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(54) REMOVING IRREGULARITIES FROM SEISMIC DATA CAUSED BY TUBE WAVES

ENTFERNUNG VON STÖREINFLÜSSEN IN SEISMISCHEN DATEN, WELCHE DURCH ROHRWELLEN VERURSACHT WERDEN

ELIMINATION D'IRREGULARITES DE DONNEES SISMIQUES CAUSEES PAR DES ONDES TUBULAIRES

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Description

[0001] The present invention relates to removing irregularities from seismic data caused by tube waves. Tube waves are sound waves in a borehole. Such tube waves are encountered when a seismic survey is carried out such that the seismic sources or the seismic receivers or both the seismic sources and the seismic receivers are located in a borehole. A disadvantage of tube waves is that the seismic signals from relevant events are mixed with the signals generated by the tube waves, and therefore the valuable information is substantially invisible.

[0002] USA patent specification No. 4 992 995 discloses a method for attenuating noise in seismic data. The method comprises obtaining a set of seismic data sorted into gathers of seismic signals, aligning selected coherent events, sorting the gathers in order to disorder the sequential order of the seismic signals in each gather, filtering the disordered gathers with a spatial filter, resorting the filtered signals in their original order, and combining the filtered signals with a respective gather of seismic singles to obtain a gather of seismic signals that is substantially free of unwanted coherent and random noise.

[0003] USA patent specification No. 5 237 538 also discloses a method of removing coherent noise from seismic traces.

[0004] USA patent specification No. 5 392 213 discloses a method for suppressing coherent noise from seismic or borehole data, which method comprises horizontally aligning the traces, comparing the.amplitude, phase and/or shape of neighbouring traces, and subtracting traces from neighbouring traces only when the local correlation is high.

[0005] It is an object of the present invention to provide a method that effectively removes the irregularities caused by tube waves.

[0006] To this end the method of removing irregularities caused by tube waves from seismic data obtained in a borehole seismic survey, using a first set of transducers (seismic receivers or sources) and a second set of transducers (seismic sources or receivers) and wherein at least the transducers of the first set are arranged in a borehole, according to the present invention comprises the steps as outlined in claim 1.

[0007] The invention will now be explained by way of example in more detail with reference to the accompanying drawings, wherein

Figure 1 shows schematically and not to scale a first configuration of the transducers for application of the method according to the present invention;
Figure 2 shows schematically and not to scale a second configuration of the transducers for application of the method according to the present invention;
Figure 3 shows schematically and not to scale a third configuration of the transducers for application of the method according to the present invention;
Figure 4 shows an untreated common receiver gather;
Figure 5 shows the common receiver gather after subjecting the data to a time shift;
Figure 6 shows the time-shifted, predicted tube wave data;
Figure 7 shows the time-shifted, predicted tube wave data after the correlation check;
Figure 8 shows the predicted tube wave data set in the original domain;
Figure 9 shows the common receiver gather of Figure 4- after subtraction of the predicted tube waves; and
Figure 10 shows the final result of applying the method of the present invention on the common receiver gather of Figure 4.

[0008] In order to apply the method according to the present invention there are needed two sets of transducers: a first set of transducers (seismic receivers or sources) and a second set of transducers (seismic sources or receivers). The possible configurations of these two sets are now discussed with reference to Figures 1-3.

[0009] Reference is now made to Figure 1. The first set of transducers is a set of seismic receivers 10 arranged in a borehole 12 extending from surface 13 into the earth 14 and the second set of transducers is a set of seismic sources 18 arranged at the surface 13.

[0010] Reference is now made to Figure 2. In this Figure the sets are interchanged. The first set of transducers is now a set of seismic sources 20 arranged in a borehole 22 extending from surface 23 into the earth 24, and the second set of transducers is a set of seismic receivers 28 arranged at the surface 23.

[0011] Reference is now made to Figure 3. The first set of transducers is a set of seismic sources 30 arranged in a first borehole 32 extending from surface 33 into the earth 34 and the second set of transducers is a set of seismic receivers 38 arranged in a second borehole 39 extending from the surface 33 into the earth 34.

[0012] It will be understood that the boreholes 12, 22, 32 and 39 are filled with a liquid, that they need not be vertical and that the boreholes can be cased.

[0013] The first step of the method of removing irregularities caused by tube waves from seismic data obtained in a borehole seismic survey is obtaining a set of original seismic data $p_m(t,k)$, wherein the integer k refers to the k'th transducer of the first set of transducers and the integer m refers to the m'th transducer of the second set of transducers. The seismic data for a fixed k and m is also called a trace.

[0014] The original seismic data set $p_m(k,t)$ can be grouped in two ways. A first way is to combine for each seismic source a number of traces equal to the number of seismic receivers. When the data are grouped in this way each set of traces is called a common source (or common shot) gather. It will be understood that there are as many different common source gathers as there are seismic sources. However, the data can also be grouped in a different way: for each seismic receiver a number of traces equal to the number of seismic sources. This is called a common receiver gather, and there are as many different common receiver gathers as there are receivers.

[0015] The method according to the invention will now be explained with reference to the Figures 1-3.

[0016] In the configuration shown in Figure 1, the seismic receivers 10 (the first set of transducers) are arranged in the borehole 12 and the seismic sources 18 (the second set of transducers)'are arranged at the surface 13. The first step of the method according to the present invention is obtaining a set of original seismic data $p_m(t,k)$, wherein the integer k refers to the k'th seismic receiver of the set of seismic receivers 10 (the first set) in the borehole 12 and the integer m refers to the m'th seismic source of the set of seismic sources 18 (the second set).

[0017] When the seismic receivers are arranged in the borehole, it is convenient to group the original seismic data in a common source gather, thus for each source 18m there are grouped a number of traces, each trace belonging to a receiver 10k, wherein k is in the range of from 1 to the number of receivers. The number of common source gathers can equal the number of sources.

[0018] The method of the present invention removes the effect of tube waves generated in the borehole 12 in which the seismic receivers 10 are arranged. Thereto the original seismic data set is subjected to a time-shift based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_m(t, k)$ is obtained.

[0019] Then a structurally oriented, edge-preserving filter is applied to the time-shifted seismic data set $\tilde{p}_m(t, k)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_m(t, k)$. The time shift for the time-shifted, predicted tube wave data set $\tilde{q}_m(t, k)$ is undone to obtain a set of predicted tube wave data $q_m(t,k)$. Subsequently the predicted tube wave data set $q_m(t,k)$ is subtracted from the original seismic data set $p_m(t,k)$ to obtain a set of corrected seismic data $p^c{}_m(t, k)$, and the original seismic data set is replaced by the corrected seismic data set.

[0020] The now original seismic data set (common source gather) has been corrected for tube wave in the borehole 12 having an estimated velocity in one direction, and next a correction is made for a tube wave having this velocity in opposite direction. This is done by repeating the steps that are described in the preceding paragraph. The result of this two-step operation is a set of seismic data of which irregularities caused by tube waves in the borehole 12 have been removed.

[0021] An edge-preserving filter is a filter that removes noise and other unwanted components from data without destroying discontinuities in the data, and a structurally oriented filter is an adaptive filter that acts differently in different directions, wherein the directions are computed from the data. An advantage of an edge-preserving filter is that it does not suppress the first arrival.

[0022] Subjecting the data set $p_m(t,k)$ to a time-shift to align the tube waves in time is done in accordance with the following equation $\tilde{p}_m(t, k) = p_m(t \pm z_k / v_{tube}, k)$. Undoing the time shift for a time-shifted, predicted tube wave data set $\tilde{q}_m(t, k)$ is done in accordance with the following equation $q_m(t, k) = \tilde{q}_m(t \mp z_k / v_{tube}, k)$. In these equations t is time, z_k is the depth along the borehole 12 of receiver k, v_{tube} is the magnitude of the tube wave velocity, and the plus sign refers to tube waves in one direction and the minus sign to tube waves in the opposite direction.

[0023] In the configuration shown in Figure 2, the seismic sources 20 (the first set of transducers) are arranged in the borehole 22 and the seismic receivers 28 (the second set of transducers) are arranged at the surface 23. The first step of the method according to the present invention is obtaining a set of original seismic data $p_m(t,k)$, wherein the integer k refers to the k'th seismic source of the set of seismic sources 20 (the first set) in the borehole 22 and the integer m refers to the m'th seismic receiver of the set of seismic receivers 28 (the second set). When the seismic sources are arranged in the borehole, it is convenient to group the original seismic data in a common receiver gather, thus for each receiver 28m there are a number of traces, each trace belonging to a source 20k, wherein k is in the range of from 1 to the number of sources. The number of common receiver gathers can equal the number of receivers.

[0024] The method of the present invention removes the effect of tube waves generated in.the borehole 22 in which now the seismic sources 20 are arranged. Thereto the original seismic data set is subjected to a time-shift based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_m(t, k)$ is obtained.

[0025] Then a structurally oriented, edge-preserving filter is applied to the time-shifted seismic data set $\tilde{p}_m(t,k)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_m(t,k)$. The time shift for the time-shifted, predicted tube wave data set $\tilde{q}_m(t,k)$ is undone to obtain a set of predicted tube wave data $q_m(t,k)$. Subsequently the predicted tube wave data set $q_m(t,k)$ is subtracted from the original seismic data set $p_m(t,k)$ to obtain a set of corrected seismic data $p^c{}_m(t, k)$, and the original seismic data set is replaced by the corrected seismic data set.

[0026] The now original seismic data set (common receiver gather) has been corrected for tube wave in the borehole 22 having an estimated velocity in one direction, and next a correction is made for a tube wave having this velocity in opposite direction. This is done by repeating the steps that are described in the preceding paragraph. The result of this two-step operation is a set-of seismic data of which irregularities caused by tube waves in the borehole 12 have been removed.

[0027] Subjecting the data set $p_m(t,k)$ to a time-shift to align the tube waves in time is done in accordance with the following equation $\tilde{p}_m(t,k) = p_m(t \pm z_k / v_{tube}, k)$. Undoing the time shift for a time-shifted, predicted tube wave data set $\tilde{q}_m(t,k)$ is done in accordance with the following equation $q_m(t, k) = \tilde{q}_m(t \mp z_k / v_{tube}, k)$. In these equations, t is time, z_k is the depth along the borehole 22 of source k, v_{tube} is the magnitude of the tube wave velocity, and the plus sign refers to tube waves in one direction and the minus sign to tube waves in the opposite direction.

[0028] Please note that the depth z_k refers to the depth along the borehole of the transducer that is present in the borehole, which is in Figure 1 the seismic receiver and in Figure 2 the seismic source.

[0029] In the configuration shown in Figure 3, the seismic sources 30 (the first set of transducers) are arranged in the borehole 32 and the seismic receivers 38 (the second set of transducers) are arranged in the borehole 39. Thus now there are two boreholes in which tube waves occur. The effect of the tube waves in both boreholes has to be removed. Because there are two boreholes, the seismic data can now be grouped in a common source gather or in a common receiver gather. The method now comprises two correction steps. The first correction step is done on the data grouped in a common source gather and the second correction step is done on the corrected data from the first step grouped in a common receiver gather. Please note that the sequence of the correction step is not relevant.

[0030] The first step of the method according to the present invention is obtaining a set of original seismic data $p_m(t, k)$, wherein the integer k refers to the k'th seismic source of the set of seismic sources 30 (the first set) and the integer m refers to the m'th seismic receiver of the set of seismic receivers 38 (the second set). The data are at first grouped in a common receiver gather, thus for each receiver 38m there are a number of traces, each trace belonging to a source 30k, wherein k is in the range of from 1 to the number of sources. The number of common receiver gathers can equal the number of receivers.

[0031] The method of the present invention removes the effect of tube waves generated in the borehole 32 in which now the seismic sources 30 are arranged. Thereto the original seismic data set is subjected to a time-shift based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_m(t,k)$ is obtained.

[0032] Then a structurally oriented, edge-preserving filter is applied to the time-shifted seismic data set $\tilde{p}_m(t, k)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_m(t,k)$. The time shift for the time-shifted, predicted tube wave data set $\tilde{q}_m(t, k)$ is undone to obtain a set of predicted tube wave data $q_m(t,k)$. Subsequently the predicted tube wave data set $q_m(t,k)$ is subtracted from the original seismic data set $p_m(t,k)$ to obtain a set of corrected seismic data $p^c_m(t, k)$, and the original seismic data set is replaced by the corrected seismic data set.

[0033] The now original seismic data set (common receiver gather) has been corrected for tube wave in the borehole 32 having an estimated velocity in one direction, and next a correction is made for a tube wave having this velocity in opposite direction. This is done by repeating the steps that are described in the preceding paragraph. The result of this two-step operation is a set of seismic data of which irregularities caused by tube waves in the borehole 32 have been removed.

[0034] Subjecting the data set $p_m(t, k)$ to a time-shift to align the tube waves in time is done in accordance with the following equation $\tilde{p}_m(t, k) = p_m(t \pm z_k / v_{tube}, k)$. Undoing the time shift for a time-shifted, predicted tube wave data set $\tilde{q}_m(t, k)$ is done in accordance with the following equation $q_m(t, k) = \tilde{q}_m(t \mp z_k / v_{tube}, k)$. In these equations, t is time, z_k is the depth along the borehole 32 of source k, v_{tube} is the magnitude of the tube wave velocity, and the plus sign refers to tube waves in one direction and the minus sign to tube waves in the opposite direction.

[0035] Then the tube waves in the borehole 39 are removed. To this end the data are grouped in a common source gather.

[0036] The next step is arranging the data in a common source gather, $p_n(t,l)$, wherein the integer l refers to the l'th seismic receiver of the set of seismic receivers 38 (the second set) in the borehole 39 and the integer n refers to the n'th seismic source of the set of seismic sources 30 (the first set). Thus for each source 30n there are a number of traces, each trace belonging to a receiver 381, wherein l is in the range of from 1 to the number of receivers. The number of common source gathers can equal the number of sources.

[0037] To remove the effect of tube waves in the second borehole 39, hereto the seismic data set previously obtained is subjected to a time-shift based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_n(t,l)$ is obtained.

[0038] Then a structurally oriented, edge-preserving filter is applied to the time-shifted seismic data set $\tilde{p}_n(t,l)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_n(t, l)$. The time shift for the time-shifted, predicted tube wave data set $\tilde{q}_n(t,l)$ is undone to obtain a set of predicted tube wave data $q_n(t,l)$. Subsequently the predicted tube wave data set $q_n(t,l)$ is subtracted from the original seismic data set $p_n(t,l)$ to obtain a set of corrected seismic data $p^c_n(t,l)$, and the original seismic data set is replaced by the corrected seismic data set.

[0039] The now original seismic data set (common source gather) has been corrected for tube wave in the borehole 12 having an estimated velocity in one direction, and next a correction is made for a tube wave having this velocity in opposite direction. This is done by repeating the steps that are described in the preceding paragraph. The result of this two-step operation is a set of seismic data of which irregularities caused by tube waves in the boreholes 32 and 39 have been removed.

[0040] Subjecting the data set $p_n(t,l)$ to a time-shift to align the tube waves in time is done in accordance with the following equation $\tilde{p}_n(t, l) = p_n(t \pm z_l / v_{tube}, l)$. Undoing the time shift for a time-shifted, predicted tube wave data set $\tilde{q}_n(t,l)$ is done in accordance with the following equation $q_n(t, l) = \tilde{q}_n(t \mp z_l / v_{tube}, l)$. In these equations, t is time, z_l is the depth along the borehole 39 of receiver l, v_{tube} is the magnitude of the tube wave velocity, and the plus sign refers to tube waves in one direction and the minus sign to tube waves in the opposite direction.

[0041] The other steps of the method according to the present invention will now be described by way of example in more detail with reference to Figures 3 and 4-11.

[0042] Figure 4 shows a common receiver gather consisting of obtained by activating a set of 64 seismic sources 30 (see Figure 3) arranged in the first vertical borehole 32, the first of the seismic sources 30 was located at a depth of 800 m, and the interval between adjacent seismic sources was 1.9 m. In the second vertical borehole 39, located at a horizontal distance of 130 m from the first borehole 32, a set of 64 seismic receivers 38 were arranged at the same depths as the seismic sources 30. Figure 4 shows the common receiver gather $p_k(t,m)$ obtained for receiver k=59, wherein m=1,...,64. The original seismic data is referred to with reference numeral 40. Clearly visible are the tube waves 41 and 42. Reference numeral 43 refers to a reflection of a reflector.

[0043] The original seismic data set $p_k(t,m)$ is subjected to a time-shift based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_k(t,m)$ is obtained. Subjecting the data set to a time shift is governed by the following equation $\tilde{p}_k(t, m) = p_k(t \pm z_m / v_{tube}, m)$, wherein the plus sign refers to tube waves moving in one direction, and the minus sign refers to tube waves moving in the opposite direction, wherein z_m is the depth along the borehole 39 of receiver m, and wherein v_{tube} is the magnitude of the tube wave velocity. Figure 5 shows the common receiver gather after applying the time shift

$$\tilde{p}_k(t, m) = p_k(t - z_m / v_{tube}, m),$$

wherein k=59, v_{tube}=1480 m/s and m=1,...,64. Figure 5 shows clearly that by applying the time shift, the tube waves 50 are aligned in time. Please note that the data shown in Figures 5-7 have a reference time that differs from the reference time used in Figures 4 and 8-10. This was done for practical reasons and it does not affect the overall result.

[0044] Next the tube wave data will be predicted so that in the end they can be removed from the original data set. In order to predict the tube wave data a structurally oriented, edge-preserving filter is applied to each element of the time-shifted seismic data set $\tilde{p}_k(t,m)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_k(t, m)$. In this case k=59 m=1, ..., 64.

[0045] Suitably, applying the structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_m(t, m)$ to obtain a set of time-shifted, predicted tube wave data set $\tilde{q}_m(t, m)$ comprises first determining for each element of the data set $\tilde{p}_m(t, m)$ the local orientation of the time-shifted seismic data, which local orientation is the orientation of a plane tangent to the time-shifted seismic data for that element. Then for each element one determines whether there is an edge in its neighbourhood. Finally an averaging operation is carried out for each element of the data set $\tilde{p}_m(t, m)$, wherein the direction of the averaging operation is the local orientation of the data and wherein the averaging operation does not go over the edge, to obtain the set of time-shifted, predicted tube wave data set $\tilde{q}_m(t, m)$.

[0046] Applying the structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_m(t, m)$ to obtain the set of time-shifted, predicted tube wave data set $\tilde{q}_m(t,m)$ suitably comprises first defining a window of n_L+n_R+1 traces centred on trace m and $2n_t+1$ time samples centred on $t_n=t_0+n\Delta t$, wherein t_0 is the time at which sampling starts. Then a semblance measure is calculated in accordance with the following equation

$$s^0(t_n, m) = \frac{\sum_{l=-n_t}^{n_t} \left(\sum_{k=-n_L}^{n_R} \tilde{p}(t_n + l\Delta t, m + k) \right)^2}{(n_L + n_R + 1) \sum_{l=-n_t}^{n_t} \sum_{k=-n_L}^{n_R} \tilde{p}^2(t_n + l\Delta t, m + k)}.$$

[0047] To account for variations in the estimated velocity of the tube wave, two further semblance measures S^+ and S^- are calculated, wherein the data used to calculate the two further semblance measures is $\tilde{p}(t \pm \alpha z_k, m + k)$, wherein

α is a slowness parameter, and wherein z_k is the distance along the borehole between transducers m and k. Having calculated the three semblance measures the maximum value α_{max} of the slowness parameter is calculated. The maximum value of the slowness parameter is calculated as follows: given S^0, S^+ and S^- a dummy variable ξ is defined, such that S (ξ=0) =S^0, S (ξ=1) =S^+, and S (ξ=-1) =S^-, then a parabola is fit through these three values, and its maximum $S^{max}=S(\xi_{max})$ is computed on the interval [-1,1] for ξ. The maximum value of the slowness parameter then is $\alpha_{max}=\alpha.\xi_{max}$. Then the time-shifted tube wave data by taking the median of $\tilde{p}(t + \alpha_{max}z_k, m + k)$, wherein $-n_L \leq k \leq n_R$.

[0048] To account for abrupt changes in the velocity of the tube waves, the steps discussed in the above paragraph are repeated for three ranges: a left range (L), wherein $n_L=n_k$ and $n_R=0$, a central range (C), wherein $n_L=n_k$ and $n_R=n_k$; and a right range (R), wherein $n_L=0$ and $n_R=n_k$. This gives $S_L$max and $\tilde{q}_L$, $S_C$max and $\tilde{q}_C$, and $S_R$max and $\tilde{q}_R$, respectively. The integer n_k has a predetermined value. Then the time-shifted, predicted tube wave data are selected as follows, if $S_C^{max}>\varepsilon.\max(S_L^{max}, S_R^{max})$ then the time-shifted, predicted tube wave data are $\tilde{q}_C$, else, if $S_R^{max}>S_L^{max}$ then the time-shifted, predicted tube wave data are $\tilde{q}_R$, else the time-shifted, predicted tube wave data are $\tilde{q}_L$.

[0049] If the semblance measure corresponding to the chosen prediction is smaller than a threshold value S^{min}, the predicted tube wave data are set to zero.

[0050] Figure 6 shows the time-shifted, predicted tube wave data 60, for n_k=8, nt=9, $\alpha=0.03/v_{tube}$, ε=0.5 and S^{min}=0.1.

[0051] These tube wave data can be transformed by undoing the time shift for the time-shifted, predicted tube wave data set $\tilde{q}_k(t, m)$ to obtain a set of predicted tube wave data $q_k(t,m)$. And these data can be subtracted from the original data to obtain a set of correct original seismic data. However, suitably, a correction is applied on the time-shifted, predicted tube wave data in order to remove uncorrelated data, because uncorrelated data are considered not to be part of the tube wave data.

[0052] Thereto the step of applying a structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_k(t, m)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_k(t, m)$ further comprises correlating for each element of the set of time-shifted, predicted tube wave data with the time-shifted seismic data set, and removing the less well correlated elements from the set of time-shifted, predicted tube wave data.

[0053] Suitably, correlating the set of time-shifted, predicted tube wave data with the time-shifted seismic data set, and removing the less well correlated elements from the set of time-shifted, predicted tube wave data comprises determining a correlation measure and if the correlation measure is less than a predetermined minimum value C^{min}, the time-shifted, predicted tube wave data are made equal to zero.

[0054] The correlation measure is suitably

$$C(t_n, m) = 2\frac{\sum_{l=-n_t}^{n_t} \tilde{p}(t_n + l\Delta t, m).\tilde{q}(t_n + l\Delta t, m)}{\sum_{l=-n_t}^{n_t}\left\{\tilde{p}^2(t_n + l\Delta t, m) + \tilde{q}^2(t_n + l\Delta t, m)\right\}}.$$

[0055] Figure 7 shows the time-shifted, predicted tube wave data $\tilde{q}_k(t, m)$, referred to .with reference numeral 70 after the correlation check with C^{min}=0.3.

[0056] Then the time shift is undone for the time-shifted, predicted tube wave data set $\tilde{q}_k(t,m)$ to obtain a set of predicted tube wave data $q_k(t,m)$. Undoing the time shift for a time-shifted, predicted tube wave data set qi(t,j) is done in accordance with the following equation $q_i(t, j) = \tilde{q}_i(t \mp z_j / v_{tube}, j)$, and for the particular case the equation is $q_k(t, m) = \tilde{q}_k(t \mp zm / v_{tube}, m)$.

[0057] Figure 8 shows the predicted tube wave data set $q_k(t,m)$, referred to with reference numeral 80 in the original domain.

[0058] Then the predicted tube wave data set $q_k(t,m)$ is subtracted from the original seismic data set $p_k(t,m)$ to obtain a set of corrected seismic data $p^c_k(t,m)$, and the original seismic data set is replaced by the corrected seismic data set.

[0059] Then the above-described steps are repeated for a tube wave velocity that is opposite to the tube wave velocity used to obtain the result shown in Figure 9.

[0060] Then the data are grouped as common source gathers $p_n(t,l)$, and the steps as described with reference to Figure 3 for the common source gathers are repeated to remove the effect of tube waves in the borehole 32. The correction was applied with the parameters given above. Then the corrected data are grouped as common receiver gathers and the receiver gather for receiver 59 is shown in Figure 10. Figure 10 shows clearly the effect of the method according to the present invention on the final result of removing the effects of tube waves for the common receiver gather of Figure 4.

[0061] The method of the present invention includes using a structurally oriented edge-preserving filter, wherein the structurally oriented approach reduces errors due to small variations in the tube wave velocity, and wherein the edge-preserving approach allows proper handling of the start or abrupt changes in the tube waves. Optionally the method includes removing less well correlated elements from the set of time-shifted, predicted tube wave data. This optional step reduces the chance of removing a true event during the subtraction.

Claims

1. Method of removing irregularities caused by tube waves from seismic data obtained in a borehole seismic survey, using a first set of transducers which are seismic receivers or sources and a second set of transducers which are seismic sources or receivers, respectively and wherein at least the transducers of the first set are arranged in a borehole, which method comprises the steps of

   (a) obtaining a set of original seismic data $p_m(t,k)$, wherein the integer k refers to the k'th transducer of the first set of transducers and the integer m refers to the m'th transducer of the second set of transducers;
   (b) subjecting the original seismic data set to a time-shift based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_m(t, k)$ is obtained;
   (c) applying a structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_m(t,k)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_m(t, k)$;
   (d) undoing the time shift for the time-shifted, predicted tube wave data set $\tilde{q}_m(t,k)$ to obtain a set of predicted tube wave data $q_m(t,k)$;
   (e) subtracting the predicted tube wave data set $q_m(t,k)$ from the original seismic data set $p_m(t,k)$ to obtain a set of corrected seismic data $p^c{}_m(t,k)$, and replacing the original seismic data set by the corrected seismic data set;
   (f) subjecting the set of corrected, original seismic data to a time-shift based on a tube wave velocity opposite to the velocity used in step (b) to align the tube waves in time so that a set of time-shifted data $\tilde{p}_m(t,k)$ is obtained; and
   (g) repeating steps (c), (d) and (e) to obtain a set of seismic data of which irregularities caused by tube waves have been removed.

2. The method according to claim 1, wherein step (c) comprises applying a structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_m(t,k)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_m(t, k)$, correlating the set of time-shifted, predicted tube wave data with the time-shifted seismic data set, and removing the less well correlated elements from the set of time-shifted, predicted tube wave data.

3. The method according to claim 1 or 2, wherein also the transducers of the second set of transducers are located in a borehole, which differs from the borehole in which the transducers of the first set are located, which method further comprises the steps of

   (h) subjecting the set of seismic data obtained in step (i) to a time-shift to based on an estimated tube wave velocity to align the tube waves in time so that a set of time-shifted data $\tilde{p}_n(t, l)$ is obtained, wherein the integer l refers to the l'th transducer of the second set and the integer n refers to the n'th transducer of the first set;
   (i) applying a structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_n(t,l)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_n(t,l)$;
   (j) undoing the time shift for the time-shifted, predicted tube wave data set $\tilde{q}_n(t,l)$ to obtain a set of predicted tube wave data $q_n(t,l)$;
   (k) subtracting the predicted tube wave data set $q_n(t,l)$ from the original seismic data set $p_n(t,l)$ to obtain a set of corrected seismic data $p^c n(t,l)$, and replacing the original seismic data by the corrected seismic data; (l) subjecting the set of corrected, original seismic data to a time-shift based on a tube wave velocity opposite to the velocity used in step (h) to align the tube waves in time so that a set of time-shifted data $\tilde{p}_n(t,l)$ is obtained, and repeating steps (i) , (j) and (k) ;
   (m) repeating steps (i) through (l) for each transducer 1 of the first set of transducers and for each transducer n of the second set of transducers to obtain a set of seismic data of which irregularities caused by tube waves have been removed.

4. The method according to claim 3, wherein step (i) comprises applying a structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_n(t,l)$ to obtain a set of time-shifted, predicted tube wave data $\tilde{q}_n(t,l)$, correlating the set of time-shifted, predicted tube wave data with the time-shifted seismic data set, and removing the less well correlated elements from the set of time-shifted, predicted tube wave data.

5. The method according to claim any one of the claims 1-4, wherein applying a structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}i(t,j)$ to obtain a set of time-shifted, predicted tube wave data set $\tilde{q}_i(t,j)$ comprises the steps of:

1) determining for each element of the data set $\tilde{p}_i(t, j)$ the local orientation of the time-shifted seismic data, which local orientation is the orientation of a plane tangent to the time-shifted seismic data for that element;
2) determining for each element whether there is an edge in its neighbourhood; and
3) carrying out an averaging operation for each element of the data set $\tilde{p}_i(t,j)$, wherein the direction of the averaging operation is the local orientation of the data and wherein the averaging operation does not go over the edge, to obtain the set of time-shifted, predicted tube wave data set $\tilde{q}_i(t, j)$.

6. The method according to claim 5, wherein applying the structurally oriented, edge-preserving filter to the time-shifted seismic data set $\tilde{p}_i(t,j)$ to obtain the set of time-shifted, predicted tube wave data set $\tilde{q}_i(t,j)$ comprises the steps of:

(1) defining a window of n_L+n_R+1 transducers centred on transducer j and $2n_t+1$ time samples centred on $t_n=t_0+n\Delta t$, wherein t_0 is the time at which sampling starts;
(2) calculating a semblance measure in accordance with the following equation

$$S^0(t_n, j) = \frac{\sum_{l=-n_t}^{n_t}\left(\sum_{k=-n_L}^{n_R}\tilde{p}(t_n + l\Delta t, j + k)\right)^2}{(n_L + n_R + 1)\sum_{l=-n_t}^{n_t}\sum_{k=-n_L}^{n_R}\tilde{p}^2(t_n + l\Delta t, j + k)},$$

calculating two further semblance measures S^+ and S^- wherein the data used to calculate the two further semblance measures is $\tilde{p}(t \pm \alpha z_k, j + k)$, wherein α is a slowness parameter, and wherein z_k is the distance along the borehole between transducers j and k and determining the slowness parameter α_{max} that pertains to the maximum of S^+, S^0 and S^-, and calculating time-shifted tube wave data by taking the median of $\tilde{p}(t +_{\alpha}max_{zk}, j0 + k)$, wherein $-n_L \leq k \leq n_R$;
(3) repeating step (1) for a left range (L) , wherein $n_L=n_k$ and $n_R=0$, a central range (C), wherein $n_L=n_k$ and $n_R=n_k$ and for a right range (R), wherein $n_L=0$ and $n_R=n_k$ to obtain S_L^{max} and $\tilde{q}_L$, S_C^{max} and $\tilde{q}_C$, and S_R^{max} and $\tilde{q}_R$, respectively, wherein n_k is a predetermined integer; and
(4) selecting the time-shifted, predicted tube wave data as follows, if $S_C^{max} > \varepsilon.\max(S_L^{max}, S_R^{max})$ then the time-shifted, predicted tube wave data are $\tilde{q}_C$, else, if $S_R^{max} > S_L^{max}$ then the time-shifted, predicted tube wave data are $\tilde{q}_R$, else the time-shifted, predicted tube wave data are $\tilde{q}_L$, wherein ε is a predetermined constant.

7. The method according to claim 6, wherein if the semblance measure selected in step (4) is less than a minimum value the time-shifted, predicted tube wave data are made equal to zero.

8. The method according to claims 2 or 4, wherein correlating the set of time-shifted, predicted tube wave data with the time-shifted seismic data set, and removing the less well correlated elements from the set of time-shifted, predicted tube wave data comprises determining a correlation measure and if the correlation measure is less than a predetermined minimum value, the time-shifted, predicted tube wave data are made equal to zero.

9. The method according to claim 8, wherein the correlation measure is

$$C(t_n, j) = 2\frac{\sum_{l=-n_t}^{n_t}\tilde{p}(t_n + l\Delta t, j).\tilde{q}(t_n + l\Delta t, j)}{\sum_{l=-n_t}^{n_t}\left\{\tilde{p}^2(t_n + l\Delta t, j) + \tilde{q}^2(t_n + l\Delta t, j)\right\}}.$$

10. The method according to any one of the claims 1-9, wherein subjecting a data set $p_i(t,j)$ to a time-shift to align the tube waves in time is done in accordance with the following equation $\tilde{p}_i(t, j) = p_i(t \pm z_j / v_{tube}, j)$, wherein z_j is the depth along the borehole of transducer j, and wherein v_{tube} is the magnitude of the tube wave velocity, and wherein undoing the time shift for a time-shifted, predicted tube wave data set $q_i(t,j)$ is done in accordance with the following equation $q_i(t, j) = \tilde{q}_i(t \mp z_j / v_{tube}, j)$.

Patentansprüche

1. Verfahren zum Entfernen von Abweichungen, die durch Röhrenwellen von in einer seismischen Bohrlocherkundung erhaltenen seismischen Daten verursacht sind, unter Verwendung eines ersten Satzes von Signalwandlern, die seismische Empfänger oder Quellen sind, und eines zweiten Satzes von Signalwandlern, die entsprechend seismische Quellen oder Empfänger sind, und wobei zumindest die Signalwandler des ersten Satzes in einem Bohrloch angeordnet sind, umfassend die Schritte

(a) Erhalten eines Satzes von originalen seismischen Daten $p_m(t,k)$, wobei sich die ganze Zahl k auf den k-ten Signalwandler des ersten Satzes von Signalwandlern und die ganze Zahl m sich auf den m-ten Signalwandler des zweiten Satzes von Signalwandlern bezieht;
(b) Unterziehen des Satzes von originalen seismischen Daten einer Zeitverschiebung, die auf einer geschätzten Röhrenwellengeschwindigkeit basiert ist, um die Röhrenwellen in der Zeit auszurichten, so daß ein Satz von zeitverschobenen Daten $\tilde{\mathbf{p}}_\mathbf{m}\mathbf{(t,k)}$ erhalten wird;
(c) Anwenden eines strukturell orientierten, kantenerhaltenden Filters auf den Satz zeitverschobener seismischer Daten $\tilde{\mathbf{p}}_\mathbf{m}\mathbf{(t,k)}$, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_\mathbf{m}\mathbf{(t, k)}$ zu erhalten;
(d) Herausnehmen der Zeitverschiebung aus dem Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_\mathbf{m}\mathbf{(t,k)}$, um einen Satz von vorhergesagten Röhrenwellendaten $q_m (t, k)$ zu erhalten;
(e) Abziehen des Satzes von vorhergesagten Röhrenwellendaten $q_m(t,k)$ von dem Satz der originalen seismischen Daten $p_m(t,k)$, um einen Satz von korrigierten seismischen Daten $p^c m(t,k)$ zu erhalten, und Ersetzen des Satzes der originalen seismischen Daten durch den Satz der korrigierten seismischen Daten;
(f) Unterziehen des Satzes von korrigierten originalen seismischen Daten einer Zeitverschiebung, die auf einer der im Schritt (b) verwendeten Geschwindigkeit entgegengesetzten Röhrenwellengeschwindigkeit basiert ist, um die Röhrenwellen in der Zeit auszurichten, so daß ein Satz von zeitverschobenen Daten $\tilde{\mathbf{p}}_\mathbf{m}\mathbf{(t,k)}$ erhalten wird; und
(g) Wiederholen der Schritte (c), (d) und (e), um einen Satz von seismischen Daten zu erhalten, aus denen durch die Röhrenwellen verursachte Abweichungen entfernt worden sind.

2. Verfahren nach Anspruch 1, wobei der Schritt (c) das Anwenden eines strukturell orientierten, kantenerhaltenden Filters auf den Satz von zeitverschobenen seismischen Daten $\tilde{\mathbf{p}}_\mathbf{m}\mathbf{(t,k)}$ umfaßt, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_\mathbf{m}\mathbf{(t,k)}$ zu erhalten, Korrelieren des Satzes von zeitverschobenen, vorhergesagten Röhrenwellendaten mit dem Satz von zeitverschobenen seismischen Daten, und Entfernen der weniger gut korrelierten Elemente aus dem Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten.

3. Verfahren nach Anspruch 1 oder 2, wobei auch die Signalwandler des zweiten Satzes von Signalwandlern in dem Bohrloch angeordnet sind, welches sich von dem Bohrloch, in welchem die Signalwandler des zweiten Satzes angeordnet sind, unterscheidet, wobei das Verfahren weiters die Schritte umfaßt:

(h) Unterziehen des Satzes von seismischen Daten, die im Schritt (i) erhalten sind, einer Zeitverschiebung, die auf einer geschätzten Röhrenwellengeschwindigkeit basiert ist, um die Röhrenwellen in der Zeit auszurichten, so daß ein Satz von zeitverschobenen Daten $\tilde{\mathbf{p}}_\mathbf{n}\mathbf{(t,l)}$ erhalten wird, wobei die ganze Zahl 1 sich auf den 1-ten Signalwandler des zweiten Satzes und die ganze Zahl n sich auf den n-ten Signalwandler des ersten Satzes bezieht;
(i) Anwenden eines strukturell orientierten, kantenerhaltenden Filters auf den Satz von zeitverschobenen seismischen Daten $\tilde{\mathbf{p}}_\mathbf{n}\mathbf{(t,l)}$, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_\mathbf{n}\mathbf{(t,l)}$ zu erhalten;
(j) Herausnehmen der Zeitverschiebung aus dem Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_\mathbf{n}\mathbf{(t,l)}$, um einen Satz von vorhergesagten Röhrenwellendaten $q_n(t,l)$ zu erhalten;
(k) Abziehen des Satzes von vorhergesagten Röhrenwellendaten $q_n(t,l)$ von dem Satz der originalen seismischen Daten $p_n,(t,l)$, um einen Satz von korrigierten seismischen Daten $p^c n (t, l)$ zu erhalten, und Ersetzen der

originalen seismischen Daten durch die korrigierten seismischen Daten;
(1) Unterziehen des Satzes von korrigierten originalen seismischen Daten einer Zeitverschiebung, die auf einer der in Schritt (h) verwendeten Geschwindigkeit entgegengesetzten Röhrenwellengeschwindigkeit basiert ist, um die Röhrenwellen in der Zeit auszurichten, so daß ein Satz von zeitverschobenen Daten $\tilde{\mathbf{p}}_n\mathbf{(t,l)}$ erhalten wird, und Wiederholen der Schritte (i), (j) und (k);
(m) Wiederholen der Schritte (i) bis (l) für jeden Signalwandler l des ersten Satzes von Signalwandlern und für jeden Signalwandler n des zweiten Satzes von Signalwandlern, um einen Satz von seismischen Daten zu erhalten, aus denen Abweichungen, die durch die Röhrenwellen erzeugt wurden, entfernt worden sind.

4. Verfahren nach Anspruch 3, wobei der Schritt (i) die Anwendung eines strukturell orientierten, kantenerhaltenden Filters auf den Satz von zeitverschobenen seismischen Daten $\tilde{\mathbf{p}}_n\mathbf{(t,l)}$ umfaßt, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_n\mathbf{(t,l)}$ zu erhalten, Korrelieren des Satzes von zeitverschobenen, vorhergesagten Röhrenwellendaten mit dem Satz von zeitverschobenen seismischen Daten, und Entfernen der weniger gut korrelierten Elemente aus dem Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten.

5. Verfahren nach einem der Ansprüche 1-4, wobei das Anwenden eines strukturell orientierten, kantenerhaltenden Filters auf den Satz von zeitverschobenen seismischen Daten $\tilde{\mathbf{p}}_i\mathbf{(t,j)}$, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_i\mathbf{(t,j)}$ zu erhalten, die Schritte umfaßt:

1) Bestimmen für jedes Element des Satzes von Daten $\tilde{\mathbf{p}}_i\mathbf{(t,j)}$ die lokale Ausrichtung der zeitverschobenen seismischen Daten, wobei die lokale Ausrichtung die Ausrichtung einer Ebene tangent zu den zeitverschobenen seismischen Daten für dieses Element ist;
2) Bestimmen für jedes Element, ob in seiner Umgebung eine Kante ist; und
3) Durchführen einer Durchschnittsberechnung für jedes Element des Satzes von Daten $\tilde{\mathbf{p}}_i\mathbf{(t,j)}$, wobei die Richtung der Durchschnittsberechnung die lokale Ausrichtung der Daten ist, und wobei die Durchschnittsberechnung nicht über die Kante hinausgeht, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_i\mathbf{(t, j)}$ zu erhalten.

6. Verfahren nach Anspruch 5, wobei das Anwenden des strukturell orientierten, kantenerhaltenden Filters auf den Satz von zeitverschobenen seismischen Daten $\tilde{\mathbf{p}}_i\mathbf{(t,j)}$, um einen Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_i\mathbf{(t,j)}$ zu erhalten, die Schritte umfaßt:

(1) Definieren eines Fensters von n_L+n_R+1 Signalwandlern, die um Signalwandler j zentriert sind, und $2n_t+1$ Zeitproben, die um $t_n=t_0+n\Delta t$ zentriert sind, wobei to die Zeit ist, an welcher die Aufnahme beginnt;
(2) Berechnen einer Ähnlichkeitsmessung gemäß der folgenden Gleichung

$$S^0(t_n, j) = \frac{\sum_{l=-n_t}^{n_t}\left(\sum_{k=-n_L}^{n_R}\tilde{p}(t_n + l\Delta t, j + k)\right)^2}{(n_L + n_R + 1)\sum_{l=-n_t}^{n_t}\sum_{k=-n_L}^{n_R}\tilde{p}^2(t_n + l\Delta t, j + k)},$$

Berechnen zweier weiterer Ähnlichkeitsmessungen S^+ und S^-, wobei die zur Berechnung der beiden weiteren Ähnlichkeitsmessungen verwendeten Daten $\tilde{\mathbf{p}}\mathbf{(t} \pm \alpha\mathbf{z_k, j + k)}$ ist, wobei α ein Langsamkeitsparameter ist, und wobei z_k die Strecke entlang des Bohrloches zwischen Signalwandler j und k und dem Langsamkeitsparameter $^{\alpha}$max bestimmend ist, der das Maximum von S^+, S^0 und S^- betrifft, und Berechnen der zeitverschobenen Röhrenwellendaten durch Heranziehen des Medians von $\tilde{p}(t\pm a_{max}{}^{z}k, j_0+k)$, wobei α $-n_L\leq k\leq n_R$;
(3) Wiederholen des Schrittes (1) für einen linken Bereich (L), wobei $n_L=n_k$ und $n_R=0$, einen zentralen Bereich (C), wobei $n_L=n_k$ und $n_R=n_k$ und für einen rechten Bereich (R), wobei $n_L=0$ und $n_R=n_k$, um entsprechend S_L^{max} und $\tilde{q}_L$, S_c^{max} und $\tilde{\mathbf{q}}_C$ und S_R^{max} und $\tilde{\mathbf{q}}_R$ zu erhalten, wobei n_k eine vorherbestimmte ganze Zahl ist; und
(4) Auswählen der zeitverschobenen, vorhergesagten Röhrenwellendaten wie folgt, wenn $S_c^{max}>\varepsilon.\max(S_L^{max}, S_R^{max})$, dann sind die zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_C$, sonst, wenn $S_R^{max}>S_L^{max}$,

dann sind die zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{q}_R$, sonst sind die zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{q}_L$,wobei ε eine vorbestimmte Konstante ist.

7. Verfahren nach Anspruch 6, wobei, wenn die Ähnlichkeitsmessung, die in Schritt (4) gewählt ist, weniger als ein Minimumwert ist, die zeitverschobenen, vorhergesagten Röhrenwellendaten auf Null gesetzt werden.

8. Verfahren nach Anspruch 2 oder 4, wobei das Korrelieren des Satzes von zeitverschobenen, vorhergesagten Röhrenwellendaten mit dem Satz von zeitverschobenen seismischen Daten und das Entfernen der weniger gut korrelierten Elemente aus dem Satz von zeitverschobenen, vorhergesagten Röhrenwellendaten das Bestimmen einer Korrelationsmessung umfaßt, und wenn die Korrelationsmessung kleiner als ein vorbestimmter Minimalwert ist, werden die zeitverschobenen, vorhergesagten Röhrenwellendaten auf Null gesetzt.

9. Verfahren nach Anspruch 8, wobei die Korrelationsmessung

$$C(t_n, j) = 2\frac{\sum_{l=-n_t}^{n_t} \tilde{p}(t_n + l\Delta t, j)\cdot\tilde{q}(t_n + l\Delta t, j)}{\sum_{l=-n_t}^{n_t}\left\{\tilde{p}^2(t_n + l\Delta t, j) + \tilde{q}^2(t_n + l\Delta t, j)\right\}}$$

ist.

10. Verfahren nach einem der Ansprüche 1-9, wobei das Unterordnen eines Satzes von Daten $p_i(t,j)$ zu einer Zeitverschiebung, um die Röhrenwellen in der Zeit auszurichten, gemäß der folgenden Gleichung $\tilde{\mathbf{p}}_i\ \mathbf{(t, j) =}$ $pi(t\pm z_j/v_{Röhre},)$ j erfolgt, wobei Z_j die Tiefe des Signalwandlers j entlang des Bohrloches ist, und wobei $v_{Röhre}$ der Betrag der Röhrenwellengeschwindigkeit ist, und wobei die Herausnahme der Zeitverschiebung für einen Satz der zeitverschobenen, vorhergesagten Röhrenwellendaten $\tilde{\mathbf{q}}_i\mathbf{(t,j)}$ gemäß der folgenden Gleichung $q_i\ (t, j) = \tilde{\mathbf{q}}_i(\mathbf{t} \mp \mathbf{z}_j / v_{Röhre},$ j) erfolgt.

Revendications

1. Procédé d'élimination des irrégularités provoquées par des ondes de tube de données sismiques obtenues dans un relevé sismique de trou de forage, en utilisant un premier ensemble de transducteurs constitués de récepteurs ou de sources sismiques et un second ensemble de transducteurs constitués de sources ou de récepteurs sismiques, respectivement, et dans lequel au moins les transducteurs du premier ensemble sont disposés dans un trou de forage, lequel procédé comprend les étapes consistant à :

(a) obtenir un ensemble de données sismiques d'origine $p_m(t,k)$, où le nombre entier k désigne le k-ième transducteur du premier ensemble de transducteurs et le nombre entier m désigne le m-ième transducteur du second ensemble de transducteurs ;
(b) soumettre l'ensemble de données sismiques d'origine à un décalage dans le temps sur la base d'une vitesse d'ondes de tube évaluée pour aligner les ondes de tube dans le temps afin d'obtenir un ensemble de données décalées dans le temps $\tilde{\mathbf{p}}_m\mathbf{(t,k)}$;
(c) appliquer un filtre de conservation de bord structurellement orienté à l'ensemble de données sismiques décalées dans le temps $\tilde{\mathbf{p}}_m\mathbf{(t,k)}$ afin d'obtenir un ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{\mathbf{q}}_m\mathbf{(t,k)}$;
(d) annuler le décalage dans le temps pour l'ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{\mathbf{q}}_m\mathbf{(t,k)}$ afin d'obtenir un ensemble de données d'ondes de tube prédites $\mathbf{q}_m\mathbf{(t,k)}$;
(e) soustraire l'ensemble de données d'ondes de tube prédites $\mathbf{q}_m\mathbf{(t,k)}$ de l'ensemble de données sismiques d'origine $\mathbf{p}_m\mathbf{(t,k)}$ pour obtenir un ensemble de données sismiques corrigées $\mathbf{p^cm(t,k)}$, et remplacer l'ensemble de données sismiques d'origine par l'ensemble de données sismiques corrigées ;
(f) soumettre l'ensemble des données sismiques d'origine corrigées à un décalage dans le temps sur la base d'une vitesse d'ondes de tube opposée à la vitesse utilisée à l'étape (b) pour aligner les ondes de tube dans

le temps afin d'obtenir un ensemble de données décalées dans le temps $\tilde{p}_m(t, k)$; et
(g) répéter les étapes (c), (d) et (e) afin d'obtenir un ensemble de données sismiques dont les irrégularités provoquées par les ondes de tube ont été éliminées.

2. Procédé selon la revendication 1, dans lequel l'étape (c) comprend les étapes consistant à appliquer un filtre de conservation de bord structurellement orienté à l'ensemble de données sismiques décalées dans le temps $\tilde{p}_m(t,k)$ afin d'obtenir un ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{q}_m(t,k)$, mettre en corrélation l'ensemble de données d'ondes de tube décalées dans le temps prédites avec l'ensemble de données sismiques décalées dans le temps et éliminer les éléments les moins bien corrélés de l'ensemble de données d'ondes de tube décalées dans le temps prédites.

3. Procédé selon la revendication 1 ou 2, dans lequel les transducteurs du second ensemble de transducteurs également sont placés dans un trou de forage, qui diffère du trou de forage dans lequel se trouvent les transducteurs du premier ensemble, lequel procédé comprend en outre les étapes consistant à :

(h) soumettre l'ensemble des données sismiques obtenues à l'étape (i) à un décalage dans le temps sur la base d'une vitesse d'ondes de tube estimée pour aligner les ondes de tube dans le temps afin d'obtenir un ensemble de données décalées dans le temps $\tilde{p}_n(t,l)$, dans lequel le nombre entier l désigne le l-ième transducteur du second ensemble et le nombre entier n désigne le n-ième transducteur du premier ensemble ;
(i) appliquer un filtre de conservation de bord structurellement orienté à l'ensemble de données sismiques décalées dans le temps $\tilde{p}_n(t,l)$ afin d'obtenir un ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{q}_n(t,l)$;
(j) annuler le décalage dans le temps pour l'ensemble de données d'ondes de tube décalées dans le temps prédites $q_n(t,l)$ pour obtenir un ensemble de données d'ondes de tube prédites q_n **(t, l)** ;
(k) soustraire l'ensemble de données d'ondes de tube prédites $q_n(t,l)$ de l'ensemble de données sismiques d'origine $p_n(t,l)$ afin d'obtenir un ensemble de données sismiques corrigées $p^cn(t,l)$ et remplacer les données sismiques d'origine par les données sismiques corrigées ; (1) soumettre l'ensemble de données sismiques d'origine corrigées à un décalage dans le temps sur la base d'une vitesse d'ondes de tube opposée à la vitesse utilisée à l'étape (h) afin d'aligner les ondes de tube dans le temps de manière à obtenir un ensemble de données décalées dans le temps $\tilde{p}_n(t,l)$ et répéter les étapes (i), (j) et (k) ; et
(m) répéter les étapes (i) à (1) pour chaque transducteur l du premier ensemble de transducteurs et pour chaque transducteur n du second ensemble de transducteurs afin d'obtenir un ensemble de données sismiques dont les irrégularités provoquées par les ondes de tube ont été éliminées.

4. Procédé selon la revendication 3, dans lequel l'étape (i) comprend les étapes consistant à appliquer un filtre de conservation de bord structurellement orienté à l'ensemble de données sismiques décalées dans le temps $\tilde{p}_n(t,l)$ afin d'obtenir un ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{q}_n(t,l)$, mettre en corrélation l'ensemble de données d'ondes de tube décalées dans le temps prédites avec l'ensemble de données sismiques décalées dans le temps et éliminer les éléments les moins bien corrélés de l'ensemble de données d'ondes de tube décalées dans le temps prédites.

5. Procédé selon l'une quelconque des revendications 1 à 4, dans lequel l'étape consistant à appliquer un filtre de conservation de bord structurellement orienté à l'ensemble de données sismiques décalées dans le temps $\tilde{p}_i(t, j)$ pour obtenir un ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{q}_i(t,j)$ comprend les étapes consistant à :

1) déterminer pour chaque élément de l'ensemble de données $\tilde{p}_i(t,j)$ l'orientation locale des données sismiques décalées dans le temps, laquelle orientation locale est l'orientation d'un plan tangent aux données sismiques décalées dans le temps pour cet élément ;
2) déterminer pour chaque élément s'il y a un bord dans son voisinage ; et
3) effectuer une opération de calcul de moyenne pour chaque élément de l'ensemble de données $\tilde{p}_i(t, j)$, dans laquelle la direction de l'opération de calcul de moyenne est l'orientation locale des données et dans laquelle l'opération de calcul de moyenne ne dépasse pas le bord, pour obtenir l'ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{q}_i(t, j)$.

6. Procédé selon la revendication 5, dans lequel l'étape consistant à appliquer le filtre de conservation de bord structurellement orienté à l'ensemble de données sismiques décalées dans le temps $\tilde{p}_i(t, j)$ afin d'obtenir l'ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{q}_i(t,j)$ comprend les étapes consistant à :

(1) définir une fenêtre de n_L+n_R+1 transducteurs centrés sur le transducteur j et de $2n_t+1$ échantillons de temps centrés sur t_n,$=t_0+n\Delta t$, où t_0 est l'instant où commence l'échantillonnage ;
(2) calculer une mesure de semblance selon l'équation suivants :

$$S^0(t_n, j) = \frac{\sum_{l=-n_t}^{n_t} \left(\sum_{k=-n_L}^{n_R} \tilde{p}(t_n + l\Delta t, j + k) \right)^2}{(n_L + n_R + 1) \sum_{l=-n_t}^{n_t} \sum_{k=-n_L}^{n_R} \tilde{p}^2(t_n + l\Delta t, j + k)},$$

calculer deux autres mesures de semblance S^+ et S^- où les données utilisées pour calculer les deux autres mesures de semblance sont $\tilde{\mathbf{p}}(\mathbf{t}\pm\alpha\mathbf{z_k},\mathbf{j+k})$, où α est un paramètre de lenteur et où z_k est la distance le long du trou de forage entre les transducteurs j et k, déterminer le paramètre de lenteur α_{max} qui appartient au maximum de S^+, S^0 et S^-, et calculer les données d'ondes de tube décalées dans le temps en prenant la valeur médiane de $\tilde{\mathbf{p}}(\mathbf{t}+\alpha_{\mathbf{max}}\mathbf{z_k}, \mathbf{j_0} +\mathbf{k})$, où $-n_L \leq -k \leq n_R$;
(3) répéter l'étape (1) pour une plage de gauche (L), où $n_L=n_k$ et $n_R=0$, pour une plage centrale (C), où $n_L=n_k$ et $n_R=n_k$ et pour une plage de droite (R), où $n_L=0$ et $n_R=n_k$ afin d'obtenir $S_L$max et $\tilde{\mathbf{q}}_{\mathbf{L}}$, $S_c$max et $\tilde{\mathbf{q}}_{\mathbf{C}}$, et $S_R$max et $\tilde{\mathbf{q}}_{\mathbf{R}}$, respectivement, où n_k est un nombre entier prédéterminé et
(4) choisir les données d'ondes de tube décalées dans le temps prédites comme suit, si $S_C$max>ε.max($s_L$max, $s_R$max) , les données d'ondes de tube décalées dans le temps prédites sont $\tilde{\mathbf{q}}_{\mathbf{C}}$, autrement, si $s_R$max>$s_L$max, les données d'ondes de tube décalées dans le temps prédites sont $\tilde{\mathbf{q}}_{\mathbf{R}}$, autrement les données d'ondes de tube décalées dans le temps prédites $\tilde{\mathbf{q}}_{\mathbf{L}}$, ou ε est une constante prédéterminée.

7. Procédé selon la revendication 6, dans lequel, si la mesure de semblance choisie à l'étape (4) est inférieure à une valeur minimale, les données d'ondes de tube décalées dans le temps prédites sont rendues égales à zéro.

8. Procédé selon la revendication 2 ou 4, dans lequel la mise en corrélation de l'ensemble de données d'ondes de tube décalées dans le temps prédites avec l'ensemble de données sismiques décalées dans le temps et l'élimination des éléments les moins bien corrélés de l'ensemble de données d'ondes de tube décalées dans le temps prédites comprennent la détermination d'une mesure de corrélation et, si la mesure de corrélation est inférieure à une valeur minimale prédéterminée, les données d'ondes de tube décalées dans le temps prédites sont rendues égales à zéro.

9. Procédé selon la revendication 8, dans lequel la mesure de corrélation se traduit par la formule :

$$C(t_n, j) = 2 \frac{\sum_{l=-n_t}^{n_t} \tilde{p}(t_n + l\Delta t, j) \cdot \tilde{q}(t_n + l\Delta t, j)}{\sum_{l=-n_t}^{n_t} \left\{ \tilde{p}^2(t_n + l\Delta t, j) + \tilde{q}^2(t_n + l\Delta t, j) \right\}}.$$

10. Procédé selon l'une quelconque des revendications 1 à 9, dans lequel l'étape consistant à soumettre un ensemble de données $p_i(t,j)$ à un décalage dans le temps pour aligner les ondes de tube dans le temps est effectuée selon l'équation qui suit $\tilde{\mathbf{p}}_{\mathbf{i}}(\mathbf{t},\mathbf{j}) = \mathbf{p}_{\mathbf{i}}(\mathbf{t}\pm\mathbf{z_j}/\mathbf{v_{tube}}, \mathbf{j})$ dans laquelle z_j est la profondeur le long du trou de forage du transducteur j, et dans laquelle v_{tube} représente l'amplitude de la vitesse des ondes de tube, et dans laquelle l'étape consistant à annuler le décalage dans le temps pour un ensemble de données d'ondes de tube décalées dans le temps prédites $\tilde{\mathbf{q}}_{\mathbf{i}}(\mathbf{t},\mathbf{j})$ est effectuée selon l'équation qui suit : $\mathbf{q_i}(\mathbf{t},\mathbf{j}) = \tilde{\mathbf{q}}_{\mathbf{i}}(\mathbf{t}\mp\mathbf{z_j}/\mathbf{v_{tube}}, \mathbf{j})$

Fig.1.

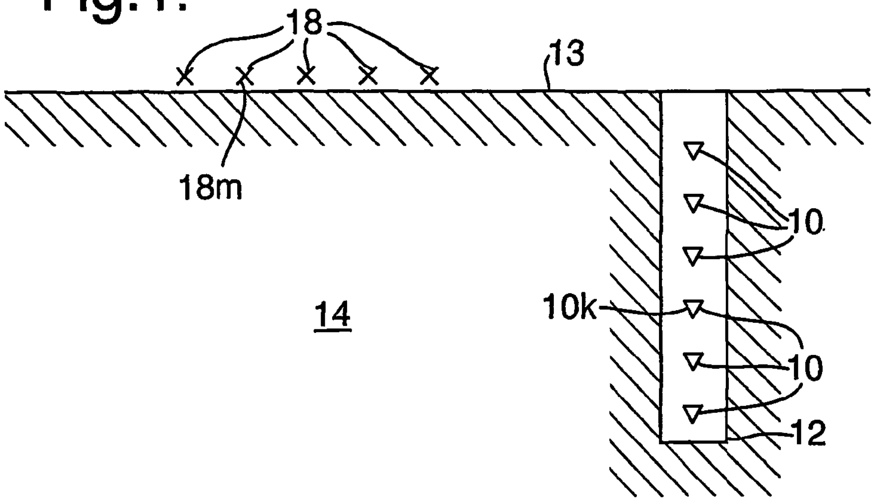

Fig.2.

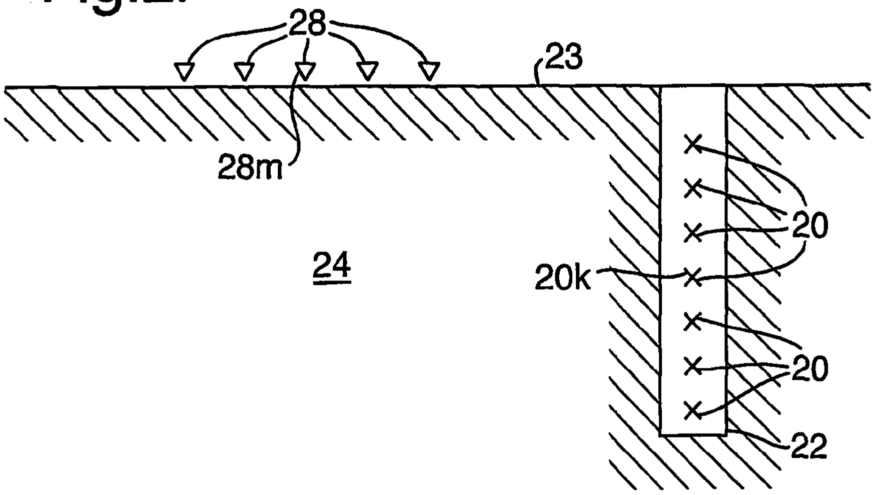

Fig.3.

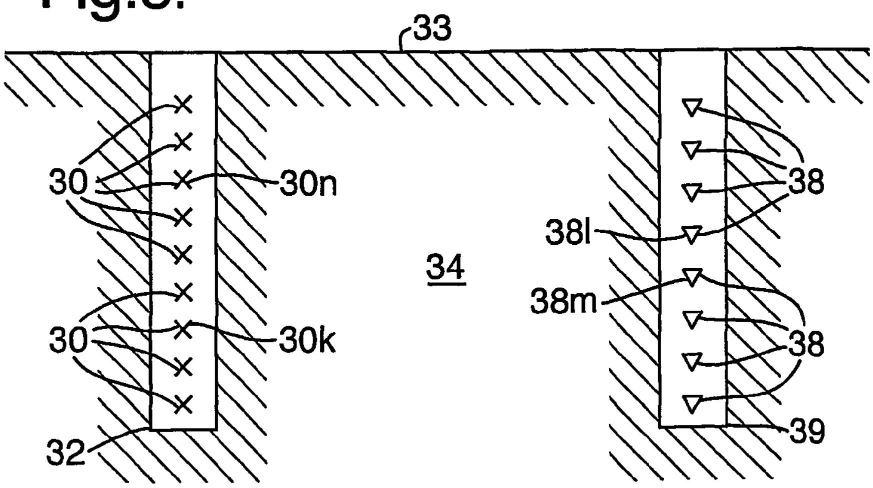

Fig.4.

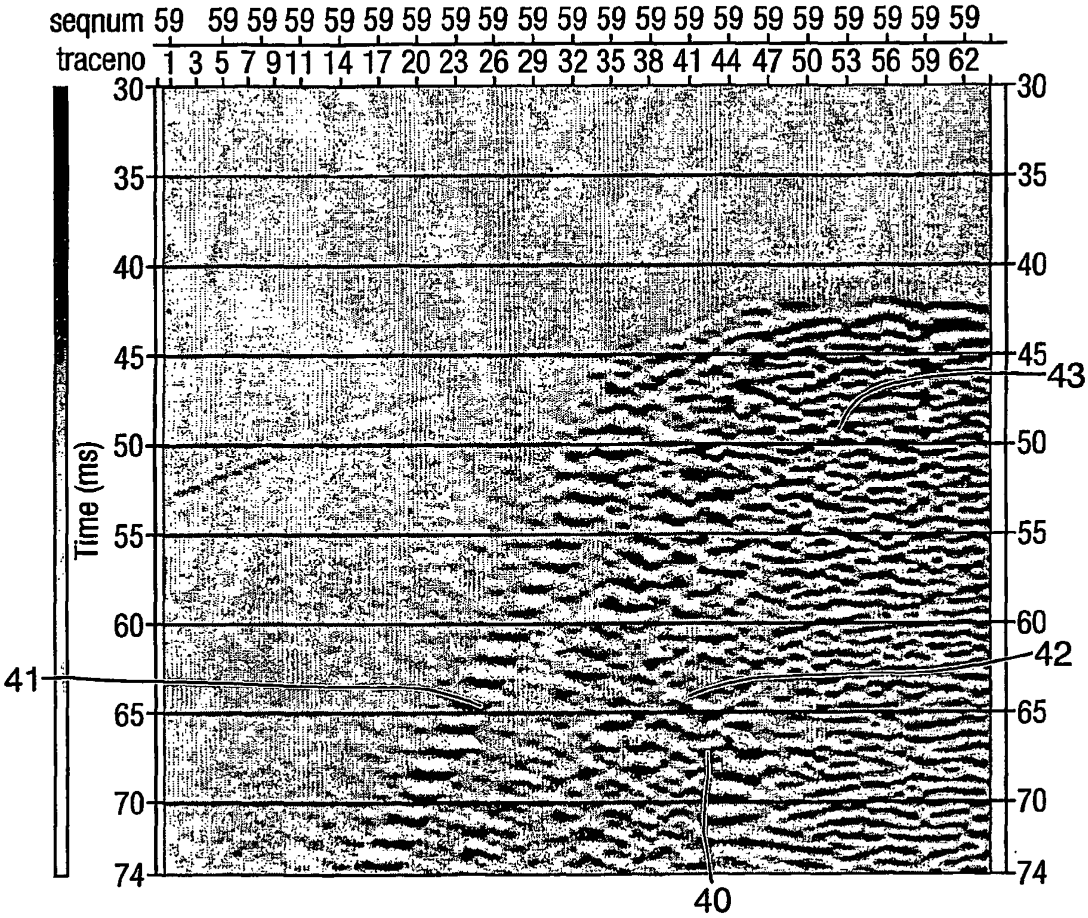
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Fig.5.

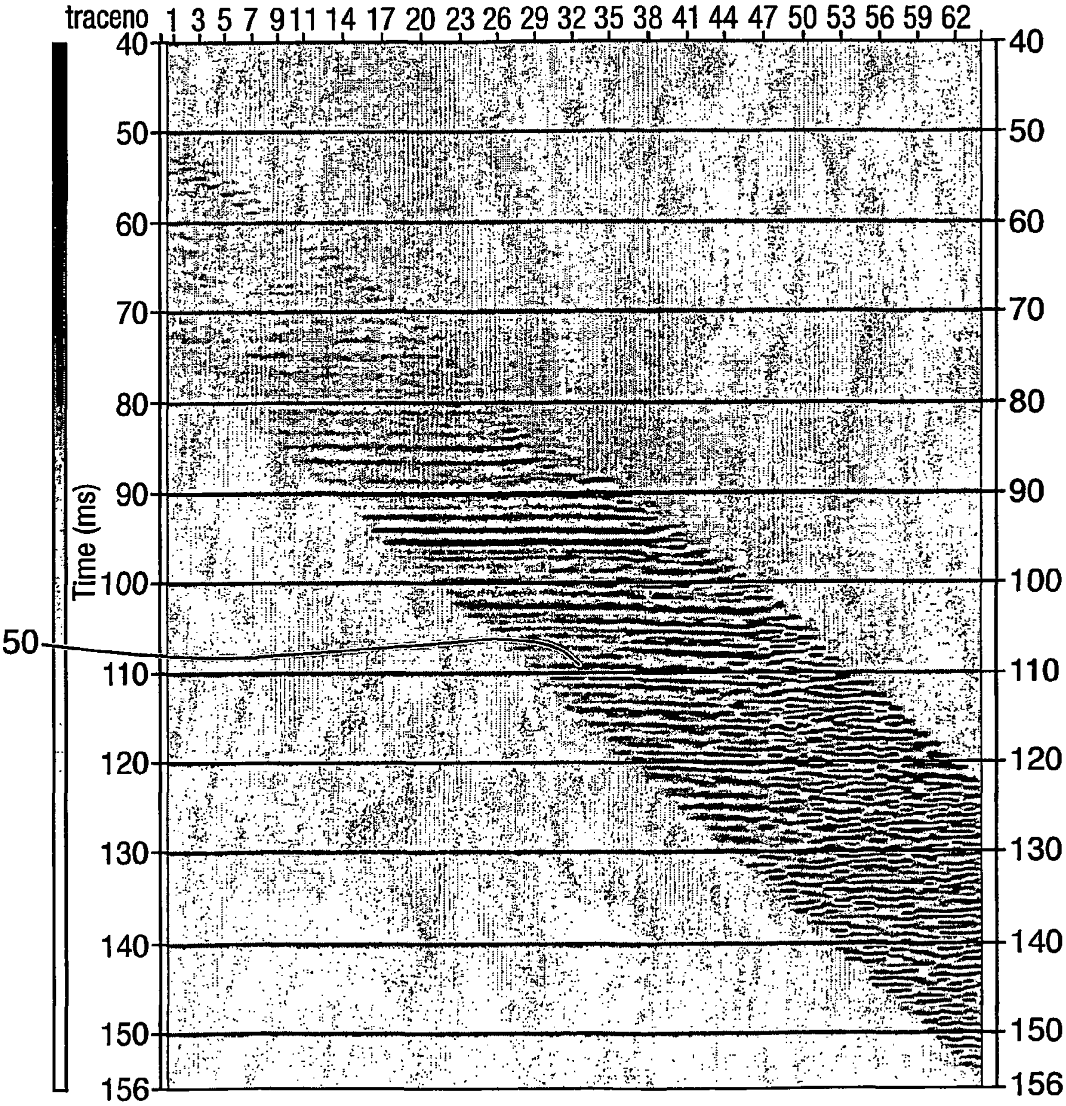
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Fig.6.

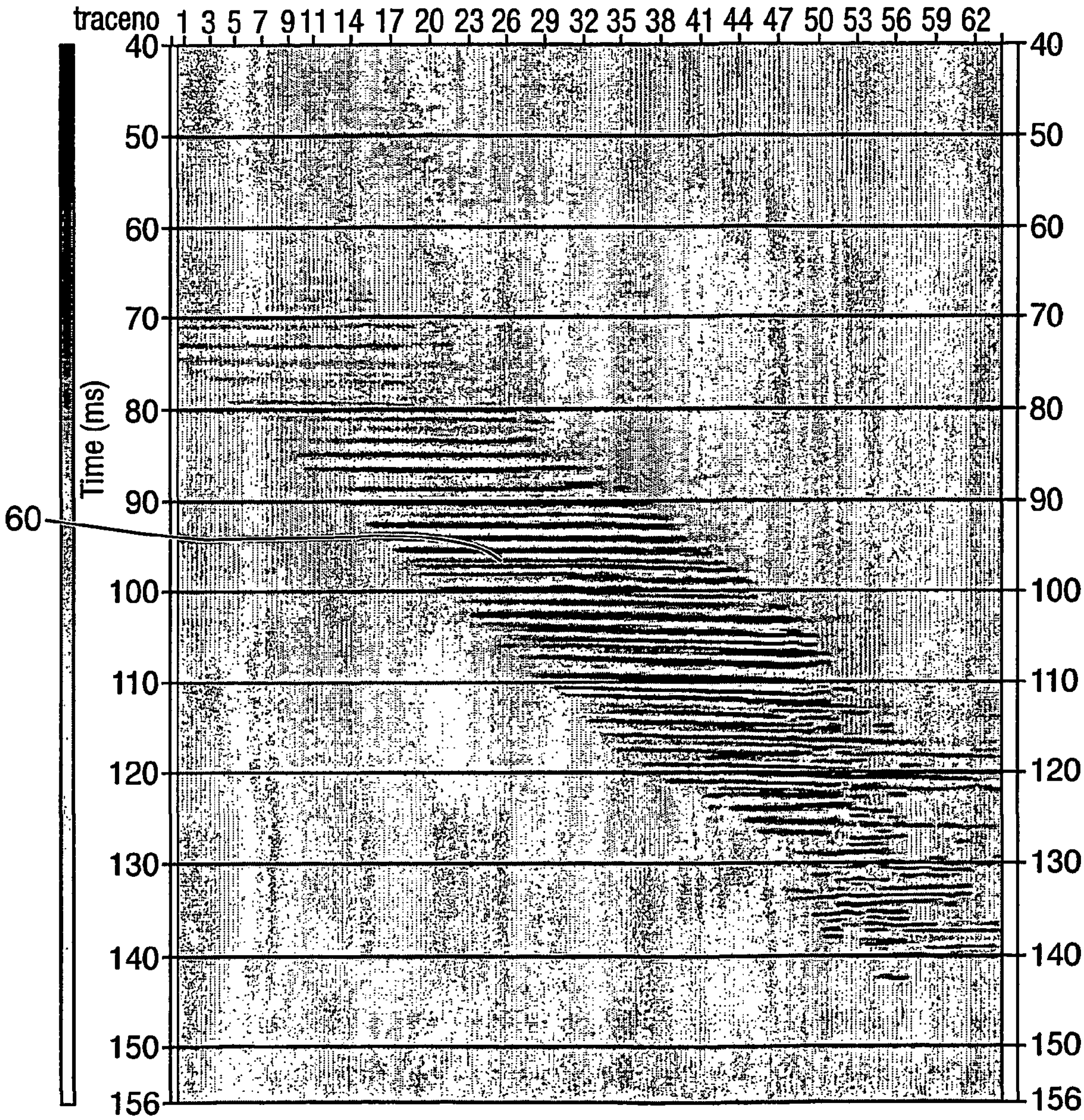
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Fig.7.

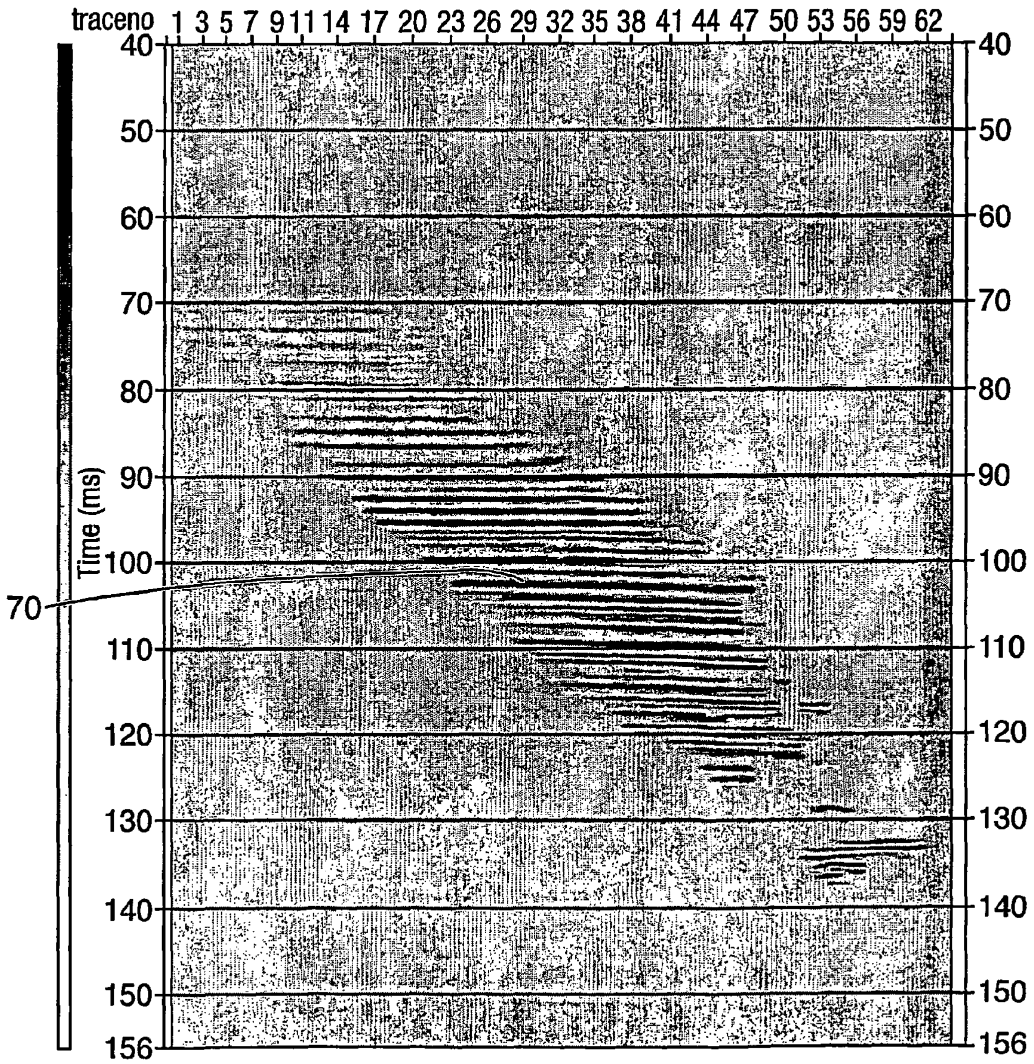
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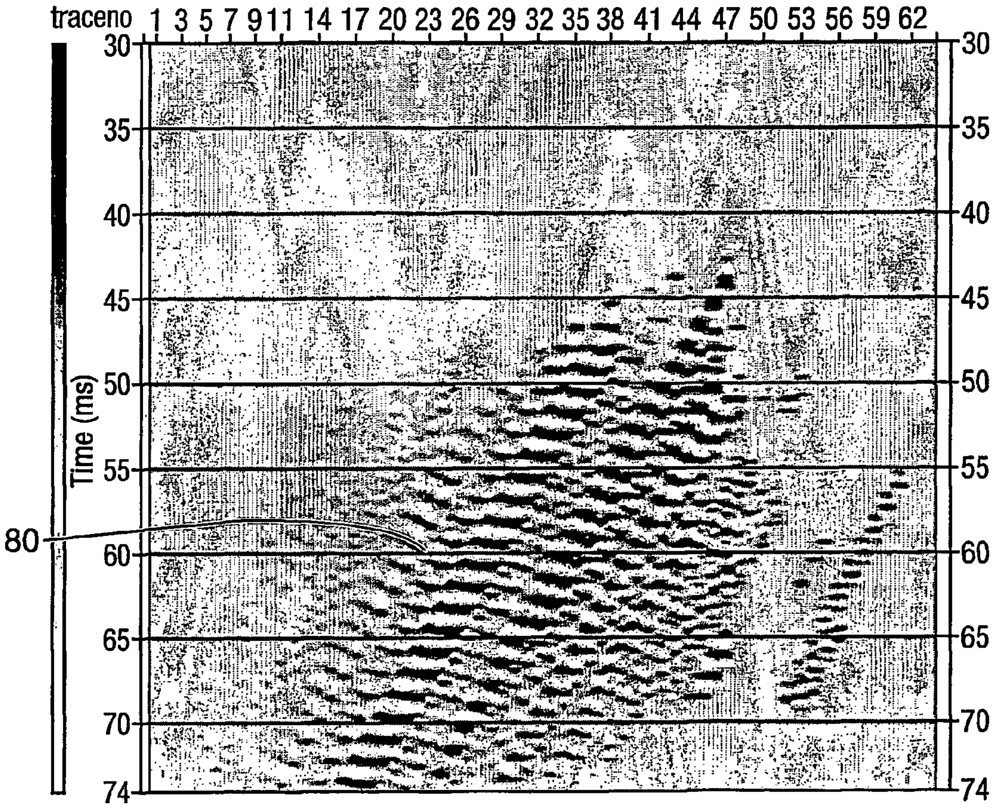
Fig.8.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Time (ms)
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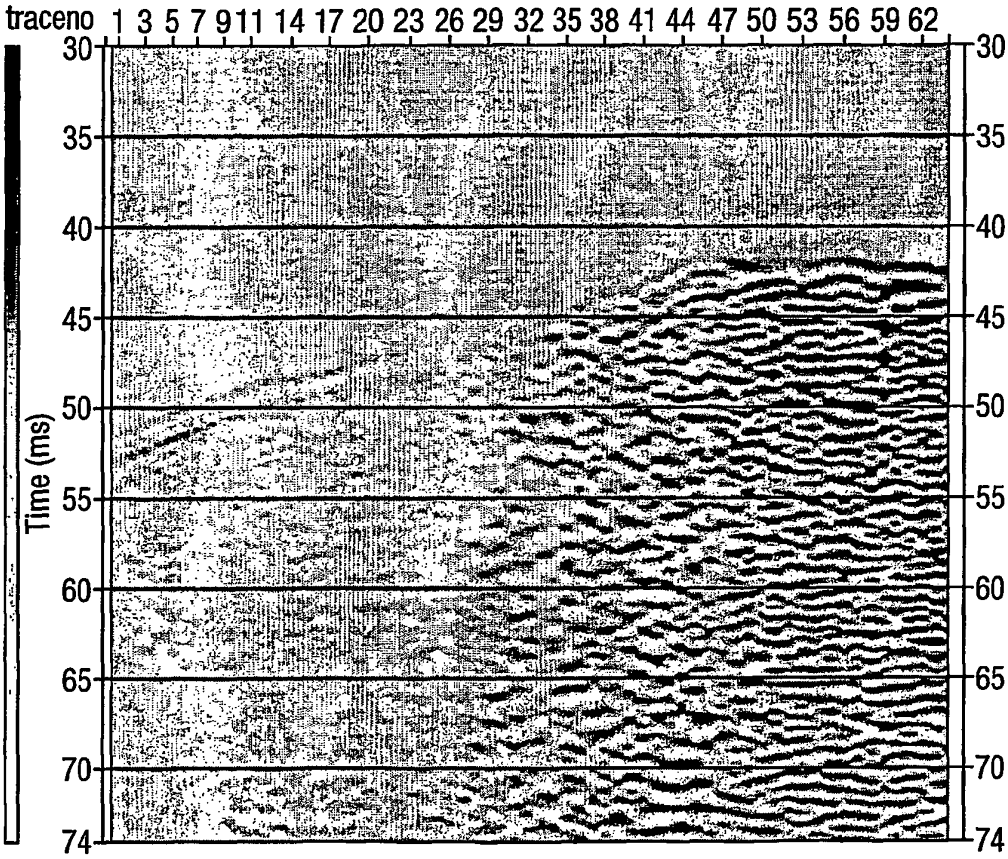
Fig.9.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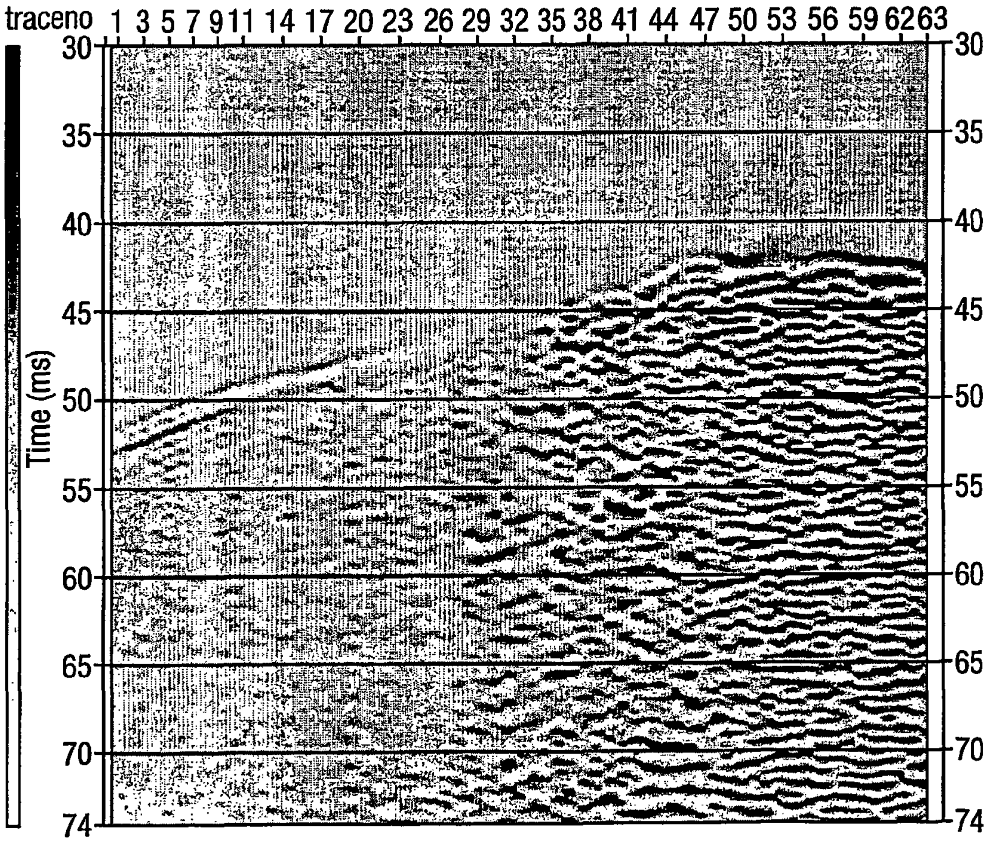
Time (ms)

Fig.10.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REFERENCES CITED IN THE DESCRIPTION

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