shape is added the "ghost" reflection from the free surface 15 of the mudpit 8 (or the sea, in offshore operations), and possibly a significant train of multiple reflections generated in the water. There is therefore a basic source-pulse complex associated with the source itself and its near-surface environment. This is regarded as the downgoing "input" to the earth.

Thereafter several agencies produce further shaping and modification of the downgoing pulse waveform. One of these is absorption, which produces a progressive loss of the high frequencies (particularly within rock formations characterized by frictional grain contacts and poor sorting). The high-cut effect on the pulse spectrum is believed to be smooth, so that the pulse broadens progressively but simply.

Another such agency is the transmission loss at interfaces. This is known to be offset at low frequencies by short-path multiple reflections in rock sequences characterized by cyclic stratification, and thus appears in practice as a high-cut effect analogous to absorption. However, the process operates by continuous removal of energy from the truly direct transmitted signal, and restoration of much of this energy in the form of a tail to the pulse. This makes the pulse broader, but it is not necessarily nor generally true that the broadening effect is simple; in general the tail added to the pulse is complicated in form, depending as it does on the reflection statistics of the interfaces traversed. This effect is discussed in detail in the article "Reflections on Amplitudes" by O'Doherty and Anstey, in Geophysical Prospecting, volume 19, no. 3, p. 430.

Further agencies which may effect the amplitude and/or form of the signal observed at the deep geophone include scattering from geological inhomogeneities, and the focusing and cusp-forming consequences of refraction. Both these agencies can add a complicated tail to the downgoing pulse, as strictly localized effects associated with particular scatterers or particular acoustic-lens systems.

Finally, the amplitude of the downgoing seismic pulse as it is detected by the borehole geophone depends on the acoustic impedance of the geological formation into which the geophone is coupled.

Those of the above agencies which have the effect of removing energy from the truly direct arrival at the borehole, and of adding back some of this energy at later times, introduce a difficulty in defining what part of the pulse 13 should be selected for timing purposes as "corresponding" to a particular part of pulse 11. This difficulty is real, since the magnitude of the transmission-loss effect in real geology is almost always so great that, for any realistic source energy, the direct transmitted signal is undetectable at depths of common concern.

The downgoing signal at the borehole geophone therefore has a stable component dependent on the source and the source environment, a depth-dependent but smooth component dependent on absorption in the geologic sequence, a depth-dependent but complicated component dependent on the nature of contrasting stratification in the geologic sequence, a location-dependent component dependent on local inhomogeneities and lenses, and a final amplitude dependent on the acoustic impedance at the geophone depth.

The signal actually observed from the geophone is the sum of this so-called "direct" downgoing arrival with numerous upcoming reflections from below the geophone. Each of these reflections has a form at least as complicated as the downging arrival, and the final interference pattern on trace 14 is therefore very complicated indeed.

Since the present invention is concerned with turning particular reflections to good account, it becomes important to reduce the complications.

The first technique, known in the prior art, is to use several or many versions of the borehole record, obtained at different depths in the borehole, and to add such signals, after the application of appropriate static time shifts, to enhance selectivity either the downgoing or upcoming components in the signals. This technique is evident from Galperin's book "Vertical Seismic Profiling" (published by SEG), and from the paper "Well Geophone Signals as an Aid to Hydrocarbon Indication", by Kennett and Ireson, read to the Society of Exploration Geophysicists in Mexico City, November 1973. The technique for enhancing the downgoing signal will be referred to hereinafter as down-stacking, and that for enhancing the reflected signal as up-stacking.

Even after the best that can be done with down-stacking, the derived signal is still very complex in nature. The complications associated with "bubbling" in the source, and the free-surface and near-surface reflection systems as described above, can be substantially removed by the process of deterministic or source-signature deconvolution; in this the knowledge of the outgoing source signal 12, and of the depth of the source and the water, it used to deconvolve the source and near-surface characteristics out of the downhole signal.

However, there still remains in this signal (even after down-stacking to suppress the upcoming reflections, and source-signature deconvolution to suppress the characteristics of the input pulse) the complicating effects of the short-path multiple phenomenon, and of absorption, scattering and refraction. These complicating effects, as noted hereinbefore, introduce fundamental and inescapable difficulties in the interpretation of arrival times and velocities. And all of these complications, plus those due to the particular reflecting sequence below the borehole geophone, are also present in an upstack made to enhance the indications of this reflecting sequence.

For highly-detailed analysis of the said reflecting sequence, it is desirable to remove from the upcoming reflection train the complexities of form and spectrum present in the downgoing signal. Indeed the resolution of events representing the top and bottom of a typical hydrocarbon reservoir can be scarcely be contemplated without the removal of such complexities, because the latter ordinarily have a form much like that to be expected from such closely-spaced reservoir reflections.

Accordingly the first novel proposal of the present invention is to use the downgoing arrival (which may be enhanced by down-stacking) to deconvolve the upcoming reflection signal.

As is well known, the process of deconvolution uses knowledge of a known pulse to compute an operator which will convert the known pulse into a desired pulse. The process is limited, in all but its deterministic applications, by the fact that the "known" pulse is usually known only statistically (that is, from the autocorrelation function of a series of pulses assumed stationary, and to the limits of the minimum-phase assumption). In the present application, however, the "known" pulse is known very well; whether observed at a single location or obtained by down-stacking, it represents the downgoing pulse complex as it passes the geophone location. Therefore the operator can be derived with good assurance, and may thereafter be applied to the raw geophone signal (without either down-stacking or up-stacking), or to a relatively up-stacked signal; in both cases the objective is to transform to a spike, or to some other simple pulse form, the component of the received signal which is due to the complexities of the down-going path from source to geophone.

Figure 3 shows the field technique appropriate to this proposal. The borehole is assumed to traverse a hydrocarbon accumulation 18 having an upper boundary 19 and a lower boundary 20. The first delineation problem is to separate and identify the seismic reflections from the boundaries 19 and 20; without the benefits of the present invention, these two reflections ordinarily defy such separation and identification.

In the simplest implementation of this aspect of the invention, which implementation does not employ down-stacking, a geophone position such as 21 is occupied; the depth of the accumulation 18 below the surface 27 might typically be 3000 m (10,000 ft), and the geophone position 21 might typically be 300 m (100 ft) above the said accumulation. Under these conditions the geophone output is likely to appear broadly as in Figure 2, in which the complex 16 represents the complicated downgoing signal, and the reflections from interfaces 19 and 20 interfere to yield an even more complicated arrival (but a substantially separated one) at 28. Then the "known" component for the deconvolution process is taken as the complex 16, suitably gated (and possibly tapered towards longer times) to ensure that the effective signal is taken as "known" is concentrated on the downgoing pulse. After such gating and tapering, the signal is taken as the known downgoing complex is likely to appear as at 29. A deconvolution operator is then calculated, by techniques well known in the art, to convert this signal into a spike. When the operator is applied to trace 14, the trace emerges as at 30. The ascribed arrival time for the downgoing signal is now represented by the approximate spike 31, while the reflections from interfaces 19 and 20 are now clearly separated and identifiable at 32 and 33. This vastly improved resolution from the reservoir allows amplitude ratio measurements and calculation of the acoustic properties of the reservoir material, according to principles well known in the art.

The degree to which the deconvolved arrival 31 represents a spike is a convenient measure of the success of the deconvolution operation. The degree to which the shape of the reflections 32 and 33 differ from that of the direct arrival 31 is a measure of the frequency-selective processes occurring in the interval between the geophone and the reservoir interfaces, and/or of any complex reflection character present at the reservoir level. Such appraisals are highly important for study of the reservoir characteristics.

If local geologic features dictate that the geophone position 21 should be closer to the reservoir 18 than suggested above, the gating and/or tapering function may need to be more severe. However, no change of principle results; the reflections 32 and 33 may be seen riding on other oscillations, and followed by other oscillations, but recognition of and numerical computations on these reflections are generally still feasible.

The reduction of the distance from geophone to reservoir may be required because the interval above the reservoir abounds with reflectors. Where conditions are such as to preclude the selection of a gate which is satisfactorily dominated by the downgoing signal, it may be desirable to enhance this downgoing signal, relative to unwanted reflections from the interval between geophone and reservoir, by down-stacking. In this case the geophone is caused to occupy a succession of positions as suggested at 21-26 (typically over a depth range of 150 m or 500 ft), and the geophone signal is recorded for each position. Preferably the source is such that its output remains sensibly constant for each of these geophone positions; if not, it may be desirable to apply a scaling factor or a source-signature deconvolution derived from the source pulse 12 obtained from the near-source hydrophone 10. Better still, a "spread" of borehole geophones is deployed on the cable 6, over the depth range suggested, and the borehole signals associated with a plurality of depth locations are obtained from a single source excitation. In either case, the plurality of geophone signals thus obtained appear as in Figure 4. The improved estimate of the downgoing signal is then obtained by applying static time shifts to these traces 34, in order to represent the delay associated with the extra depth from one position to another, and by adding the traces to obtain the new trace 35. In this new trace 35 the downward-propagating alignment 36 is enhanced and the upward-propagation (reflection) alignment 37 is suppressed. The down-stacked trace 35 is then used for the derivation of the operator, as described above, and the operator is then applied to a selected one or a plurality of the traces 34. The traces may also be up-stacked at this stage, for greater clarity of the reflection indications.

Since the geophone is likely to be coupled into formations of different acoustic impedance at the different levels 21-26, the amplitudes of the traces 34 (even for a constant source output, and after proper compensation for geometrical divergent effects) may not be equal. There may be merit in correcting these amplitude variations (from the formation velocity and density values known from the borehole logs), or in bringing their average or peak amplitude to be constant by some suitable normalization process.

It is clear from the foregoing that the present invention, in using the downgoing signal to deconvolve the upcoming signal, effects a major clarification of the form and interpretability of the upcoming reflection. Since the majority of the effects complicating the downgoing signal occur either near the source, or in the near-surface, or in the shallow unconsolidated sediments, of in sequences of highly contrasting stratification at shallow or medium depth, it is further apparent that any changes of pulse shape between the detected downgoing and upcoming signals are either small or else of interpretational significance in the context of reservoir conditions. And the resolution of the reservoir reflections is vastly better than on a surface-to-surface seismic section - not only in terms of pulse bandwidth (which defines the vertical resolution) but also in terms of the insonified area of the reservoir (which defines the horizontal resolution of reservoir irregularities).

A further aspect of the present invention, which is applicable to any type of source, becomes of particular interest in that it raises the possibility of replacing an impulsive-type source 7 by a controllable vibrator, and of designing the excitation signal for this vibrator to include at least part of the desired deconvolution. Thus the component of the downgoing signal form which is consequent on the short-path multiple phenomenon can be computed from the velocity and density logs in the borehole, and an operator inverse to this effect can be applied to the downhole signal derived from an impulsive source, or to the coded signal used to drive the vibrator. This latter possibility means that part of the transition from the complex downgoing form 16 to the simple downgoing 31 occurs in the process of transmission through the earth.

As noted above, the improved resolution of the top-reservoir and bottom-reservoir reflections, which allows their separation and measurement, yields the acoustic specification of the reservoir where it is traversed by the borehole. If this approach is to be useful for areal delineation of the reservoir, however, it is necessary to modify the technique to obtain reflection indications away from the borehole, and towards the limits of the reservoir.

Figure 5 illustrates this. Instead of a single source position at or near the wellhead, as used in conventional check-shooting practice, one or more profiles of source positions are used. In general, these profiles are disposed to pass through the wellhead, though the approach may be varied for particular purposes (for example, in the case of deviated wells). The wellhead is shown at 38, the borehole at 39, the reservoir at 40, and a typical geophone position at 41. Two representative source positions along the source profile 42 are shown at 43 and 44. In offshore operations, the mobile source is conveniently a conventional seismic survey vessel. On land it may be a vehicle-mounted vibrator or impulser, or the sources may involve the use of explosives or air-guns (in a plurality of drilled shotholes, or at or near the surface).

The dimensions and areal configuration of the source profiles are selected, with regard to the depths of the reservoir and the geophone, to provide suitable reflection paths from source to geophone via the expected outermost limits of the reservoir.

This concept of a profile of sources is then combined with the previous novel proposal of using the downgoing signal to deconvolve the upcoming signal. Thus if the source is constant and accurately repeatable along the profile (as in the marine case), the downgoing signal from a source position above the geophone(s) may be used, after selection and enhancement as described hereinbefore, to deconvolve all the borehole signals recorded from the other source positions.

The result of this operation is exemplified in Figure 6a, for several of the many source positions actually occupied. Trace 45 is the output obtained when the source is vertically above the borehole geophone(s); the direct arrival 31 and the two reservoir reflections 32 and 33 are the same as in Figure 2. Trace 46 is the output obtained when the source is at position 43 in Figure 5; the direct arrival 47 follows the dashed path 48, and the top-reservoir reflection 49 follows the path 50. Trace 51 is a similar trace obtained when the source is on the other side of the well 38. Trace 52 is the output obtained from source position 44; again the direct arrival 53 follows the path 54 and the top-reservoir reflection 55 follows the path 56. Trace 56 is the counterpart of trace 52 on the other side of the well.

The direct arrivals typified by 31, 47 and 53 have an approximate hyperbolic alignment. They may also show some broadening of form away from the apex trace 45, relative to arrival 31; in the case under discussion (constant source excitation), this broadening is due to the obliquity now associated with the short-path multiple phenomenon. If the degree of broadening is negligible, the interpreter can proceed to the analysis of the reservoir reflections. If not, it may be desirable to deconvolve each trace individually, using the separated direct arrival (which may also be specifically down-stacked, taking account of the time changes introduced by the obliquity) to deconvolve the upcoming reflections on the same trace. As is evident from the geometry of Figure 5, the obliquity associated with the reflection path is not quite the same as that associated with the direct path; however, for the circumstances of each case, it is easy to make a judgement as to whether the upcoming signals should be deconvolved from the downgoing signal on the same trace, or the vertical-incidence trace, or some other trace having a preferred degree of obliquity.

When the source signal is not precisely repeatable (in particular, for operations on land) the above options are not usually available; it becomes desirable to use each downgoing signal to deconvolve its own upcoming signal, and no other, in order that the variations of source signal shall be compensated.

When the interpreter is satisfied on these points, he proceeds to study the reservoir reflections. In the illustration of Figure 6a, the top of the reservoir (which, for a velocity-sensitive geophone, is clearly a negative reflector of computable reflection coefficient) can be traced across the arivals 32, 49, and 55 in one direction and across the arrivals 58 and 59 in the other direction; likewise the bottom (positive) reflection 33 can also be traced across the reservoir. The characteristic signature of the reservoir complex is seen to disappear by thinning between traces 52 and 60, and by faulting between traces 57 and 61. This is basically the delineation information which the interpreter is seeking.

The reservoir delineation can be made more pictorial by manipulating the display of Figure 6a into that of Figure 6b. In this illustration (which shows traces additional to those shown in Figure 6a) the time axis is made vertical to stimulate depth in the earth; further, the reflected arrivals are time-shifted to compensate their generally hyperbolic configuration, using normal-moveout corrections derived from the known velocities and horizontal distances. Thus trace 45, representing the vertical paths, is identical to the same-numbered trace on Figure 6a; the direct arrival 31 and the reflected arrivals 32 and 33 (from the top and bottom of the reservoir) are as before. After normal-moveout correction, however, the other traces show the time configuration of the reservoir - pinched-out at 73 to the right and faulted at 74 to the left - in a true pictorial representation. On these traces the direct arrivals corresponding to 31 have been suppressed for clarity.

Further useful information on the reservoir characteristics is available from a detailed study of the amplitude and form of the reflections. For this the interpreter must understand the factors influencing these reflections, which include:

(a) the directional nature of the geophone (if of velocity-sensitive type),
(b) the curvature (if any) of the reflector(s),
(c) the variation of reflection coefficient with angle of incidence,
(d) if the reflections interfere, the sensitivity of that interference to the time between reflections, and hence to the angle of incidence,
(e) refraction effects within the reservoir.

Thus the interpreter, having made approximate corrections for the first two of these factors, then proceeds to explore the effect of the others. In this he searches for the increase of a positive reflection coefficient near the critical angle, for the transition from reflection to refraction, and for events which may be recognized as conversions from compressional waves to vertically-polarized shear waves. The locations at which any or all of these phenomena appear are then interpreted in terms of reservoir characteristics, according to Snell's law and the equations for reflection coefficient.

The most obvious example of this type of analysis occurs when a highly-porous gas-saturated reservoir yields a very strong negative reflection from its upper boundary. Then the present technique allows areal mapping of the strength of this reflection, after correction for the factors listed above, from several or many profiles through the well. Of course, the most marked reservoir-induced anomalies of this type are evident on conventional seismic sections observed on a line through the wellhead; the compelling advantage of the present method is the vastly improved resolution and accuracy of measurement which becomes possible when the effects of the near-surface and shallow section are substantially removed.

Another significant advantage arises in the mapping of the fluid contact. This is always a positive reflection, and so can be studied advantageously at wide angle, and by refraction, if the source profile 42 is extended to sufficient distance.

It is apparent from the geometry of Figure 5 that one geophone location 41 may be sufficient to explore the limits of a reservoir in all directions if the well is approximately central in the reservoir and if the geophone is placed a suitable distance above the reservoir. The larger the areal extent of the reservoir, the further the geophone is ordinarily spaced above the reservoir. If the well is not believed to be central, it may be appropriate to occupy a plurality of geophone positions, in order to ensure appropriate reflection paths from the near limits and the far limits of the reservoir. Of course, it is inevitable that the deconvolution process can remove the effects of less of the overburden if the limit of the reservoir is distant from the well (and the geophone is therefore at shallow depth).

The possibility of occupying a plurality of geophone positions for each horizontal profile of source positions is an interesting one. First, it allows the partial separation of angle-of-incidence effects from simple reflection-coefficient effects, in that it becomes possible to select reflection paths representing a constant angle of incidence, and to map the derived reflection strengths. Further, and more important, it allows common-depth-point stacking of borehole signals. This is illustrated in Figure 7.

Figure 7a depicts three ray-paths, from sources 62 to geophones 63, for a conventional surface-to-surface common-depth-point gather. As it is widely used in the prior art, common-depth-point stacking of the plurality of paths 64 to a common depth-point 65 on a reflector 66 is accomplished by first estimating a velocity to be ascribed to the over-burden 67; this velocity is that which allows all ray-paths 64 to be corrected to that time value which would apply if source and receiver were coincident. Then, after these normal-moveout corrections, the several components in the common-depth-point gather are added to yield a single stacked trace of improved signal-to-noise ratio and improved primary-to-multiple ratio.

The concept of common-depth-point stacking of borehole signals is illustrated in Figures 7b and 7c. The borehole is shown at 70, and the target reflector at 71. Then the combinations of sources 68 and geophone positions 69 are chosen to provide a common depth-point 72 on the reflector 71. The objective of the operation is similar to that of the surface-to-surface stacking in Figure 7a, but there is a fundamental difference. In surface-to-surface stacking the common nature of the depth point follows from the geometry of the situation, and the essential determination is that of the stacking velocity; in surface-to-borehole stacking the velocity is known rather precisely from the basic check-shooting operation (particularly as improved by the deconvolution technique disclosed hereinbefore) and the essential determination is that of selecting the combinations of source and geophone position which yield a common depth-point.

The field work for borehold cdp-stacking must include the shooting of a profile or source positions into each one of a plurality of borehole-geophone positions. For each of a plurality of common depth-points on the target reflector appropriate combinations of source position and geophone depth are then selected, and a common-depth-point gather is made.

For the simplest assumption of straight ray-paths and horizontal reflectors, appropriate combinations of source position and geophone are based on the equation

$$x/p = 1+/(1-d/z),$$

where x = distance of source from well head (or vertical through geophone),
p = distance of common depth-point from borehole (or vertical through geophone),
d = depth of borehole geophone,
z = depth of target reflector.

For more complicated situations the appropriate combinations of source position and geophone depth are found using the concept of rms velocity, or by a ray-tracing exercise which takes into account all the reflector dips and all the known velocities. For a first estimate of reflector dips it is an advantage to have a conventional seismic reflection section on each source profile, and in some cases it makes good sense to associate the shooting of the source profile into the borehole geophone with the double function of shooting a conventional spread of surface geophones.

After the appropriate combinations of source positions and geophone depths have been determined, normally for each of a plurality of common depth-points, the relevant traces are assembled into common-depth-point gathers. Each trace is deconvolved according to one of the techniques set out hereinbefore (the deconvolution advantageously being arranged so that it also compensates variations in trace amplitude associated with acoustic impedance of the material local to each geophone position), and each trace is also compensated for the effects of geometrical divergence by techniques well known in the art.

The first and major utility of the common-depth-point gathers is, of course, that the traces can be corrected for moveout and other time variations (using the known velocity information, as discussed previously), and stacked. This yields an improved version of the signal reflected from each depth-point, and allows an improved map of reflection strength over the reservoir area. Where faults are recognized on the gathers, the stacking may be done selectively, not to use paths which can be seen to have passed through a faulted zone.

Various auxiliary measurements can also be made on the common-depth-point gathers. One of these is the variation of reflection coefficient with angle of incidence, since the gathered paths represent the same reflection zone observed at different angles. Thus critical-angle effects, and the transition into refraction at a measurable velocity, can be observed very clearly, and interpreted in terms of the contrast and anisotropy of both velocity and acoustic impedance existing at the reflector. These wide-angle effects are very much in evidence, because with the usual reservoir depths and extents there is every unducement to occupy source positions representing an x/p ratio as high as 3 or more, thus incurring incidence angles of 45° or more. Another auxiliary measurement is therefore the amplitude, velocity and phase change associated with the wave converted at oblique incidence from compressional to vertically-polarized shear. Where shear conversions can be identified from the top and bottom of the reservoir, the shear velocity within the reservoir can be obtained; this, and its ratio to the compressional velocity, is also a quantity to be mapped over the extent of the reservoir. The compressional and shear velocities in the materials overlying the reservoir are also measured, since it is observed that anomalous mineralization sometimes introduces significant variations in velocity in the rocks locally above hydrocarbons.

It is also true that many or all of the operations and measurements disclosed in this specification may be employed with horizontally-polarized shear waves. This requires specially adapted sources and an array of horizontally-sensitive units in the borehole geophone.

A further variation of interest becomes possible if several boreholes exist in the reservoir area; then there is merit in disposing borehole geophones in a plurality of them simultaneously, and of recording the signals derived from profiles of sources between the wellhead locations, as well as generally radially from each borehole.

The techniques of this invention are also generally applicable to the case where the seismic source can itself be disposed in a borehole, below the worst of the near-surface frequency-selective agencies.

Attention is drawn to copending application No. 45226/78 (serial No. 1569582), the claims of which are directed to methods of obtaining common-depth-point groups of traces.

WHAT I CLAIM IS:-

1. A method of processing seismic signals from a borehole geophone, which signals include both a direct downgoing arrival and one or more reflected upcoming arrivals, comprising the following steps:

a. isolating the direct downgoing arrival,

b. deriving therefrom a deconvolution operator to transform the pulse form of the downgoing arrival into a more desirable pulse form,

c. applying this operator to selected arrivals,

d. displaying the results.

2. The method of claim 1, wherein the said isolation is accomplished by selectively gating and/or tapering the said direct downgoing arrival.

3. The method of claim 1 or 2, wherein the said isolation is improved by appropriate time-shifting and addition of a plurality of recordings of the said downgoing arrival from geophone locations spaced apart in the borehole.

4. The method of any of the preceding claims, wherein the deconvolution operator derived from the direct downgoing arrival is applied to the reflected upcoming arrivals.

5. The method of claim 4, wherein the said reflected upcoming arrivals are enhanced by appropriate time-shifting and addition of a plurality of recordings from geophone locations spaced apart in the borehole.

6. The method of any of the preceding claims, wherein the amplitudes of the deconvolved downgoing and upcoming arrivals are used to estimate the reflection coefficient of a seismic reflector.

7. The method of claims 1-5, wherein the frequency contents of the deconvolved downgoing and upcoming arrivals are used to estimate the frequency-selective action of the material between the borehole geophone and a seismic reflector.

8. The method of any of the preceding claims, wherein the said signals are generated by a seismic source at one or more positions at or near the surface, wherein the said upcoming arrivals are reflected from the boundaries of a hydrocarbon reservoir, and wherein the locations of the said source positions are chosen to facilitate the vertical and/or horizontal delineation of the reservoir.

9. The method of claim 8, wherein the processed and corrected signals are displayed in a format representing a section through said reservoir.

10. A method of obtaining a common-depth-point group of traces derived from the seismic reflection at the boundary of a hydrocarbon reservoir, using the following steps:

a. making records of the arrivals obtained at a borehole geophone for each source position along one or more extended source profiles, for each of a plurality of geophone locations,

b. selecting a groups of records which, having regard to the geometry of the ray-paths, the dip of the strata and the velocity distribution, represent a common reflection zone on the said boundary,

c. selecting and isolating a particular direct downgoing signal,

d. calculating a deconvolution operator to transform this downgoing signal into a more desirable pulse form, and

e. applying this operator to one or more members of the group of reflection traces.

11. The method of claim 10, which further includes the steps of compensating the records within each group for the delays consequent on the obliquity of the ray-paths, and of adding together the compensated reflection traces to form a single trace.

12. A method of delineating a hydrocarbon reservoir substantially as described in the preceding specification and accompanying drawings.

NIGEL ALLISTER ANSTEY

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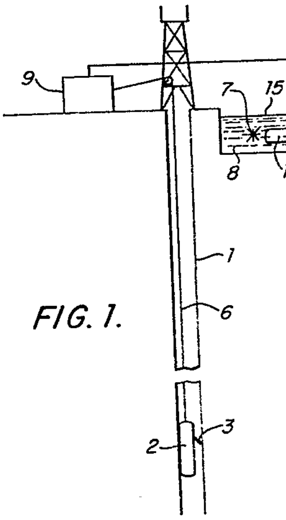

FIG. 1.

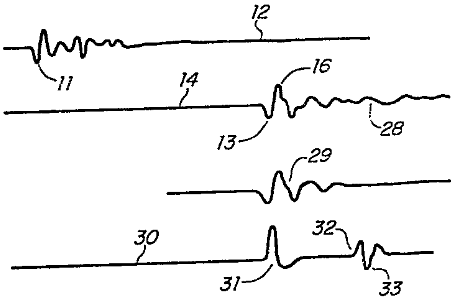

FIG. 2.

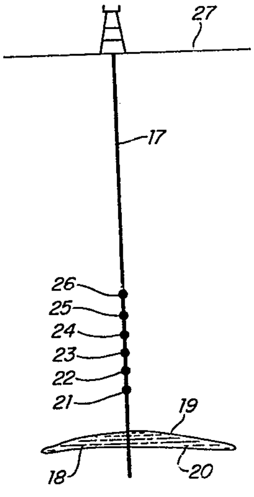

FIG. 3.

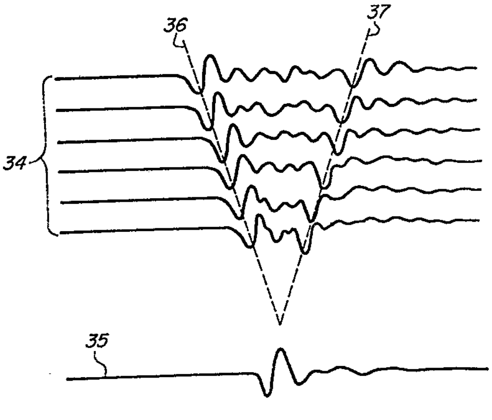

FIG. 4.

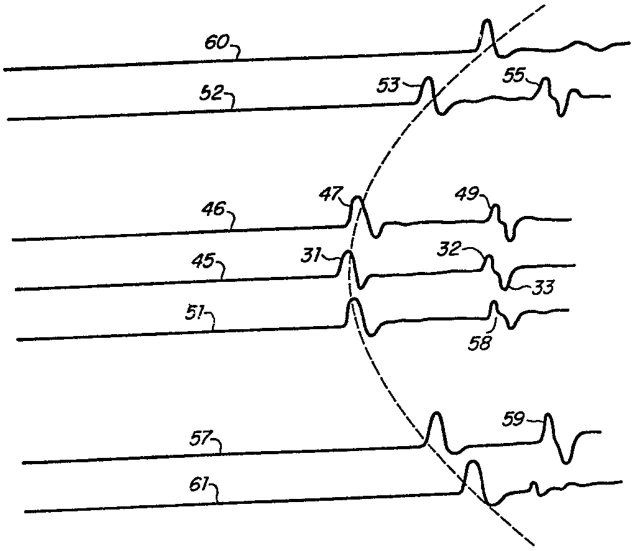

FIG. 6A.

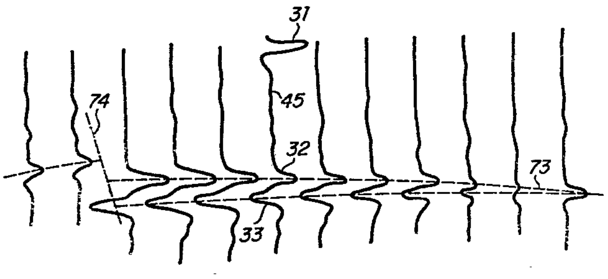

FIG. 6B.

1569581 COMPLETE SPECIFICATION

3 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 3

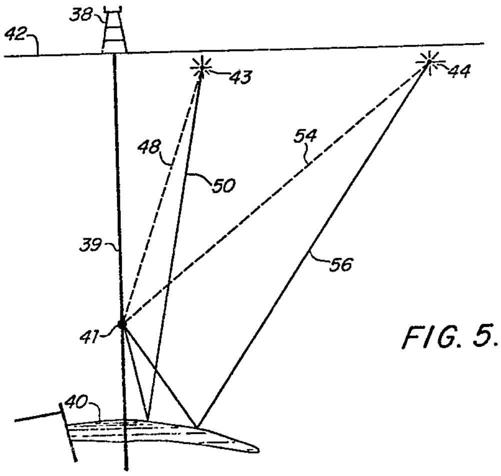

FIG. 5.

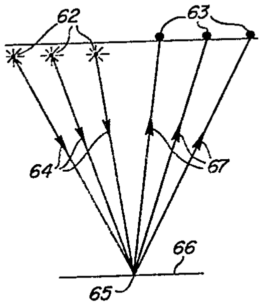

FIG. 7A.

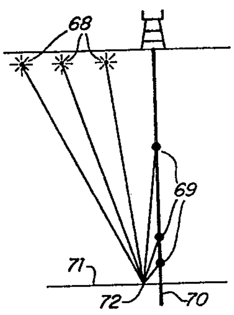

FIG. 7B.

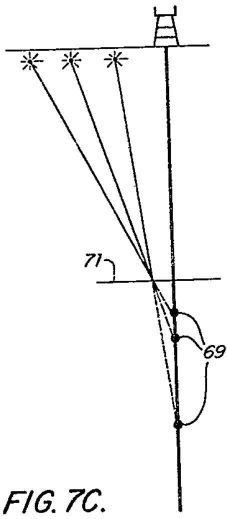

FIG. 7C.