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METHODS OF PERMAFROST STUDIES

SEISMIC STUDIES IN FROZEN GROUND

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The specificity of seismic soundings in frozen ground is defined by the features of the permafrost-related wavefield. According to years-long experience of the authors, shear-wave surveys with the use of the *SH* phase are an efficient tool to study unfrozen layers (taliks) above permafrost and the subsurface structure. Joint use of compressional and shear velocity data is workable in estimating the state and properties of frozen ground.

INTRODUCTION

The permafrost-related seismic wavefield, especially that of soft sediments, has a number of specific features. They result from the seismic and lithological heterogeneity of the section and its variations in space and time associated with seasonal temperature change and other factors. The wave patterns may bear prominent reflection contrasts and velocity reversals. Many sections comprise a shallow-lying thin layer with high seismic velocities. Such layers may be seasonally frozen ground, frozen coarse soil, or pavement (concrete or asphalt) within urban or industrial areas. These layers produce velocity reversals in the seismic section [*Skvortsov, 2005*] and cause the respective dramatic changes to the *SH* (horizontally polarized) shear-wave field. The geocryological seismic sections of this kind [*Skvortsov, 1997*] require special acquisition methods. The awareness of the permafrost specificity can make basis for the appropriate choice of techniques and is a prerequisite of their efficiency.

Seismic surveys in permafrost have many objectives [*Melnikov et al., 2010*] that belong to three main groups: (i) estimating the depth to the permafrost table, (ii) imaging the section structure, and (iii) studying the state and properties of frozen ground.

ESTIMATING THE DEPTH TO THE PERMAFROST TABLE

The depth to the permafrost table is estimated in the course of contouring natural and man-caused layers of unfrozen ground (taliks) and measuring their thickness, which may be tens of meters.

The problem is successfully resolved with refraction surveys commonly used in shallow seismic exploration in land conditions of a normal seismic section [*Skvortsov, 1997*]. However, *P*-wave refraction shooting is poorly applicable to permafrost sections because some layers may remain unresolved [*Tsarev et al., 2010*]. The missed layers, often a zone of full hydraulic saturation, introduce large errors (up to 40 % or more) to the estimates of talik thickness (Fig. 1, *a*). Higher resolution in this case can be achieved with *SH* refractions [*Ponomareva and Skvortsov, 2006*].

A still better alternative is to use a special technique of high-resolution shear-wave reflection (SWR) profiling with *SH* phases designed at the Institute of Earth's Cryosphere (Tyumen). The phenomenological background of the new method consists in dramatic changes of the *SH* wavefield in cases of velocity reversal [*Skvortsov, 2005*]. Thus the respective reflections from shallow (few meters) interfaces become recordable at certain favorable conditions [*Snegirev et al., 2003*].

See Fig. 1 for some examples of refraction and SWR data used to predict the geometry and thickness of man-caused onshore taliks.

Studying inner-shelf taliks (shallow water, tidal zone) has gained ever more importance lately with the development of the Arctic shelf, but there were no appropriate acquisition methods till recently.

Research in this line has been run at the Institute of Earth's Cryosphere since 2006 [*Skvortsov et al., 2007a, b; Sadurtdinov et al., 2009*]. The shelf section was found out to bear a thick undersaturated layer below the ground surface in which water saturation of rocks is impeded by entrapped air. The layer thickness is highly variable and can reach 2 m or more. *P*-wave surveys are often inapplicable in this case as they can provide acceptable resolution only outside the tidal zone. As the available experience shows, the *P*-wave method has the same limitations also in lakes and rivers within or outside the permafrost zone.

On the other hand, *SH* surveys are workable in estimating the depth to the permafrost table under

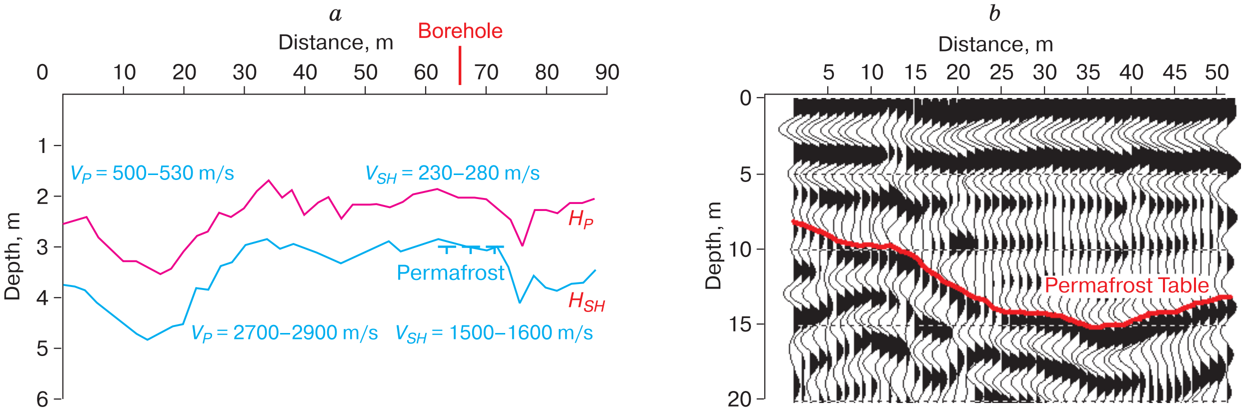

Fig. 1. Examples of contouring man-caused unfrozen layers with the use of refracted (*a*) and reflected (*b*) *SH* waves.

a: Mirnyi; *b*: Norilsk; H_P and H_{SH} are depths to permafrost surface estimated with compressional (*P*) and shear (*S*) waves, respectively; V_P and V_{SH} are compressional and shear (*SH*) wave velocities, respectively.

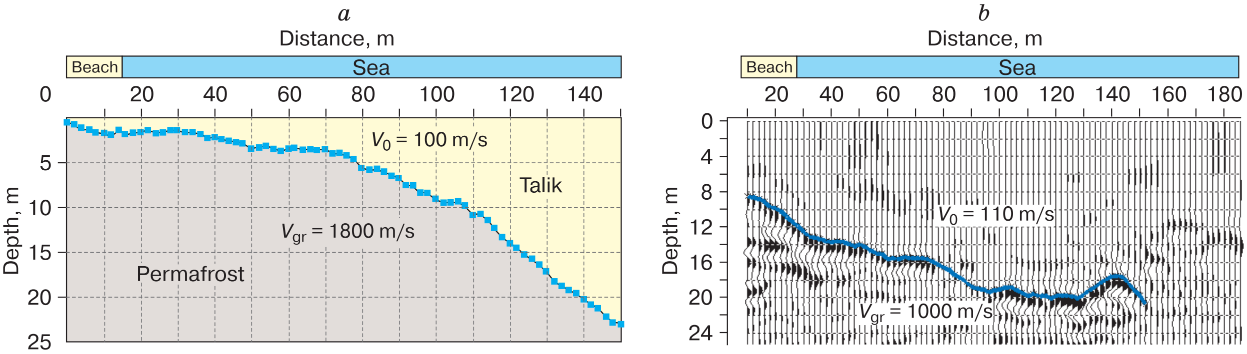

Fig. 2. Examples of contouring unfrozen layers in inner shelf with the use of refracted (*a*) and reflected (*b*) *SH* waves.

a: Yamal, Cape Kamennyi; *b*: Pechora mouth, Bolvansky site; V_0 is *SH* velocity in unfrozen layer; V_{gr} is interface *SH* velocity at permafrost surface.

shallow water. Shallow interfaces are resolvable with refracted waves (Fig. 2, *a*), but deeper taliks are better resolved with *SH* reflections (Fig. 2, *b*).

Special methods and technology of bottom surveys have been developed additionally for offshore survey.

IMAGING THE PERMAFROST SECTION

When sounding frozen ground, one has to bear in mind the specificity of its seismic section, namely, the presence of many prominent interfaces and velocity reversals, including those near the permafrost surface. In these conditions, refraction shooting is often difficult or impossible, and reflection surveys become a better choice [*Malkova et al., 2008; Skvortsov et al., 1992, 2009*], especially, *SH* reflections. The absense of converted waves make the *SH* wavefield simpler to provide more reliable seismic data [*Skvortsov, 2001*].

Summer acquisition in frozen ground faces difficulties associated with the active layer, especially if the thaw depth is multiple of the wavelength. In the

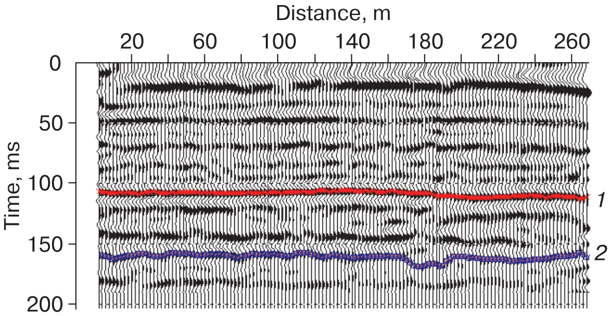

Fig. 3. A high-resolution SWR cross section near a kimberlite pipe in Yakutia.

1 – a reflection from Jurassic clay surface at depth about 55 m; *2* – Ordovician limestone surface at a depth of 80–90 m with a local low which may be a trap for placer diamond.

latter case, the wavefield bears intense reverberation multi-cycle waves [*Skvortsov, 2002*], and reflections from seismic interfaces within permafrost become ill resolvable. At shallow thaw depths, reflections are recordable if the source is placed on the permafrost surface [*Skvortsov et al., 1992*]. For this reason, it is preferable to image the structure of frozen ground in winter seasons to avoid thaw effects. Better results are obtained if land measurements with the SWR method are checked against downhole vertical seismic profiling (VSP) where possible.

Figure 3 presents an example permafrost section to a depth of 100 m collected with SWR profiling and checked against VSP data [*Skvortsov, 2005*].

STUDYING THE STATE AND PROPERTIES OF FROZEN GROUND

Compressional- and shear-wave velocity data have implications for elastic properties, strength, and strain of rocks, including frozen ground.

In the latter case, there is a separate problem of estimating the degree of permafrost "sluggishness", for which an approach based on Poisson's ratio patterns was suggested in [*Melnikov et al., 2010*].

Poisson's ratios in frozen sand-clay sediments at a low salinity of pore fluid are known to range between 0.25 and 0.40 depending on the grain-size composition but can reach 0.47–0.50 in water-saturated unfrozen sediments. Thus, Poisson's ratio can be a proxy of sluggishness associated with the amount of unfrozen water.

According to our results, joint analysis of velocity patterns and velocity ratios can provide reliable estimates of permafrost sluggishness. Therefore, the suggested approach is applicable to detect cryopegs (brine lenses) and zones of high-salinity pore fluid.

CONCLUSIONS

The choice of seismic acquisition methods and techniques should stem from knowledge of wavefield specificity within the study area.

Supra-permafrost unfrozen ground, including that under shallow water, is resolvable by *SH* refraction seismic surveys in the case of a normal velocity profile but *SH* reflections are more efficient in the presence of velocity reversals.

High-resolution shear-wave reflection (SWR) profiling with the use of *SH* phases is an advantageous tool for studying the structure of frozen ground.

Joint analysis of velocity patterns and velocity ratios (Poisson's ratio) is useful to estimate the elastic constants and the state of permafrost.

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