Diffractions Over Deposit Edges

Boris Zavalishin

When oil or gas substitutes for water in a layer, the physical properties of the layer are changed. Reflection seismology tries to evaluate this change, to correlate anomalies of different parameters and thus to predict presence or absence of a product. It promises great economy in drilling for and discovery of nonstructural deposits.

At least three physical parameters are known to change their values within and outside the oil-gas saturated part of a layer: the reflection coefficient of the top and the reflection coefficient of the bottom of a layer, velocity and frequency dependent attenuation. Each of these parameters can be calculated, in principle, separately for each horizon or time interval, but not every change of any definite parameter is considered as a reliable sign of a deposit. But simultaneous anomalous behavior of all three parameters can give a reliable clue. Therefore parameters are not considered individually, but rather some integral effect. Hence, it is desirable to find some features of a wave field which would exibit the integral effect.

All measurements are being done now with reflected waves. Change of every parameter within a deposit causes changes of different features of reflected waves: reflection coefficient-amplitudes, velocity-times, attenuation- frequencies. To make accurate measurements of these features possible, it is necessary to have reflections properly seen and undistorted at long distance within and outside a deposit. Sometimes they are properly seen on CMP sections, but to what extent they may be considered undistorted is always a question. There is at least one reason for them to be distorted. This reason is diffraction on the edges of a deposit, which must occure if discontinuity of physical properties does exsist. It was noticed that seismograms are often more complicated towards periphery of extensive oil-gas deposits and diffractions are a good explanation of this. While diffractions are unwanted factors for conventional measurements and hinder accurate calculations especially for less extensive deposits, they may become very useful if we pay more attention to them.

Physically it is clear that rapid changing of any parameter essential for wave propagation must produce diffraction. Changing is rapid if it takes place within a distance of wave length order. The linearity of the wave propagation process implies that simultaneous changing of several parameters must magnify diffraction. Then the integral energy of diffracted waves may become a suitable measure for evaluation of changing of all important parameters together and that is what is needed for localization of the deposit's edge. From a geological point of view, contouring of a deposit--or, finding its edges, in many cases is more an actual task than just stating the possibility of its existence.

We define integral energy of diffractions as total energy of all diffracted or partially diffracted waves on a common shot gather. It presumes integrating both along t and x axes within the gather. Integrating along t axis is suggested because each boundary underlying an oil or gas deposit is supposed to produce diffractions (Zavalishin, 1975). Integrating along x of a common shot gather is suggested because it provided averaging and compression of data. Suggesting to calculate energy of diffraction effects, it is necessary to point out how to select these effects from ordinary reflected energy. There is one remarkable feature that separates diffracted waves from ordinary reflections. That is a change of polarity of diffracted waves at the boundary of geometric shadow (Trorey, 1970; Klem-Mysatov, 1980). As reflected waves have no such singularity it helps to separate them in principle. To make clear our suggestion, which will follow, let us consider the simplest possible model of an oil-gas deposit. A very thin layer d (Figure 1) is saturated with a product to the right from point D and with water to the left.

Reflection coefficient R, velocity V and attenuation Q are step-functions along d, with singularity at D. There may be many layers underlying d, which reflect energy upward. We chose one of them l_n. It is easy to show (Zavalishin, 1975) that a reflector responds with four upcoming waves to an excitement at any surface (S) point, for example A (Figure 1). For arbitrary receiver C arrival time of these four waves are proportional to the paths: ABC-reflected wave, $AEDC$-reflected-diffracted wave, $ADFC$-diffracted- wave, $ADGDC$-diffracted-reflected-diffracted wave. Not trying to describe behavior and features of all these waves we just point out as an example, that the boundary of geometric shadow for reflected-diffracted wave $AEDC$ coincides with AK, where A_1 is the image source for reflector l_n. It means that wavelets of a given wave have an opposite sign of polarity to the right and to the left of K. If shot point is at M exactly above D, then all mentioned diffracted waves change their polarity at M and have an opposite sign to the right and to the left of this point. Also arrival times of all diffracted waves are symmetrically equal around this point. If we subtract traces symmetrically about M from each other, all amplitudes of diffracted waves will double and reflected waves will be attenuated. If no discontinuity

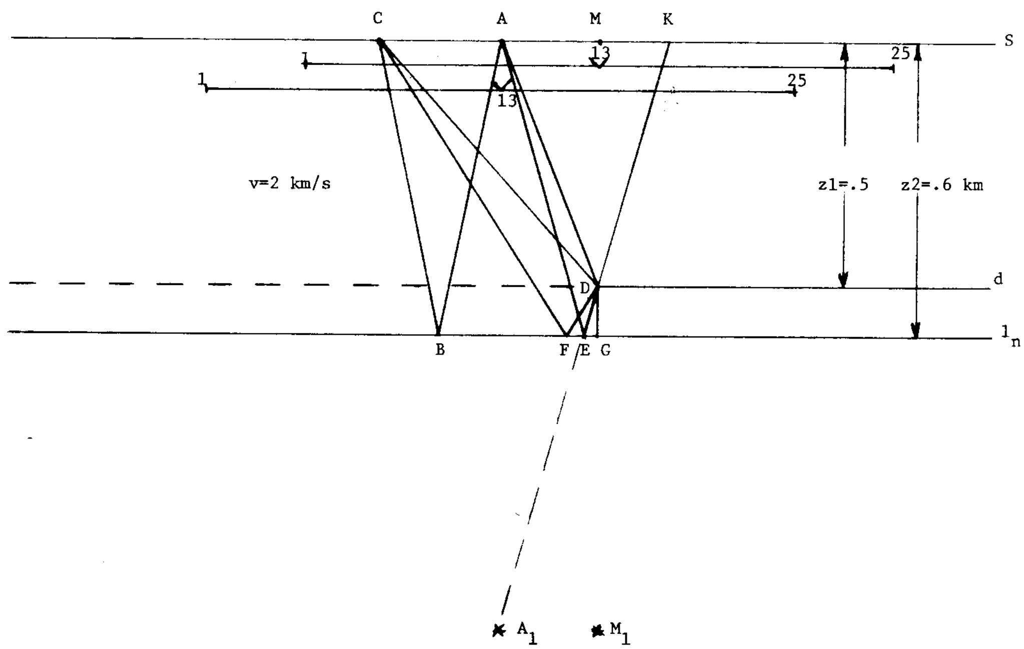

FIG. 1. Geometry of diffraction from a deposit edge.

above l_n exists, then such subtraction would give zero result because no diffractions are observed in this case and amplitudes of reflected wave are symmetric with respect to the shot point. Consideration of the simplest geological situation--horizontal layered media, serves the purpose to give the principal idea of suggested algorithm. All complications which would quite naturally appear for more common geological model or acquisition technic are subject for a known routine processing procedures.

Now we understand that subtraction of traces symmetrically with respect to the shot point preserves energy of diffractions and attenuates or even annihilates energy of reflected waves. Two extra cases are: (1) when the shot point and the spread are very far from discontinuity (2) when the shot point is exactly above a discontinuity. In the first case seismic energy on a residual seismogram is theoretically expected to be zero. In the second case it is expected to be maximal. If we analyze integral energy on a succession of residual seismograms, a kind of a bell function should be observed with a maximum above the edge of a discontinuity. The magnitude of the maximum depends mostly of two factors: quantitative characteristics of a discontinuity and a number of boundaries underlying it.

To illustrate what is proposed and to show that discontinuity of any parameter mentioned above provides diffractions, we will take into consideration only one type of a diffraction wave which is the easiest to simulate on a computer. It will be a reflected-diffracted wave, which is represented by the ray path $AEDC$ on Figure 1.

To simulate this wave on surface S together with the wave reflected from l_n we may use image sources and accurate Kirchoff integral algorithm with a grid coinciding with d plane. For image sources A_1 and M_1 which correspond to the shot points A and M (Figure 1) we calculate two split-spread seismograms 25 channel each with 13 chance coinciding with a shot point. Distance between the geophones is $50m$.

It is necessary to point out that by replacing a real surface source with its image we disdain downgoing diffraction and thus distort somehow real energy distribution between diffractions and reflection in favor of the last. But this fact is not very important for our present discussion aiming only to outline main ideas.

To calculate wave field on the surface S we use Kirchhoff formula in the form (Zavalishin, 1975)

$$\Phi_s(t) = \frac{1}{4\pi}\int_\sigma\int\left[\left(\frac{r_o}{\rho r^3}+\frac{\rho_o}{r\rho^3}\right)f\left(t-\frac{\rho+r}{v}\right)+\frac{1}{\rho v r}\left(\frac{r_o}{r}+\frac{\rho_o}{\rho}\right)\frac{\partial f\left(t-\frac{\rho+r}{v}\right)}{\partial t}\right]d\sigma$$

where σ is the plane coinciding with boundary d, $\rho_0=0.5km$ and $r_0=0.7km$ - shortest distances from S to d and from the image source (A_1) to d, ρ and r- distances from a given point on S and A_1 to an arbitrary point on d, $V=2km/s$- velocity, f and $\partial f/\partial t$- wave form and its derivative. The size of the grid of σ is $2.5\times 2.5M^2$.

Reflection Coefficient

First we simulate a case, when a reflection coefficient R changes its value at D (Figure 1) and is 30 percent bigger to the right of D than to the left. It means that when we consider an upcoming wave, reflected from l_n or emitted by an image source (A_1 or M_1), virtual Huygens-waves emitted from the right part of the σ plane have 30 percent smaller amplitudes. On Figures 2a, c, two seismograms shown represent shot points M and A. First of them is exactly above D (the edge of the deposit) and second is $200M$ away from D to the left. On those seismograms the diffracted wave can hardly be seen, so weak it is compared to the reflected wave. As proposed we subtract channels symmetrically with respect to the shot point to get two residual seismograms (Figures 2c and d). Channel 1 on these seismograms is the difference between the 25th and 1st channels of original seismograms, *channel* 2=24−2 and so on. The diffracted wave on the residual seismogram can be easily seen, especially in Figure 2c. In this case due to time symmetry of both diffraction and

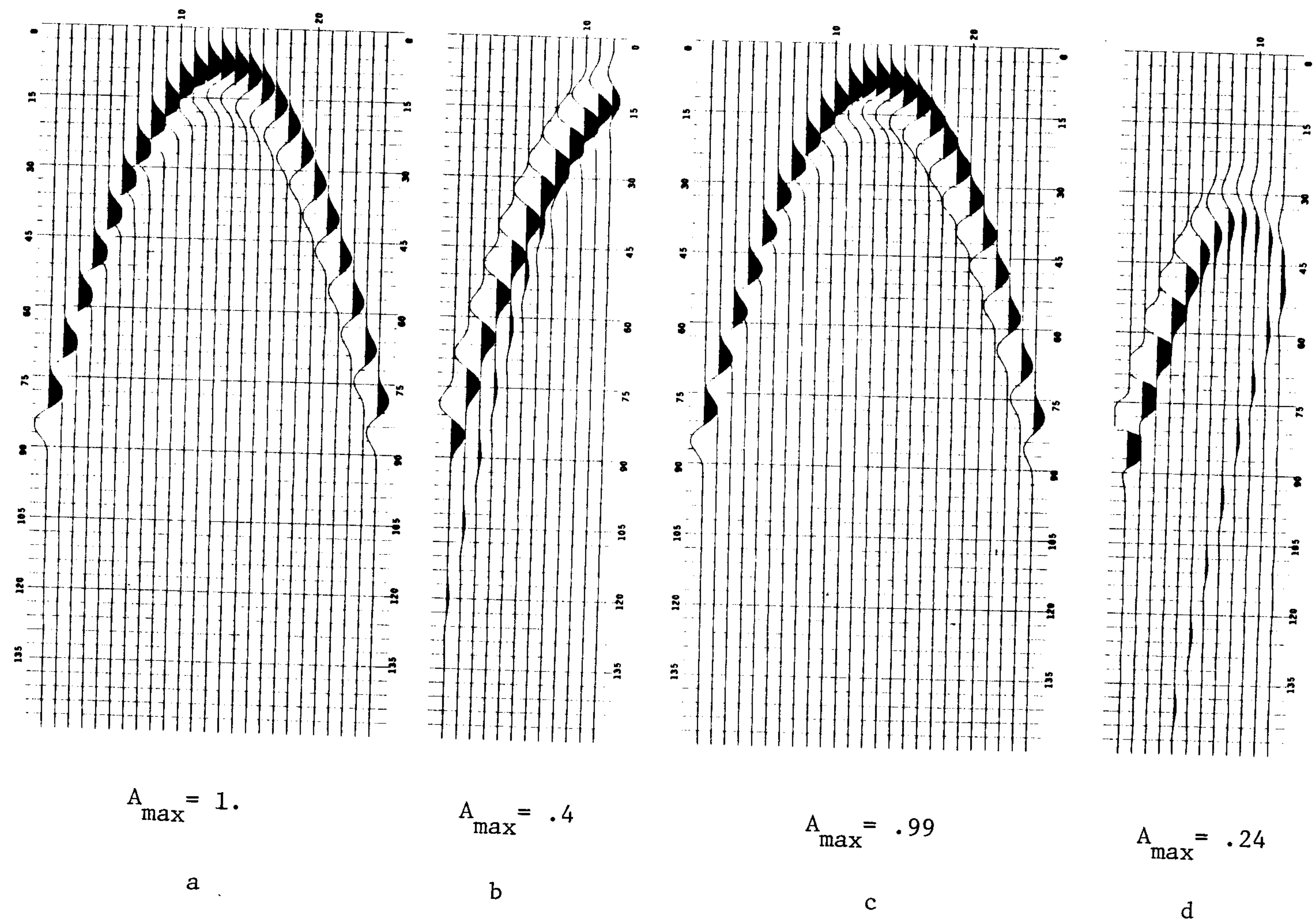

FIG. 2. Diffraction caused by reflection coefficient discontinuety

reflection as regards to point M and the opposite polarity of diffraction on symmetrical channels of the original seismogram (Figure 2a) diffraction amplitudes are doubled and reflection amplitudes are decreased. In order to give an opportunity to judge about the residual amplitudes of the reflected wave after subtraction, values of maximum amplitudes on each seismogram are shown in proportion to maximum amplitude of seismogram (Figure 2a), which corresponds to its 10th channel. To make it easier to understand what is seen on the residual seismogram (Figure 2d), it's advisable to point out that the reflected wave on the seismogram (Figure 2c) is symmetrical with regard to the point A, which coincides with the 13th channel, while hyperbola of the diffracted wave is symmetrical with regard to the 17th channel of the same seismogram. The reflected wave is undisturbed before the minimum arrival time of the diffracted wave. (See Figure 3c where the diffracted wave is stronger.) That is why its energy diminishes to zero at the beginning of the residual seismogram (Figure 2d). We may say that the presence of a diffracted wave is the reason why a reflected wave does not diminish to zero when symmetrically subtracted at later times. The behavior of the diffracted wave on the residual seismogram (Figure 2d) is explained by the fact that its hyperbola is not symmetrical with regard to the 13th channel. That is why two branches of it are seen. One is interfering with the residual reflection and another is seen on bigger times.

The purpose of the two next experiments is to show that the change of velocity or frequency dependent attenuation along d also leads to diffraction. They also give some quantitative data to compare diffraction effects caused by discontinuity of each parameter under consideration.

Velocity

Figure 3 represents the case when the velocity has a step-function-like discontinuity along d with a singularity at D. As was mentioned above, d is considered to be a very thin layer and we can change the velocity inside this layer. To be definite we chose the thickness of the layer equal to $40m$. In the left part of it the velocity $2.0km/s$ is the same as in the rest of the model, in the right part 10 percent lower and equal to $1.8km/s$. Then the average velocity in the left and right part of the model differs only by less than 0.37 percent. The seismograms for this case are shown in Figures 3a, c and their residuals in Figure 3b, d respectively. Diffraction here is much stronger than in previous cases and can be seen not only on the differenced traces but on the original seismograms as well. It is easy to explain. When the velocity is changed even slightly, it creates the same effect as if we shift a part of the boundary along the z axis, in which case we have two terminated half

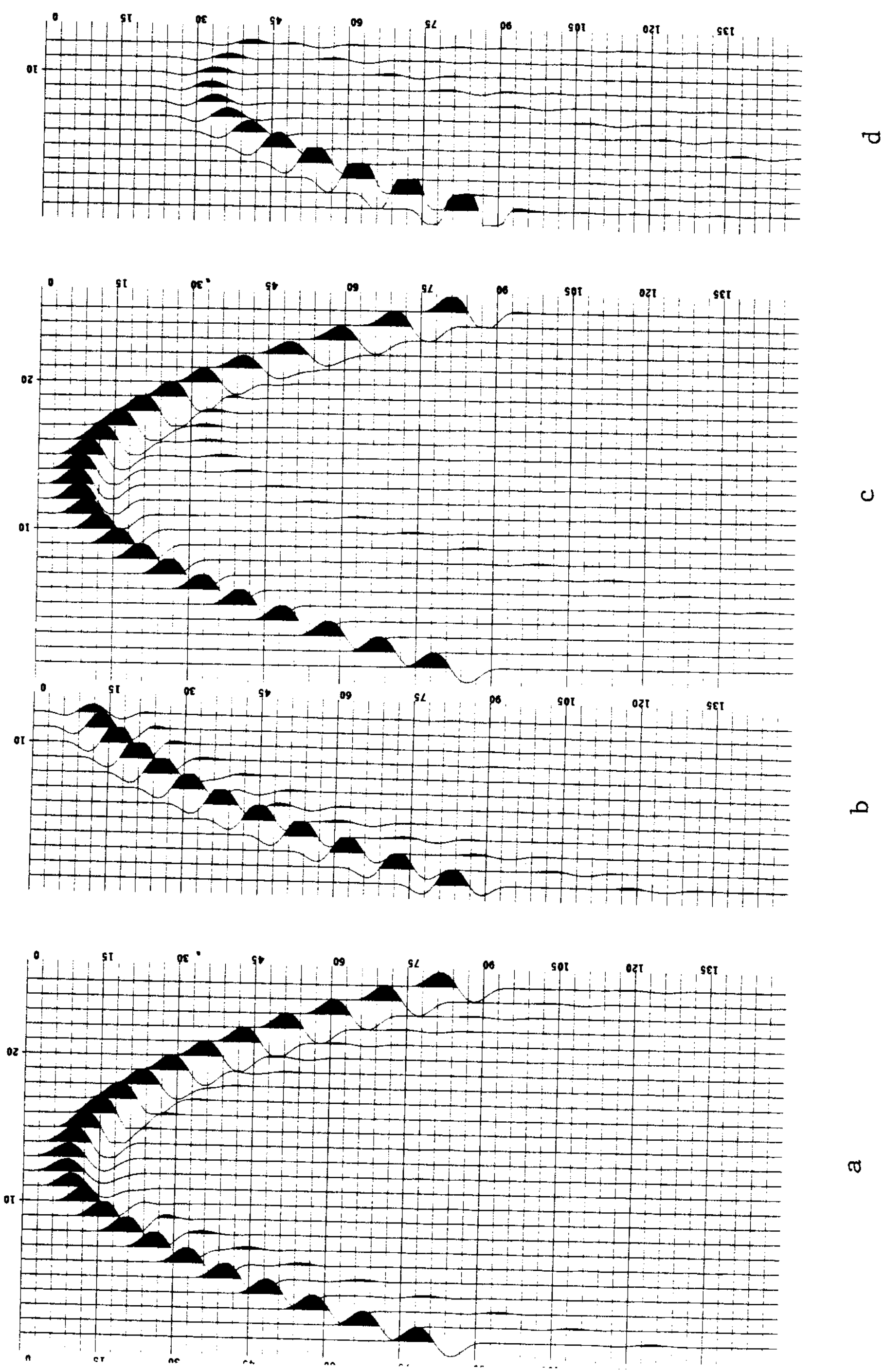

FIG. 3. Diffraction caused by velocity discontinuety

planes. This is known to produce strong diffractions. The diffracted wave has the opposite polarity on symmetrical chanals with respect to the line of geometrical shadow. This fact is can be proven theoretically and can be perceived in Figure 3a. In the case of the seismogram in Figure 3a, this line crosses the surface S on the central 13th geophone. An opposite polarity of a diffracted wave is seen here on the channels symmetrical to the center of a seismogram.

Absorption

As frequency dependent attenuation (absorption) of seismic energy by an oil-gas deposit has complicated and an insufficiently studied mechanism, simulation of its influence on diffraction for the purpose of present study was made in the simplest possible way. We presumed ideal elasticity without absorption for the left part of our model (Figure 1) and existence of absorption linearly dependent upon frequency for the right part. To calculate Kirchhoff's integral in this case we used two different wave forms for two parts of the boundary d, divided by D. A regular Ricker pulse which has been used in our previous modeling was applied for the left part of the boundary and it was Q-filtered for the right part of the boundary. Dave Hale kindly supplied me with the appropriate filter. Both pulses and their normalized amplitude spectrums are shown in the left part of Figure 4, solid line corresponds to Q-filtered pulse. As an amplitude of the filtered pulse is approximately 25 percent smaller than that of the unfiltered pulse we expect that the diffraction effects would be in this case a little bit smaller than in the case where we changed reflection coefficients. But there is yet another reason for some diffraction effect due to change of the spectrum, which is difficult to predict quantitatively. Seismograms of Figure 4 show that the total effect visually seems to be smaller than that of Figure 2, where the reflection coefficient was changed 30 percent. But taking into consideration the difference in frequencies between the seismograms on Figure 2 and Figure 4 it is advisable not to be in a hurry to conclude that frequency dependent absorption alone does not contribute noticeably in diffraction. It is interesting to compensate the attenuation by multiplying Q-filtered pulse by the factor 1.33 making its amplitude equal to the original pulse. Then we study the diffraction effects caused only by the change of spectrum of the pulse within and outside a deposit. Figure 5 presents this case and leads to the conclusion that the frequency dependent absorption within a deposit also contributes to diffractions.

Presentation of data which are being described here has one substantial limitation caused by the fact that all shown seismograms are automatically normalized by the output program according to an average amplitude on each of them. An average amplitude changes

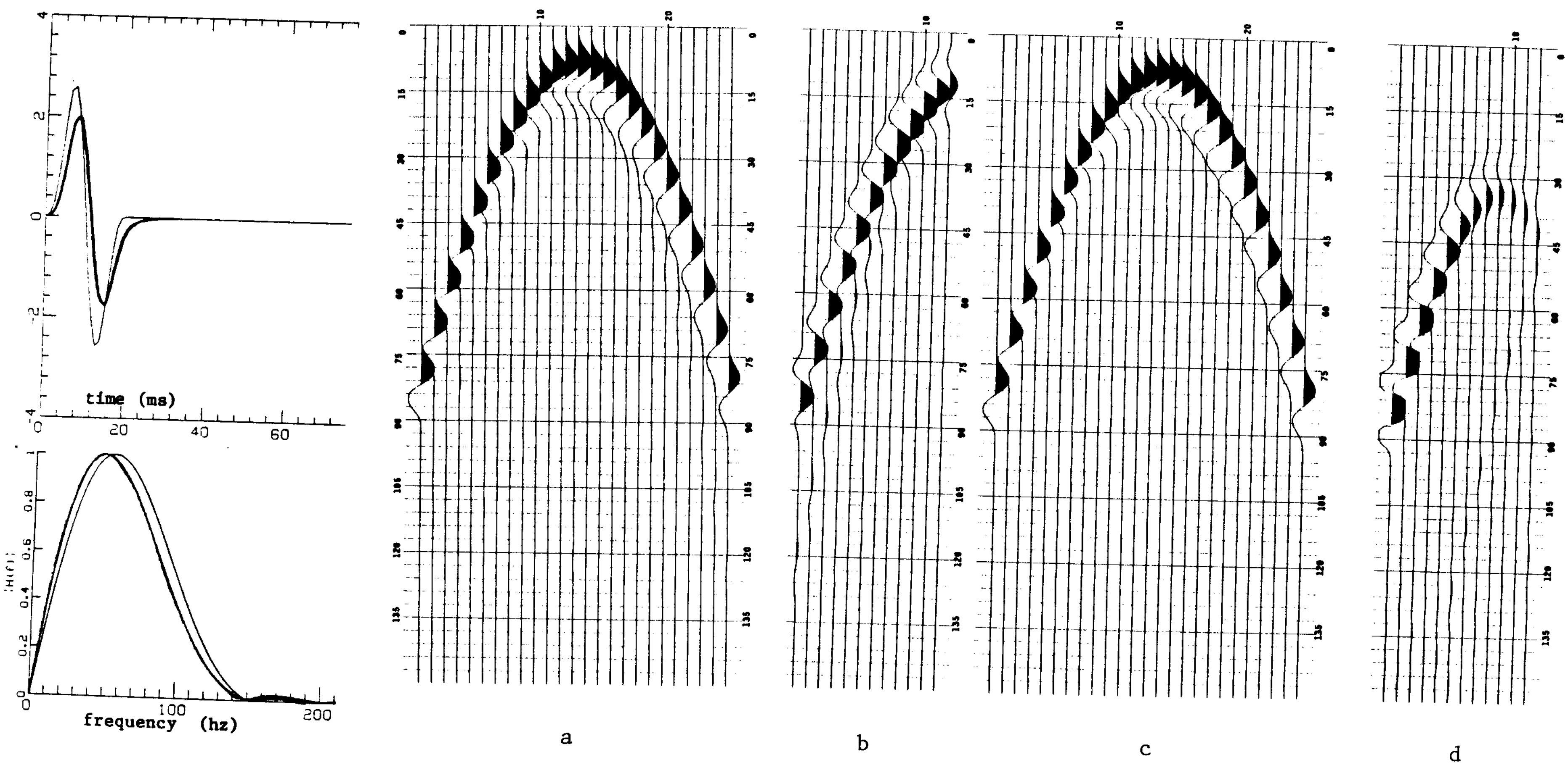

FIG. 4. Diffraction caused by attenuation discontinuety

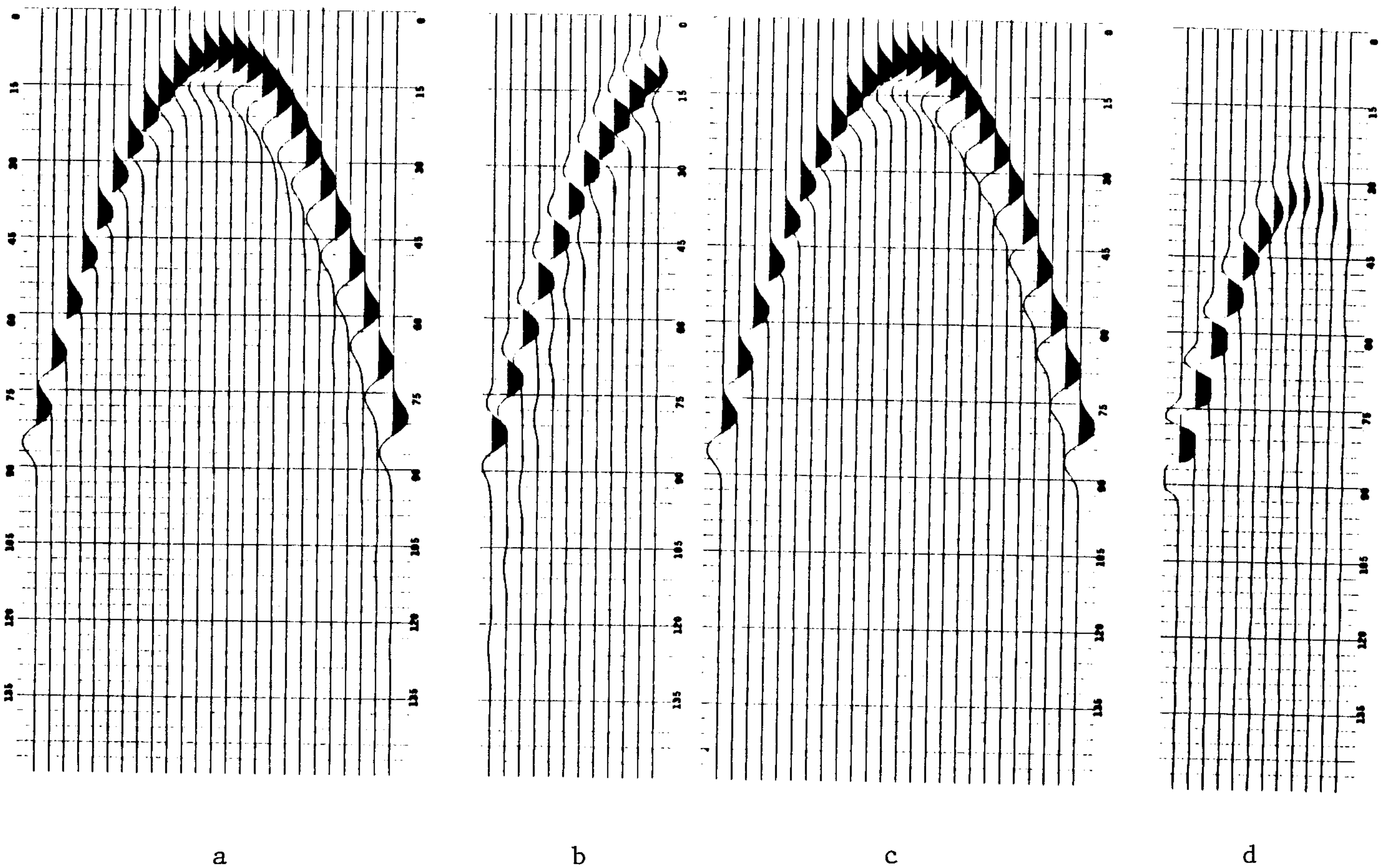

FIG. 5. Diffraction caused by absorption discontinuety

slightly when we change different parameters under discussion. It prevents us from more quantitative description of diffractions caused by different reasons. But examples which were shown here support our earlier supposition that a change of any parameters discussed here produce a diffraction wave and each of the diffracted waves has singularity at the boundary of the geometrical shadow. The last feature helps to select the diffracted waves from reflections. Application of the superposition principle allows us to presume that diffraction energy must increase, where several factors, producing it are put together.

These experiments also show that when parameters within and outside a deposit change within limits which can be reasonably expected in nature, individual diffracted waves are much weaker than reflections. In the field experiment they interfere both with more strong reflections and with diffractions originated by deeper reflectors which creates a complicated wave pattern. That is why it's doubtful to expect that known suggestions to look for particular diffracted waves (for example, those originated at water-to-product contacts) are perspective in common case.

Taking into consideration that each reflector underlying a deposit's edge produces three diffracted waves and that there are many such reflectors, we suppose that the total energy of diffractions may be sufficient to point out a deposit's edge.

To calculate diffraction's energy we suggest:

1. To subtract the channels symmetrical as regards to a shot point thus attenuating reflections.

2. To calculate energy of each trace of residual seismogram. Depending on an *a priori* information, it may be energy of full time length trace or in a chosen time window, or cumulative energy.

3. To accumulate energy of all traces of each residual seismogram and to plot graphic of this energy above the conventional cross section.

To describe this algorithm we chose the simplest geoseismical model of horizontally stratified media and the most convenient shooting scheme. Real data may demand some corrections, which can not spoil the whole idea. For example, with an one-sided shooting scheme NMO correction should precede. Reflected energy would not collapse to zero in this case, while subtracted but to some small constant level. As this level is constant it creates no additional problems. In the case of dipping reflectors it would be necessary to apply a kind of Dip Move-Out correction or to move a center of symmetry along a spread and time and so on. As some other reasons may produce anomalies of diffracted energy (faults, for example), the final diagnosis is to be made according to all seismic and geological data available as always.

Conclusions

Features of diffractions investigated here and the suggested scheme of their detection give grounds to hope that this simple algorithm may help in discovery and countering of primarily shallow deposits, sealed inside flat strata. It may turn out to be important because conventional processing of seismic data does practically everything possible to keep from discovering them.

References

1. Klem-Mysatov, K.D., 1980, "The Theory of Edge Diffracted Waves and its Applications in Seismology," *Nayka*, Novosibizsk
2. Trorey, A.W., 1970, "A Simple Theory for Seismic Diffractions, *Geophysics 35*, N5.
3. Zavalishin, B.R., 1975 "Screening Effect of an Oil-Gas Saturated Layer," *Applied Geophysics N79*, Nedra, Moscow.