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METHOD OF INTERPRETING SEISMIC REFLECTION DATA IN THE VILYUI SYNCLINE

BY

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PREFACE

The interpretation of observations obtained from geophysical prospecting is complicated in permafrost regions by the low ground temperatures and high ice contents causing higher seismic velocities and electrical resistivities than in thawed strata. Knowledge of these variations is essential in obtaining accurate information on geological structures in the exploration of petroleum and other mineral resources.

This paper deals with seismic surveying in the Vilyui syncline located to the west of the Lena River in Eastern Siberia where the permafrost varies in thickness from 200 to 600 metres. Information is presented on seismic velocities occurring in different types of rock with varying permafrost conditions. This translation was undertaken because the Soviet literature on this increasingly important aspect of geophysical exploration in permafrost regions is sparse.

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N.B. Hutcheon
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Title: Method of interpreting seismic reflection data in the Vilyui syncline

(K metodike interpretatsii dannykh MOV v usloviyakh Vilyuiskoi sineklizy)

Authors: A.E. Shutkin and O.I. Kharlova

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METHOD OF INTERPRETING SEISMIC REFLECTION DATA IN THE VILYUI SYNCLINE

During seismic surveying on the territory of the Vilyui syncline the data are usually interpreted with the use of a single curve $v_{av}(z)$, obtained by averaging the effective velocities. It has been established that the method used leads to substantial inconsistencies between data obtained by deep drilling and seismic surveying (the divergence at times reaches 200 m). Since the region is characterized by conformable bedding of reflecting horizons, it was suggested that the main reason for the divergence between drilling data and seismic data is the horizontal change in mean velocities in the area owing to a warm zone in the permafrost[4] which varies in thickness here from 200 to 600 m.

To check out this suggestion, a joint party of the All-Union Research Institute for Geophysics and the Yakut Geological Service logged eight parametric drillholes 500-600 metres deep in the Tolon area and in the middle reaches of the Vilyui River. The drillholes were located in uniform permafrost and in warm zones where there are unfrozen strata which have a lower velocity (in sandy areas, swamps, shores of lakes and the shores of the Vilyui River).

The graph of velocities (Figure 1b) indicates a sharp velocity differentiation in vertical and horizontal cross sections. The greatest change in velocities occurs in the depth range of from 0 to 150-200 metres (the depth was measured from ground level in each hole and the difference in altitude of the holes did not exceed 10 metres). The range of variation in velocities over the area in this part of the cross section reaches 2400 m/sec. This is explained by the difference in the temperature regime of the permafrost, since geological cross sections of the holes are lithologically quite uniform. Permafrost has a velocity range of 3100-4000 m/sec, whereas strata in the warmer zone have a velocity range of 1600-2500 m/sec. In the transition from permafrost to zones of higher temperature the change in velocities is gradual. The concept of permafrost uniformity is relative, since velocities in permafrost vary from 4000 m/sec (and at times higher according to data on direct wave velocities) to 2500-3000 m/sec.

At depths greater than 150-200 m the velocities in all holes are similar - the scattering of values does not exceed 400-600 m/sec. At these depths there are no unfrozen formations, and the difference in velocities is due not so much to differences in temperature as to differences in physical properties of the strata.

Depending on the distribution of velocities, the graphs of mean velocities (see Figure 1a) for holes located under different surface conditions differ noticeably. In the zones with higher temperature the velocity values are lower and the gradient is positive, with the exception of sections where there is a high velocity layer of frozen soil on the surface (hole 8-P). In the frozen sections the mean velocities are higher and the number of points of mean velocity inversion may vary from 1 to 3, depending on the complexity of the structure of the permafrost zone. At a depth of 500 m, owing to the difference in velocities in the sequence of zones with higher temperature and homogeneous permafrost strata long the profile, the mean velocity may vary by 1000 m/sec.

In order to estimate the possible variation in mean velocity at depths of 600-1000 m (the depths of the first reference horizon in the middle Vilyui and neighbouring areas), we calculated the mean velocities to a depth of 1000 m for models of media (Figure 2) characteristic of homogeneous permafrost (hole K-3, depth of logging 1000 m) and for the higher temperature zone (hole 4-P, depth of logging 600 m; hole 1-P, depth of logging in the range of 300-1800 m).

Calculations show that for the models investigated the mean velocities at a depth of 600 m differ by 750 m/sec, and at a depth of 1000 m by 350 m/sec. With this variation in velocities over the area, an interpretation with a constant law of mean velocities can lead to errors in determining the relative depth of the first reflecting horizon of up to 200 m. Hence it is clear that corrections must be introduced for the non-uniformity of the permafrost zones.

It is difficult and not always possible to apply the method used in studying low velocity layers. Because of the shielding effect characteristic of regions in Yakutia it is impossible to trace continuously the refracting boundaries at small depths (below the level of velocity stabilization at depths of 200-500 m). Therefore, in order to take into account the non-uniformity of the permafrost we suggest using effective velocities determined by travel-time curves of reflected waves which vary along the profile depending on the structure of the zone. The effective velocity would be determined most accurately from travel-time curves for the first reference horizon (basin of the Vilyui River), since at these depths the mean velocity is close to the minimum for homogeneous permafrost. The error in determining effective velocities from single travel-time curves in this case does not usually exceed ± 100 m/sec.

To elucidate the applicability of effective velocities instead of mean velocities for interpretation, we made a theoretical calculation of v_{av} and v_{ef} for various models of media typical of the given region. We examined the following types of models:

(a) Media that are highly differentiated along the vertical, with no horizontal gradient;

(b) Media with a substantial horizontal velocity gradient associated with variation in velocities of permafrost zones in moving from frozen to thawed sections.

The effective velocities were determined for horizons lying at a depth of 750 m, using theoretical travel-time curves 450 m long and applying the difference travel-time curve method.

As a basis of the velocity characteristics for the model of the first type we took the velocity cross section for hole K-3. Only at depths of 0-150 m did we use different velocities selected on the basis of log data for parametric and shallow holes. Calculations were carried out for three models, and velocity data are shown in Table I.

Theoretical travel-time curves were calculated from formulae (III.26) and (III.27) taken from reference 2.

For these models the mean and effective velocities differ insignificantly - by not more than 80 m/sec. An exception is the third model, which is rarely encountered in practice, where on the surface there is a thick layer of unconsolidated sand with a low bed velocity of 500 m/sec, for which the effective velocity is higher than the mean by 240 m/sec. Thus the inflection of the rays owing to the abrupt velocity differentiation along the vertical, typical of this region, in the overwhelming majority of cases does not lead to any substantial difference between the mean and effective velocities.

For the second type of model we use the linear law of variation in mean velocities along the horizontal

$$v_x = v_0 (1 + \beta x) = v_0 + Kx, \tag{1}$$

where $K = v_0\beta$ is the horizontal velocity gradient, v_0 is the value of the mean velocity at the point of origin ($x = 0$).

In reference 1 there is a simple approximate formula for calculating travel-time curves for reflected waves where there is a linear variation in velocity along the horizontal

$$t = \frac{\sqrt{x^2 + 4H^2}}{v_0 + \frac{Kx}{2}}, \tag{2}$$

which was used for constructing theoretical travel-time curves. In this reference it was shown that even for large velocity gradients ($K = 1$ sec^{-1}) the formula ensures the construction of travel-time curves with an accuracy sufficient for interpretation.

For depths of 800 m, on the basis of all available data on velocities for v_0, we selected the value of 3000 m/sec as the most frequently encountered in places of homogeneous permafrost.

The values of the horizontal velocity gradients K were selected on the basis of actual values of time increment Δt_0 at neighbouring explosion points obtained in the Tolon area. The maximum values for Δt_0 when the reflecting boundary is horizontal, in places of transition from homogeneous permafrost to warmer zones, have a value of about 0.1 sec with an explosion interval of 425 m. Correspondingly, the maximum values of K obtained from profile observations would be 0.95 sec^{-1}. Calculations were carried out for K values of -0.95 sec^{-1} and -0.7 sec^{-1}, as well as for -0.515 sec^{-1}.

With theoretical travel-time curves constructed with the use of formula (2) we determine the effective velocity by the difference travel-time curve method taking into account the slope of the reflecting boundary, using the formula

$$v_{ef} = \sqrt{\frac{l}{t_{av}\frac{dt_{\Delta}}{dx} + \frac{(t_{02}-t_{01})^2}{2l}}}, \qquad (3)$$

where l is the distance between the explosion points, t_{01} and t_{02} are zero times at the first and second explosion points, t_{av} is the mean time on the travel-time curve calculated from the formula

$$t_{av} = \frac{1}{4}(2t_{B3} + t_{01} + t_{02});$$

$\frac{dt_{\Delta}}{dx}$ is the slope of the difference travel-time curve.

The effective velocity computed with the use of formula (3) was compared with the mean arithmetic value of the mean velocity at the edge of a spread 500 m long. The results are given in Table II.

It can be seen from Table II that the values of effective velocities obtained with formula (3) are close to the mean values and can be used in interpreting for the models of media used.

From a consideration of the models of media one can make the following conclusions.

1. The horizontal velocity characteristic of permafrost in the region of investigation, as a rule, leads to deviations in effective velocities from the mean which do not exceed the error in determining the effective velocity.

2. When there is a horizontal gradient in the mean velocity, in places of transition from homogeneous permafrost to zones of higher temperature, the effective velocity differs little from the mean. The effective velocity should be determined with formulae used in the difference travel-time curve method taking into account the slope of the reflecting boundaries.

Regardless of the abrupt changes in velocities over the area, the accuracy in determining the effective velocity from single travel-time curves is not sufficient for direct use in interpretation. In order to increase the accuracy in determining the effective velocity values we used the time summation method[3]. This method is applicable if the slope of the boundary does not exceed 10° and there is no horizontal velocity gradient for the area intended for summation. The first condition is fulfilled in the region of operation; the reflecting boundaries are at a small angle. To fulfill the second condition, the profiles were subdivided into portions within the range of which the horizontal velocity gradient could be neglected.

It has been established that in the area under consideration the structural features of the permafrost strata are to a substantial degree controlled by surface conditions. Sections of homogeneous permafrost as a rule are covered by larch forests, sections with higher ground temperatures are covered by pine forests growing on sand deposits. Higher temperature zones are also found under swamps, lakes and rivers. Time summation is carried out within the limits of sections having approximately the same surface conditions and similar velocities of direct waves. Then, using the system of counter travel-time curves, we determined the effective velocity with the use of the counter and difference time-travel curve methods.

The data obtained indicate rather stable velocity values for the middle reaches of the Vilyui River and the Tolon area within the range of the homogeneous permafrost sections and zones with higher temperatures. The sections covered by larch forests have velocities of 2650-3000 m/sec, sections covered by pine forests, swamps, lakes and the Vilyui River have 2200-2600 m/sec. Within the limits of each section the velocity values are constant outside of any dependence on the averaging base, which indicates that the method of determining velocities by averaging travel-time curves for the sections having specific surface conditions is correct*. In the transitional sections between the permafrost and zones with higher temperature, which as a rule are not extensive and are characterized by horizontal changes in velocities, the summation method was not used.

Cross sections were plotted for those sections of the profile where we determine the effective velocity by the time summation method. When there is a continuous correlation between the reflected waves and the conformably bedded reflecting boundary on sections with complex surface conditions of small dimensions, there is no particular difficulty in establishing the boundary.

A comparison of cross sections along the first reflecting horizon obtained from a difference approximation of the velocity cross section of the

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* Possibly the regularities noted by the author are strictly local. To confirm them, more systematic investigations are required (Editor's note).

medium along the profile connecting rotary drilled holes P-2, P-1 and P-3 in the middle reaches of the Vilyui River is shown in Figure 3. The position of the boundaries 1 and 2 coincides approximately with hole P-2; in holes P-1 and P-3 the boundaries are noticeably deflected because in constructing boundary 2 the warmer zones directly adjacent to the Vilyui River were not taken into consideration.

The second interpretation variant, according to which the difference in depth along the first reflecting horizon between holes P-1 and P-2 is approximately 340 m, is close to drilling data, which give a difference of 358 m between these holes using the horizon lying at a depth of 1292-1650 m. Interpretation with the constant velocity law gives an increase of only 120 m over the first reflecting horizon between the same holes.

Thus, regardless of the complex variation in surface seismic-geological conditions, one can make quantitative interpretations of the reflected wave data with a greater accuracy by using information dealing with effective velocities.

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Table I

Model No.	v_{strata}, m/sec						v_{av}, m/sec	v_{ef}, m/sec
	Stratum 1	Stratum 2	Stratum 3	Stratum 4	Stratum 5	Stratum 6		
	Δh, m							
	50	100	100	200	200	100		
1	4000	2500	3400	3000	2700	2100	2780	2860
2	3000	1500	3400	3000	2700	2100	2490	2570
3	500	1500	3400	3000	2700	2100	1960	2200

Table II

v_0, m/sec	K, sec^{-1}	Δt_0, sec	v_{ef}, m/sec	v_{av}, m/sec	$v_{ef} - v_{av}$ m/sec
3000	-0.95	0.1	2780	2760	20
3000	-0.7	0.07	2840	2825	15
3000	-0.515	0.05	2860	2870	-10

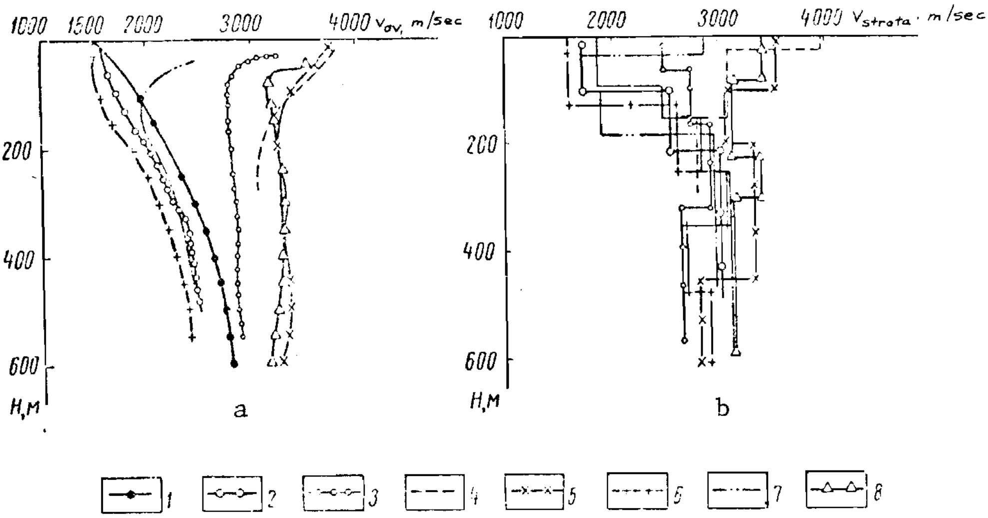

Fig. 1

Combined curves for mean (a) and strata (b) velocities in parametric holes.

1 - hole 2-P; 2 - hole 7-P; 3 - hole 3-P; 4 - hole 1-P; 5 - hole 5-P; 6 - hole 4-P; 7 - hole 8-P; 8 - hole K-3

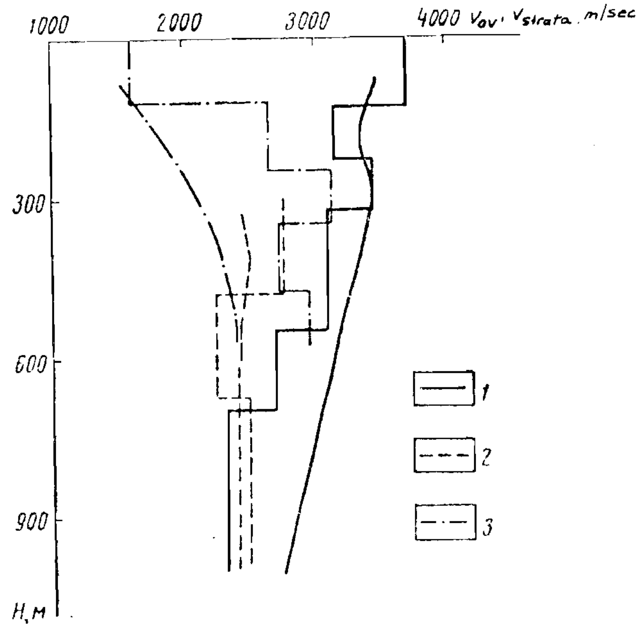

Fig. 2

Curves of strata and mean velocities for homogeneous permafrost and higher temperature zone.

1 - hole K-3; 2 - hole 1-P; 3 - hole 4-P

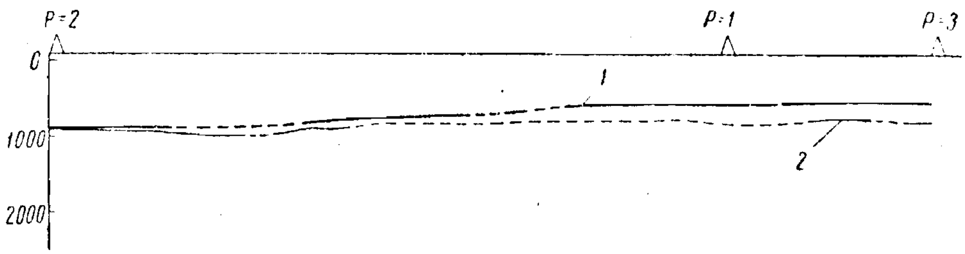

Fig. 3

Seismic-geological cross section between rotor drilled holes P-2, P-1 and P-3 constructed from the first reflecting horizon by various means.

1 - boundary constructed by the suggested method taking into account horizontal change in velocity;
2 - boundary constructed with a constant velocity law (in the production group)