GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Seismic studies of frozen ground in Russian Arctic areas

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ABSTRACT
This report shows the results of a study of permafrost conditions in the coastal and nearshore areas of the Russian Arctic seas that was carried out through seismic methods. For this study, the researchers developed a new technique for using seismic methods on the bottom of shallow waters, combining bottom and downhole surveys. In order to more reliably identify frozen state deposits, Poisson's ratio was used as an added seismic criterion. The results obtained show that in seismic surveys on the sea bottom, SH-waves are preferable to P-waves.

RÉSUMÉ
L'article présente les résultats d'une étude de la condition du pergélisol dans les régions côtières de la mer arctique russe par l'utilisation des méthodes sismiques. Une technique spéciale de relevés sismiques en eaux peu profondes a été développée pour ces études. La technique inclus des relevés de fond et de puits. L'utilisation du coefficient de poisson est proposée à titre de critère sismique supplémentaire pour améliorer l'identification des dépôts gelés. Les résultats obtenus montrent que les ondes SH sont préférables aux ondes P lors de l'utilisation des relevés sismiques de fond de bassin.

1 INTRODUCTION

In Russia and many other countries, much attention has been paid in recent decades to the study of the nearshore area of the Arctic areas [Hunter et al, 1978; McGee, 2000; Melnikov et al., 2010 et al]. The primary reason for this has been the development of new hydrocarbon deposits on the shelf, making it necessary to build appropriate infrastructure (ports, pipelines, building zones, etc.) on the coastal part of the shelf in order to facilitate exploitation of these deposits. To do this, it is necessary to have greater knowledge of the geological structure and permafrost conditions of the areas of interest, as well as of the physical and mechanical properties of local geology.

Traditionally, only P-waves are used in seismic problem solving. However, previous studies have shown that using only P-waves significantly limits the possibilities to study the physical properties of rocks [Carlson et al, 2007; Hobson, 1967; Hunter et al, 1990 et al].

Researchers at the Institute of the Earth's Cryosphere have developed original seismic techniques for investigations in shallow waters that simultaneously employ P- and SH-waves. This technique employs both bottom and downhole surveys.

This report presents the results of research undertaken in the permafrost key-sites "Marre Salle" (in the Yamal Peninsula) as well as "Bolvansky" and "Kashin Island" (in the Pechora river delta). A map of the research areas is shown in fig. 1.

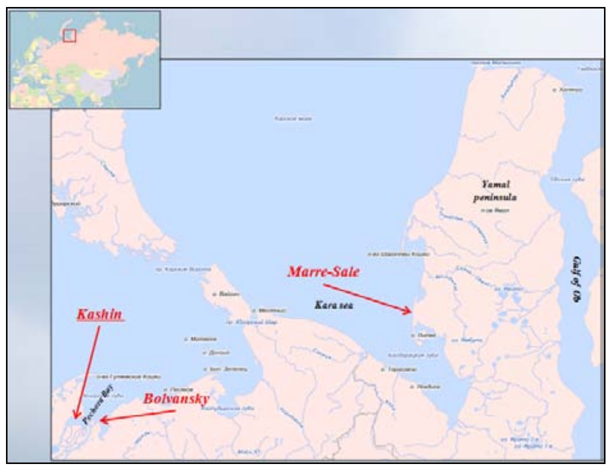

Figure 1. Key-sites of seismic investigations.

2 SEISMIC EQUIPMENT

The researchers developed special equipment for seismic waves excitation and detection on the bottom within shallow water areas. This original equipment can be used for the to work with P- and SH- waves simultaneously.

2.1 Seismic Waves Excitation

In order to excite and detect seismic waves on the bottom of shallow water areas, both mechanical and electromagnetic power sources were used. The common feature of these sources is that they can excite P- and SH-waves simultaneously. Using these sources, the researchers could excite vibrations at a 45 angle to the sea floor in two opposite directions. During research on the sea bottom, the source could be positioned so as to excite vibrations along a plane perpendicular to the profile.

During borehole research, the source could be positioned close to a borehole's collar to excite vibrations along a plane perpendicular to the borehole's direction. A special folding source was developed for seismic surveys on bottom in ice-covered waters. When folded, this source can be put into the hole through the ice, making a small hole with a diameter of 20 cm or less. In a work state, this source can be used in only one direction, creating excitation at a 45˚ angle. To excite vibration in the opposite direction, the source must be rotated 180˚.

2.2 Seismic Waves Recording

The researchers used seismic cable to register vibrations on the bottom, employing cables containing a range of 1 to 12 receivers. Every bottom receiver included both vertical and horizontal geophones. The horizontal geophones were oriented perpendicular to the in-line. The distance between the receivers varied, ranging from 1 to 5 m. Throughout the investigation, both the sources and the receivers were located from the shore or vessel in accordance with the scheme of observation.

In the borehole studies, seismic vibrations were registered by a logging sonde using three components and one point of contact. This logging sonde featured one vertical receiver and two horizontal ones.

The logging sonde can be lowered to a given depth in its folded state, where it can be opened using an inertial mechanical device and pressed to a borehole wall. It can then move along the borehole in a determined direction. Seismic records from two impacts in opposite directions received by vertical geophone are summed up, received by horizontal geophone are subtracted.

3 THE WAVE FIELD STRUCTURE IN THE SHALLOW PARTS OF NEARSHORE AND COASTAL PARTS OF THE NORTHERN SEAS

In this section, we will discuss the characteristics of P- and SH-wave fields in the shallow areas of the Northern Seas. These characteristics served as the basis for our techniques of bottom seismic surveys.

3.1 Seismic Research on bottom

The seismic records of P- and SH-waves in transition for land to waters in the coastal areas of the Pechora Bay are shown in fig. 2. As this shows, the direct P-wave $\mathbf{T_p^{0}}$ has a velocity of 270 m/s in the field of P-waves on the beach (source point: 4 m) and at the water's edge (source point: 16m). It propagates in a layer in the incomplete water saturation zone, which has a thickness of about 2 m.

The refracted wave $\mathbf{T_p^{0}}$ with a velocity of 1550 m/s corresponds to full water saturation. Wave $\mathbf{T_p^{ref\ perm}}$ is a refracted wave on a permafrost table. Because of the presence of high-amplitude direct and surface waves, P-waves reflected from the permafrost table could not be seen. The reason for different $\mathbf{t_0}$ values in transition from the beach to the water is the lateral variability within the layer of incomplete water saturation.

This layer presence is probably caused of continuous tidal movement of water. Therefore, it contains a small amount of air. The presence of a layer of incomplete water saturation causes the spectrum of seismic records in this coastal area to be relatively low – 110-130 Hz. This layer disappears only at a distance of about 100 m from the coastline (source point: 116 m, the end of intertidal zone). This is demonstrated by the sharp increase of records approaching or greater than 650 Hz, and by the direct wave velocity of 1550 m/s. In this area, the depth of the water is about 1.5-1.6 m.

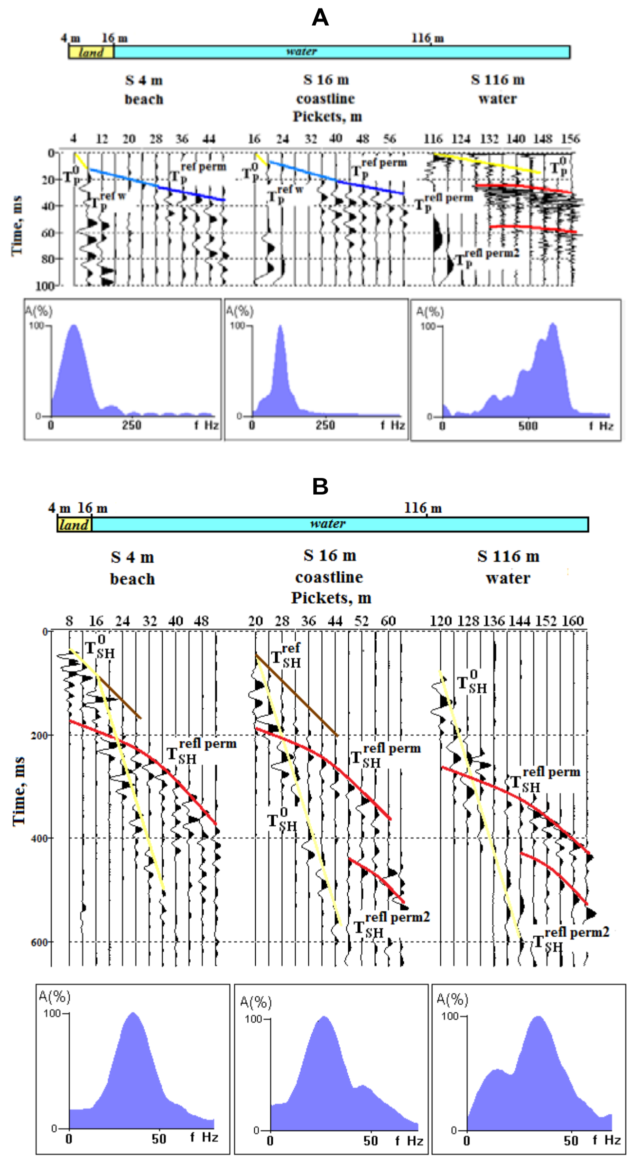

Figure 2. P-waves (a) and SH-waves (b) seismic records the coastal area of the Pechora Bay, geocryological key-site "Bolvanskiy". $\mathbf{T_p^{0}}$ – direct p-wave; $\mathbf{T_p^{ref\ w}}$ – P-wave refracted on boundary of water saturated zone; $\mathbf{T_p^{ref\ perm}}$ – P-wave refracted on permafrost table; $\mathbf{T_p^{refl\ perm}}$, $\mathbf{T_p^{refl\ perm2}}$– P-waves reflected on permafrost table and on boundary in permafrost; $\mathbf{T_{SH}^{0}}$ – direct SH-wave; $\mathbf{T_{SH}^{ref}}$ – refracted SH-wave; $\mathbf{T_{SH}^{refl\ perm}}$ – SH-wave reflected on permafrost table; $\mathbf{T_{SH}^{refl\ perm2}}$ – SH-wave reflected on boundary in permafrost.

The higher spectrum of seismic vibrations leads to a higher resolution in the seismic record, allowing reflected waves from permafrost table $\mathbf{T_p^{refl\ perm}}$ and from the lithological border in permafrost layer $\mathbf{T}_{\mathbf{p}}^{\mathbf{refl\ perm2}}$ to be seen.

In contrast to the P-waves spectrum, the SH-waves spectrum (fig. 1B) remains unchanged between the beach and the water area. A characteristic feature of seismic cross-sections is that during a transition from land to water, a steep decrease in SH-wave velocity $\mathbf{T}_{\mathbf{SH}}^{\mathbf{0}}$ occurs. In this area, velocity decreased from 160 m/s to 70 m/s. This decrease in velocity is due to the appearance of an additional thin later in the cross-section, caused by the movement of water in the intertidal zone.

As a result of this movement, bottom deposits in this area include air (in addition to water and soils), contained in a “suspended” state. In the field structure, low intensity waves appear to be refracted from the base of the “suspended” layer – $\mathbf{T}_{\mathbf{SH}}^{\mathbf{ref}}$. This layer of low-intensity presence is an advantage in registering SH-waves reflected from different permafrost borders, such as SH-waves $\mathbf{T}_{\mathbf{SH}}^{\mathbf{ref}}$, $\mathbf{T}_{\mathbf{SH}}^{\mathbf{refl\ perm}}$, $\mathbf{T}_{\mathbf{SH}}^{\mathbf{refl\ perm2}}$. It should be noted that the intensity of SH-waves refracted from the permafrost table is low, and was not accounted for in the seismic records.

The regularities of the P-wave and SH-wave field structures have been determined in prior research, both in and out of cryolithic zones [Sadurtdinov et al., 2012, 2014 et al].

3.2 Borehole Investigations

Seismic records of both P- and SH-waves gathered in a 20 m deep borehole in the shallow shelf of the Kara Sea are displayed in fig. 3. This borehole is located near the geocryological site Marre-Sale, off the west coast of the Yamal Peninsula, about 900 m from the coastline. The borehole was steel cased. The research was intended to determine the permafrost conditions of the Marre-Sale key-site.

It was impossible to obtain high-quality data using P-waves (fig. 3A) because of the high level of noise caused by the pipe. High quality data was obtained only through the use of SH-waves (fig. 3B). In addition to the low intensity tube wave $\mathbf{T}_{\mathbf{tube}}$, SH-wave data can be clearly traced, as shown by direct SH-wave $\mathbf{T}_{\mathbf{SH}}$ and SH-wave $\mathbf{T}_{\mathbf{SH}}^{\mathbf{refl}}$, which was reflected from the lithologic boundary in the loam layer.

4 RESULTS

Some results of seismic surveys in shallow waters are shown below. These were obtained in the Arctic areas with different geocryological structure.

Figure 4 shows the seismic cross-section in the shallow waters of Pechora Bay (in the “Bolvansky” key-site). This data was obtained using reflected SH-waves. In this area, the depth of permafrost table gradually increases from 8 to 20 meters at distances over 140 meters from the shore. Over this distance, reflection from the permafrost table gradually disappears. The permafrost

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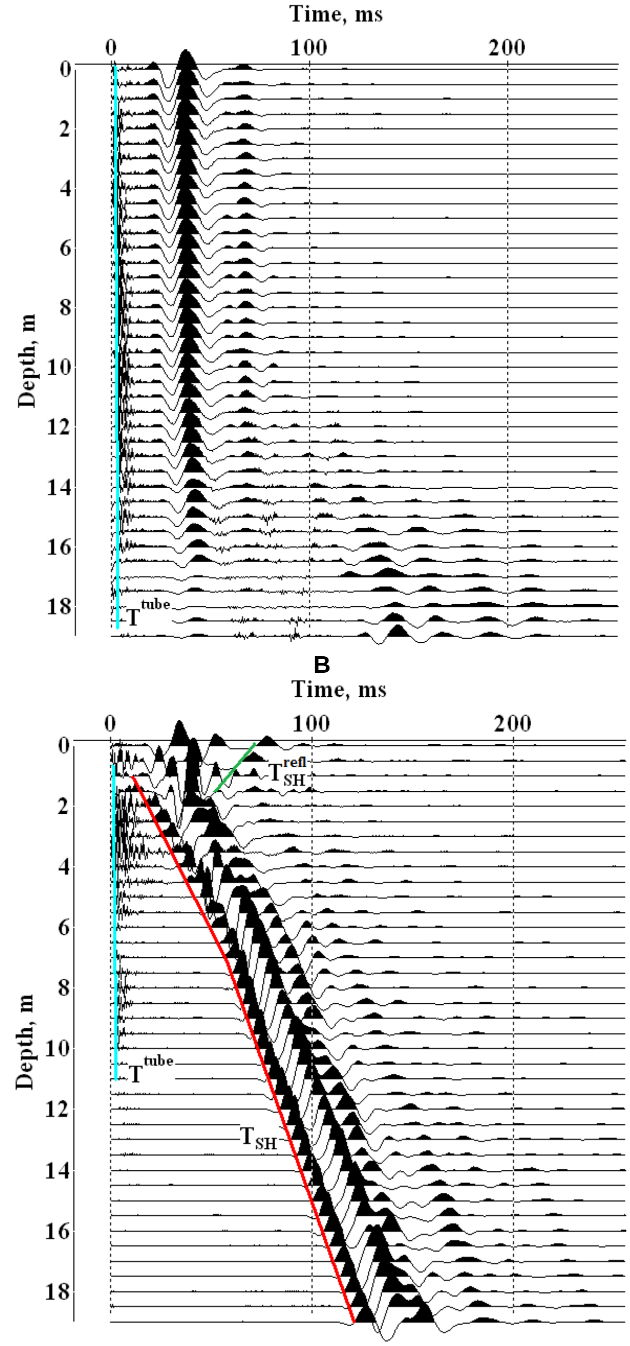

Figure 3. Seismic data obtained in boreholes in the shallow part of the Kara Sea shelf (900 m from shoreline): P-waves (A) SH-waves (B). 1 - tubewave; 2 - direct SH-wave; 3 - SH- wave reflected from the lithologic boundary.

levels were determined using the values of velocity and Poisson’s ratio [Skvortsov et al, 2014].

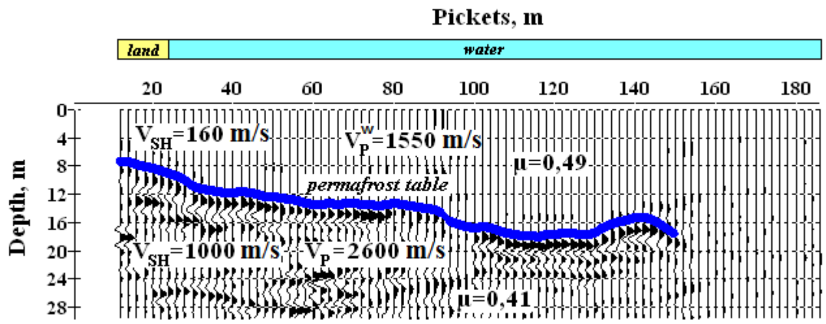

Figure 4. Seismic cross-section in Pechora Bay. Reflected SH-waves. “Bolvansky” key-site (delta of Pechora river). $\mathbf{V_P^W}$ – P-wave velocity in full water saturation zone.

Figure 5 shows the results of seismic investigation in the nearshore areas of the Kara Sea. (“Marre-Sale” key-site, West Yamal). Here, the geocryological structure is presented by thawed, frozen and cryotic deposits. And permafrost is thin out. Generally, seismic velocity in permafrost is rather low, but Poisson’s ratio μ<0.46 shows that these deposits are in frozen state [Skvortsov et al, 2014].]. The results of the seismic investigation were confirmed by drilling as well as temperature data in the borehole. By seismic investigation on nearby crosslines, it was shown that the permafrost table gradually decreases from shore to the water area.

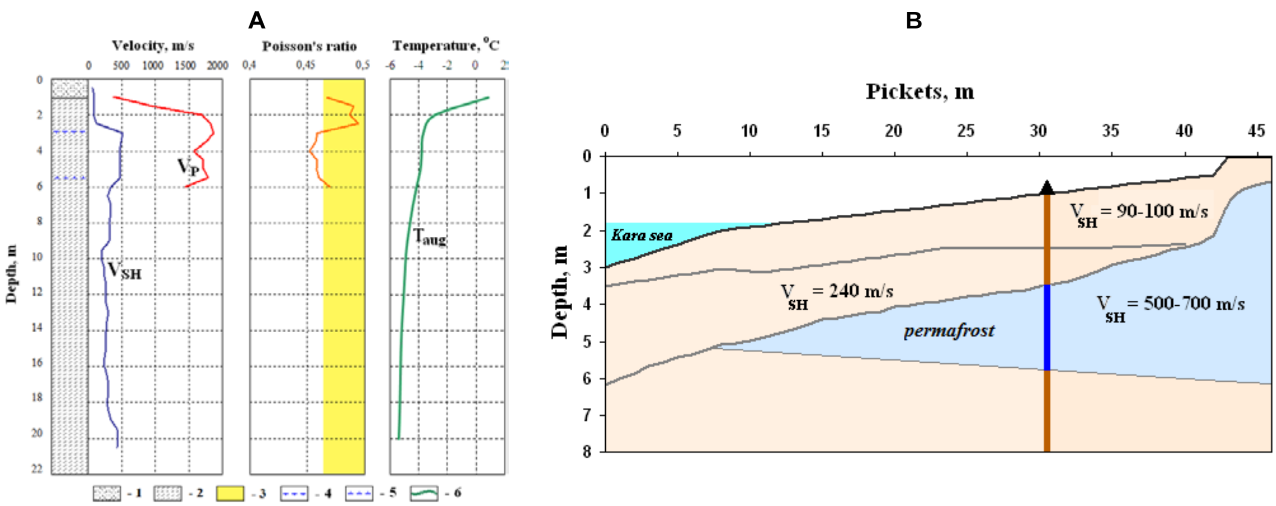

Figure 5. Seismic investigation results in nearshore area of Kara Sea (“Marre-Sale” key-site, West Yamal). A – results of seismic logging; B – cross-section obtained by reflected SH-waves.
1 – sand; 2 – loam; 3 – Poisson’s ratio range for thawed deposits; 4, 5 – top and base of permafrost; 6 – borehole temperature graph in August 2013.

Further studies in this area have shown that at large distances from the coastline there is no permafrost to depths of 20 meters.

Figure 6 shows the results of seismic logging in one of the boreholes (900 m from the coast). The velocities of SH-waves obtained in this study are not higher than 200 m/s. It should be noted that temperature in borehole was negative during measurements. In spite of this, SH-wave velocities were low, proving that deposits are cryotic.

Figure 7 shows the results of the combined application of P- and SH-waves. These surveys were conducted on the “Kashin Island” key-site (Korovinskaya Bay, in delta of the Pechora river) [Sadurtdinov et al, 2012]. SH-waves reflected off the permafrost table could be traced up to 170 meters from the coastline (fig. 7A). Further it’s sharp decreases and using refracted waves is impossible.

This boundary can also be traced by using reflected P-waves to pickets 270-275 (fig. 7B), before it disappears on the time cross-section. At this distance, structure of the time cross-section changes, and high-amplitude reflected waves can be traced to approximately 70 ms, corresponding to a boundary at a depth of about 60 meters. The effective velocity of this wave is 1500 m/s, indicating that there are no layers with high velocity (s.a. permafrost) until this depth. There is also a wave reflected from the vertical contact on the cross-section (represented by the red lone on fig. 7). Probably it reflected on a “corner” of the permafrost. Thus, this permafrost table and it form were obtained through the combined usage of different classes of P- and SH-waves.

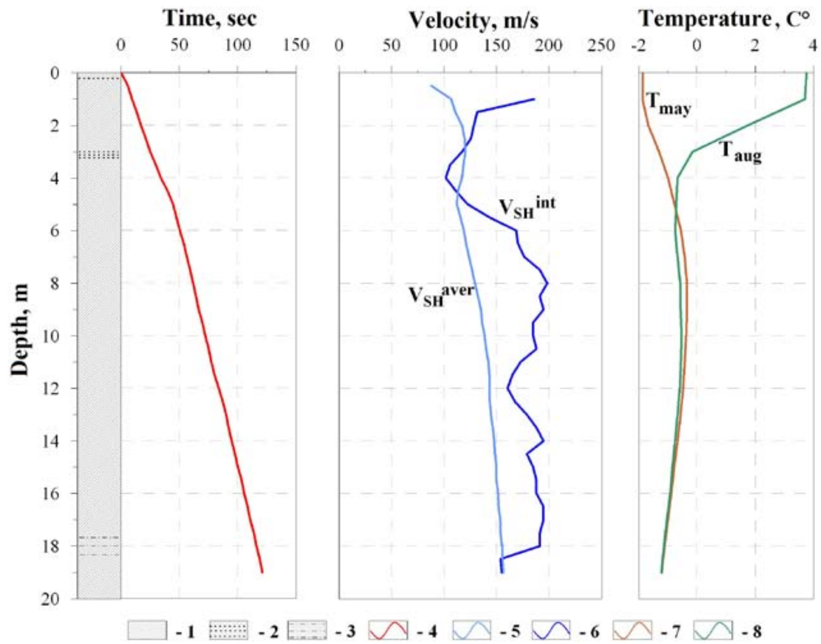

Figure 6. Seismic logging results in borehole in the Kara Sea shelf (900 m from the shoreline) 1 – loam; 2 – loam with sandy impurities/interbedded sand; 3 – loam with impurities/interbedded siltstone; 4, – SH-wave hodograph, 5, 6 – SH-waves average and interval velocities; 7, 8 – borehole temperature graph in May and August 2014.

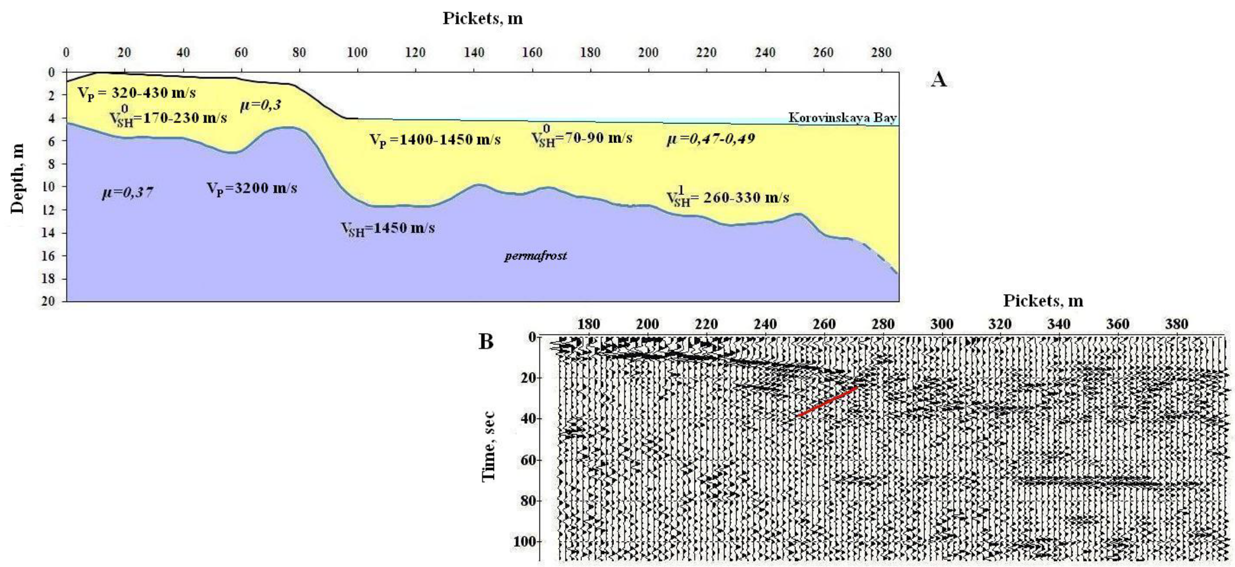

Fig. 7. Seismic investigation's results in nearshore area of Korovinskaya Bay. "Kashin Island" key-site (delta of Pechora river). A – depth cross-section obtained by refracted SH-waves; B – time cross-section obtained by reflected P-waves.

5 CONCLUSIONS

The mains results of our research are as follows:

The technique for seismic bottom investigations developed in the Institute of the Earth's Cryosphere is effective for the study of permafrost conditions on shallow Arctic waters.

New equipment designed and constructed for this study can be successfully used for the excitation and detection of P- and SH-waves simultaneously.

The main features of the seismic waves field structure in nearshore and coastal areas were determined.

To more reliably identify deposits in a frozen state, Poisson's ratio should be used as an additional seismic criterion.

The effectiveness of the overall method, including the efficacy of newly developed equipment, field work techniques, and the use of Poisson's ratio, was confirmed by positive results in different states of different geocryological and natural conditions at water depths of up to 5 m, and distances of more than 20 km from the coastline.

This technique has been used successfully outside of the cryolithic zone.

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