SCIENTIFIC JOURNAL
EARTH'S CRYOSPHERE

Earth`s Cryosphere, 2014, vol. XVIII, No. 2, pp. 75–80 http://earthcryosphere.ru/

METHODS FOR PERMAFROST STUDIES

SEISMIC CRITERIA FOR INDENTIFYING FROZEN SOIL

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Unfrozen and frozen soils of sand to clay grain sizes can be discriminated using seismic criteria, especially Poisson's ratio. According to the available published evidence and experimental results collected for years in the areas of Arctic West Siberia and European North, Poisson's ratios (μ) in the range 0.45–0.46 mark the boundary between frozen and unfrozen states of water-saturated soils. The values $\mu > 0.46$ and $\mu < 0.45$ correspond, respectively, to unfrozen and frozen soils, irrespective of their composition, temperature and salinity. Poisson's ratio is thus an additional permafrost proxy and an effective tool of geocryological studies.

Poisson's ratio, P and S waves, permafrost, frozen clay, seismic logging

INTRODUCTION

Discriminating between frozen and unfrozen states of ground and outlining the permafrost boundaries is a common objective of seismic surveys in high-latitude areas. The problem is easy to resolve with reference to *a priori* evidence, e.g., from borehole logs, but seismic criteria acquire primary importance if no such data is available.

The conventional seismic criteria include wave velocity and amplitude patterns and *PSP*-conversion at the permafrost table in refraction shooting. However, these criteria are not always workable, especially in frozen soil rich in plastic clay, and some additional proxy may be needed.

SEISMIC CRITERIA FOR IDENTIFYING FROZEN SOIL

Velocities of compressional (*P*) and shear (*S*) elastic waves are most often used to trace the extent of permafrost as they are markedly higher in frozen rocks than in their unfrozen water-saturated counterparts [*Rogers and Morack, 1978; Neave and Sellmann, 1983; Dzhurik, 1988; Goryainov, 1992; Voronkov et al., 1997; Frolov, 1998*]. The velocity contrast on transition to the frozen state depends on grain size and is larger in coarser soils.

There is however a problem that the ranges of *P* and *S* velocities measured in frozen and unfrozen wet soils of sand to clay grain sizes overlap (Fig. 1, compiled using published data [*Goryainov, 1992; Voronkov et al., 1997; Frolov, 1998; Voronkov, 2009*] and results of our years-long studies in the areas of Arctic West Siberia and European North). Thus, the velocity-based seismic permafrost will be ambiguous without *a priori* knowledge of lithology or impossible to constrain in the case of clay. More ambiguity may come from variations in soil temperature and salinity, two other velocity controls besides the grain size [*Frolov, 1998; Zykov, 2007; Voronkov, 2009*].

Note that the *S*-wave velocities show a much smaller overlap than the *P* velocities (Fig. 1), and can be expected to provide more reliable distinction of frozen and unfrozen soils.

The permafrost table, the major interface detectable by geophysical methods in high latitudes, may also appear in *P* wavefields as a *PSP* refraction event [*Goryainov, 1992*], much stronger than the *P* refractions (Fig. 2, *a*). However, strong conversion events

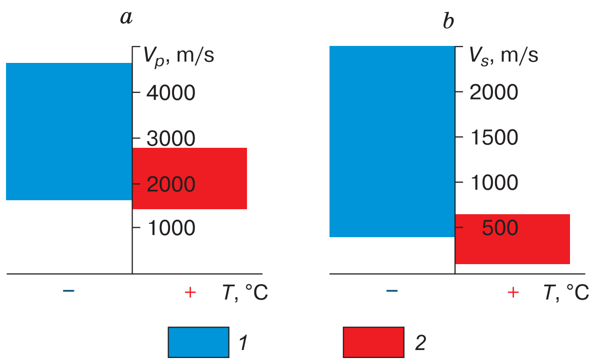

Fig. 1. Ranges of *P* (*a*) and *S* (*b*) velocities in frozen (*1*) and unfrozen (*2*) water-saturated sand-clay soils, after *Voronkov et al.* [*1997*], *Voronkov* [*2009*], *Goryainov* [*1992*], *Frolov* [*1998*], and *Skvortsov et al.*

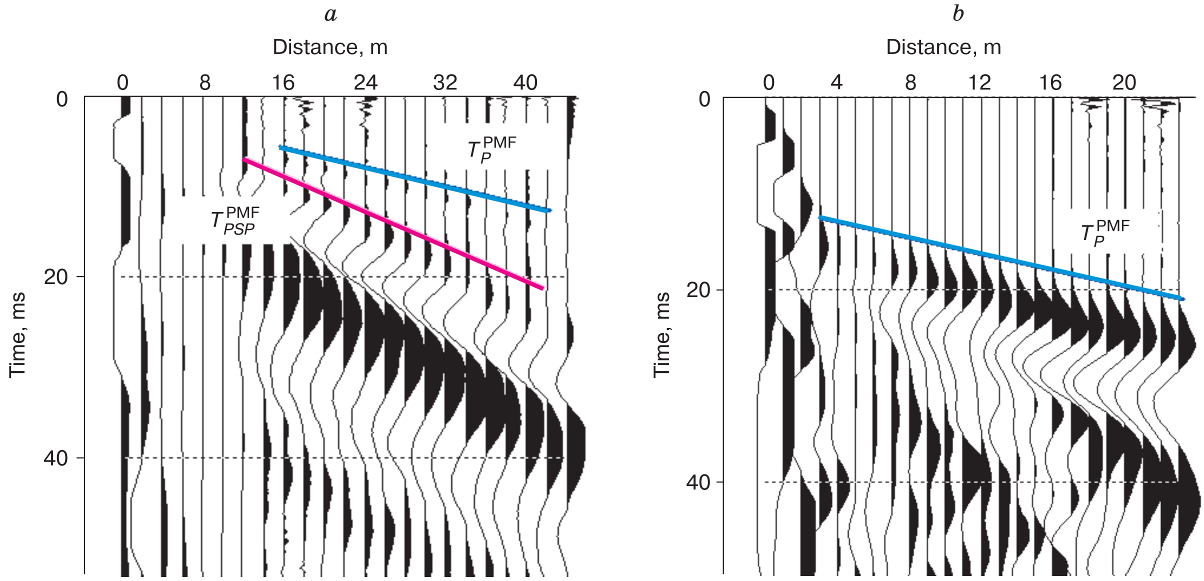

Fig. 2. The *P* wavefield in sand (*a*) and clay (*b*), Yamal Peninsula.

a – Kamennyi Cape Village; *b* – Marre-Sale permafrost monitoring site.

T_P^{PMF} is *P* refraction at permafrost table; T_{PSP}^{PMF} is *PSP* conversion at permafrost table. PMF stands for permafrost table.

form most often at sharp interfaces and can trace the permafrost table in sand and silt, but the *PSP* phase is hard or impossible to resolve in unfrozen and/or saline soil. See for instance the pattern of Fig. 2, *b* where no *PSP* phase is evident while the 1800 m/s *P* refraction cannot be unambiguously related to the permafrost table. Thus, seismic velocities not always reliably indicate the presence of frozen soil and are inapplicable in the case of abundant fine plastic clay.

There have been other seismic criteria suggested in the literature for detecting permafrost, such as amplitude patterns in marine reflection profiling data [*Sedov, 1988*] or reflection coefficients [*Hobson, 1967*], but they have been mostly restricted to experimental studies and are very rarely used in the practice of engineering seismic surveys in permafrost areas.

USE OF POISSON'S RATIO AS A PERMAFROST PROXY: THEORETICAL BACKGROUND

Poisson's ratio (μ) is found uniquely from velocities of compressional and shear waves

$$\mu = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)},$$

where V_p and V_s are the *P* and *S* velocities, respectively [*Goryainov, 1992*], and varies from 0 to 0.5.

See Table 1 for Poisson's ratios in frozen and unfrozen water-saturated soils of sand to clay grain sizes after [*Goryainov, 1992; Frolov, 1998; Voronkov, 2009*]. The μ values in Table 1 are the highest (approaching the upper bound of 0.5) in unfrozen wet soils but their averages and ranges differ in different references. Namely, they are from 0.40 to 0.45 according to *Frolov* [*1998*] and *Voronkov* [*2009*] but reach 0.48–0.49 in estimates by *Goryainov* [*1992*], which agree with the μ = 0.46–0.49 values reported in other publications [e.g., *Gurvich, 1970; Gurvich and Nomokonov, 1981*].

We never observed Poisson's ratios lower than 0.46 in our surface and downhole measurements of Quaternary wet unfrozen soils in coastal and shelf areas of Arctic West Siberia and European North [*Sadurtdinov and Skvortsov, 2008; Sadurtdinov et al., 2009, 2010, 2012; Skvortsov et al., 2011a,b*].

Analysis of published evidence and our data prompts that low Poisson's ratios reported by *Frolov* [*1998*] and *Voronkov* [*2009*] for wet unfrozen sand and silt may result from specific mineralogy (the cited authors mention) and structural binds in relatively old rocks. Or, they may be low because of undersaturation, which is indicated implicitly by the fact that low μ correspond to low *P* velocities (V_p = = 700–1300 m/s).

On the other hand, the areas of saturation are resolvable in seismic data because the *P* velocity jumps to at least 1450 m/s (about that in water) as the three-phase medium (air–water–solid) changes to a two-phase one, almost void of air. This method of estimating saturation is broadly used in seismic surveys [*Goryainov, 1992*].

Table 1. **Poisson's ratios in frozen and unfrozen soils of different grain sizes**

Soil	State	Poisson's ratio (μ), after different authors	
		[*Goryainov, 1992*]	*Voronkov et al.* [*1997*], *Voronkov* [*2009*], *Frolov* [*1998*]
Sand	Frozen	0.29	0.27
Silt		0.30	0.38
Clay silt		0.29	0.33
Clay		0.35	0.38
Sand	Unfrozen (water-saturated)	0.49	0.40
Silt		0.48	0.40
Clay silt		0.49	0.45
Clay		0.48	0.45

Poisson's ratios in frozen soil are about the average over the whole range (Table 1); they vary as a function of the amount of unfrozen water and, hence, are lower at lower temperatures and clay contents [*Frolov, 1998*].

Thus, there must be some threshold μ value or a narrow range of values corresponding to the transition from unfrozen to frozen sand-clay soils as pore water changes to ice. According to Table 1, the average limit for unfrozen soil is μ = 0.46.

The highest Poisson's ratio values observed at the onset of freezing in laboratory tests by *Frolov* [*1998*] were 0.45 for clay and 0.40 for quartz sand. The latter lower ratio was attributed to very low μ in quartz, but may also be due to undersaturation (see above). We infer, with reference to the available literature and our experience (including never seeing μ < 0.45 in unfrozen saturated soil), that the threshold corresponding to the unfrozen-frozen transition in wet soils of sand to clay grain sizes fits a narrow range of μ = 0.45–0.46.

USE OF POISSON'S RATIO AS A PERMAFROST PROXY: EXPERIMENTAL BACKGROUND

The inferred existence of a critical μ value that marks the transition to the frozen state of water-saturated soil was proven valid by analyzing jointly the results of vertical seismic profiling (VSP) and geotechnical logging of several boreholes in West Siberia.

The VSP and geotechnical measurements were performed in a 220 m deep borehole located at the Urengoi oil-gas-condensate field (Fig. 3). The borehole tapped a talik (a lens of unfrozen rocks in permafrost) within the depths 70–90 m [*Drozdov and Skvortsov, 1998*].

The processed seismic logs showed Poisson's ratios to correlate with grain sizes of frozen soil (Fig. 4) [*Melnikov et al., 2010*], with higher μ in coarser sediments. This correlation agrees with the general trend of unfrozen water content increasing with the content of clay. Some ratios calculated from seismic velocities within the talik fall in the region of μ > 0.46 (yellow strip in Fig. 4), which supports the idea that frozen soil is marked by μ values below the critical range 0.45–0.46.

The possibility of using Poisson's ratio as a permafrost tracer in highly saline clayey soil was further confirmed by VSP results from boreholes at the Marre-Sale monitoring station in the western coast of the Yamal Peninsula [*Melnikov et al., 2010*].

Among others, seismic logs were collected from borehole 14-10 within the Marre-Sale site (Fig. 5) [*Skvortsov et al., 2012*], where drilling stripped a cryopeg (a lens of brine) at the depths 20–23 m. Clay soil within the cryopeg is unfrozen, though being at −4.5 °C, and its Poisson's ratio is μ = 0.46. This is another line of evidence that the values μ = 0.45–0.46 mark the transition between unfrozen and frozen states in wet sand-clay soils.

The 9–11 m depth interval of frozen sand silt with low water contents is worth special attention. Low *P* velocities in this interval are actually caused by the low water content, but may lead to misinterpretation of soil as unfrozen and water-saturated if used as the only seismic criterion. In this case Poisson's ratio is indispensable for the right identification of the frozen state.

Seismic criteria of frozen soil state in surface refraction shooting surveys may be more or less reliable in different permafrost conditions. See for instance the cross sections of three sites where seismic data resolve the permafrost table (Fig. 6).

The site of Kamenny (Russian for *Rocky*) Cape is located in the western shore of the Ob Bay (Fig. 6, *a*). The upper section consists of non-saline coarse- and medium-grained sand. The profile runs across the beach and inner shelf, to the sea depth within 2.5 m. In these conditions, all seismic criteria (velocities, conversion events, and Poisson's ratios) highlight the permafrost table.

The permafrost table in beach non-saline silt and clay silt of the Pechora delta (Fig. 6, *b*) is successfully detectable from wave velocities and Poisson's ratios, but the *PSP* phase is weak. In addition to the permafrost table, the pattern of *P* waves resolves the zone of full saturation.

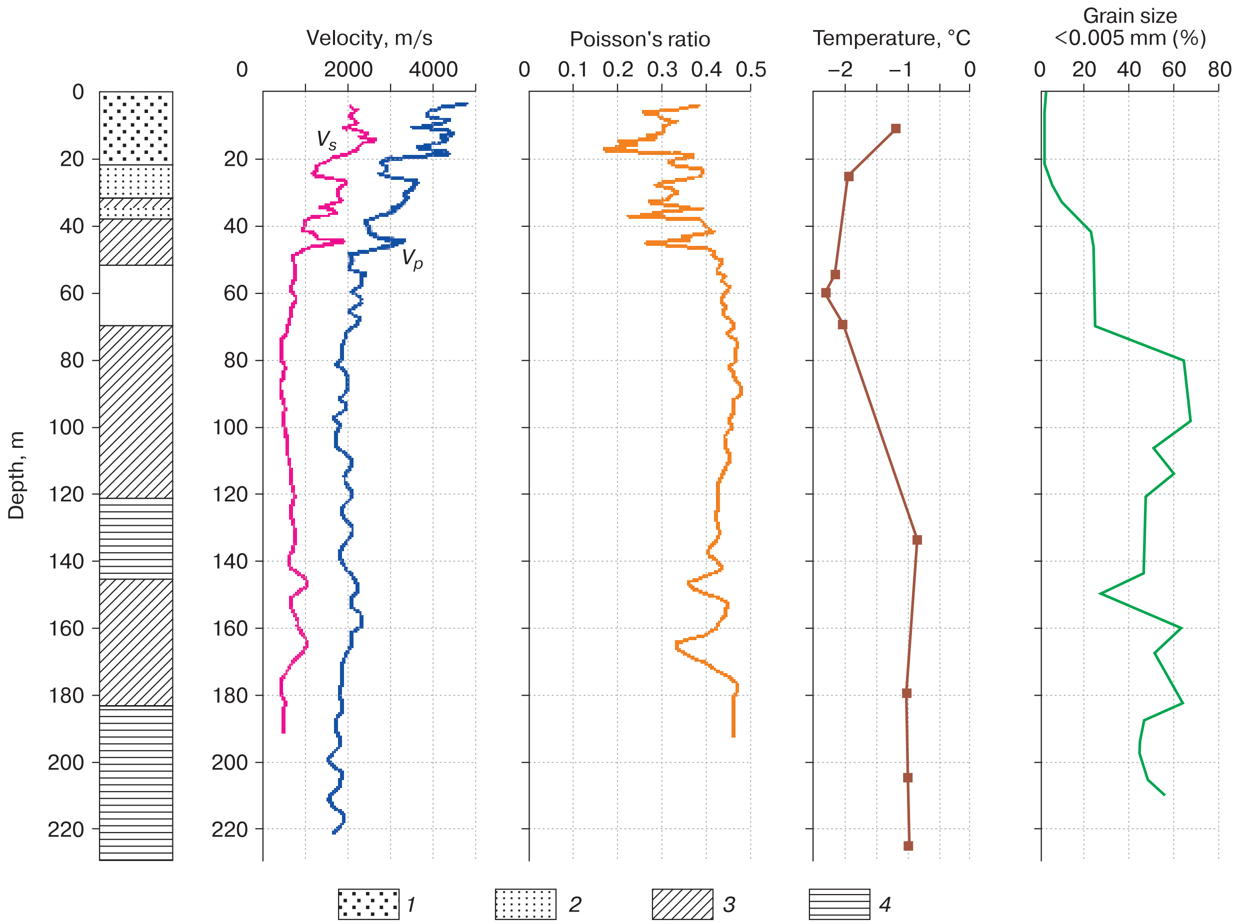

Fig. 3. VSP and geotechnical logs of borehole 1 in EnYakha flood plain, northern Urengoi oil-gas-condensate field.

1 – coarse sand; *2* – silt sand; *3* – silt clay; *4* – clay.

The frozen soil of the Marre-Sale site (Fig. 6, *c*) largely consists of saline plastic clay difficult to identify even in test boreholes. Surface seismic surveys reveal an interface at the depths 1.5–2.0 m, but it is impossible to relate it unambiguously to the permafrost table. The reason is that the same low boundary velocities of compressional (*P*) and horizontally polarized shear (*SH*) waves (1800 and 530 m/s, respectively), in the absence of the *PSP* event, can also mark the top of the saturation zone. In these conditions, Poisson's ratio becomes the key criterion: its high value of $\mu = 0.45$ indicates the presence of clay-rich frozen soil.

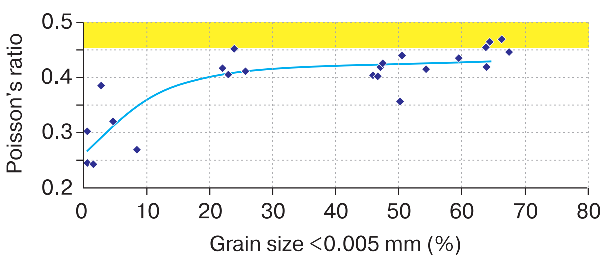

Fig. 4. Poisson's ratio as a function of grain size of frozen soil, from VSP logs in borehole 1 at Urengoi oil-gas-condensate field.

Yellow color shows zone of μ values within a talik.

The reported results show that Poisson's ratios can be used to trace permafrost and, more so, to estimate its sluggishness.

Calculated Poisson's ratios are the most accurate at μ approaching 0.5 [*Savich, 1979*]. At $\mu = 0.46$, the error is within 2 %, or 0.01, which fits the 0.45–0.46 range we suggest as the threshold corresponding to the transition between unfrozen and frozen states of soil.

Thus, Poisson's ratio is an additional reliable criterion for discriminating between unfrozen and frozen soils, especially those rich in plastic clay widespread in permafrost areas.

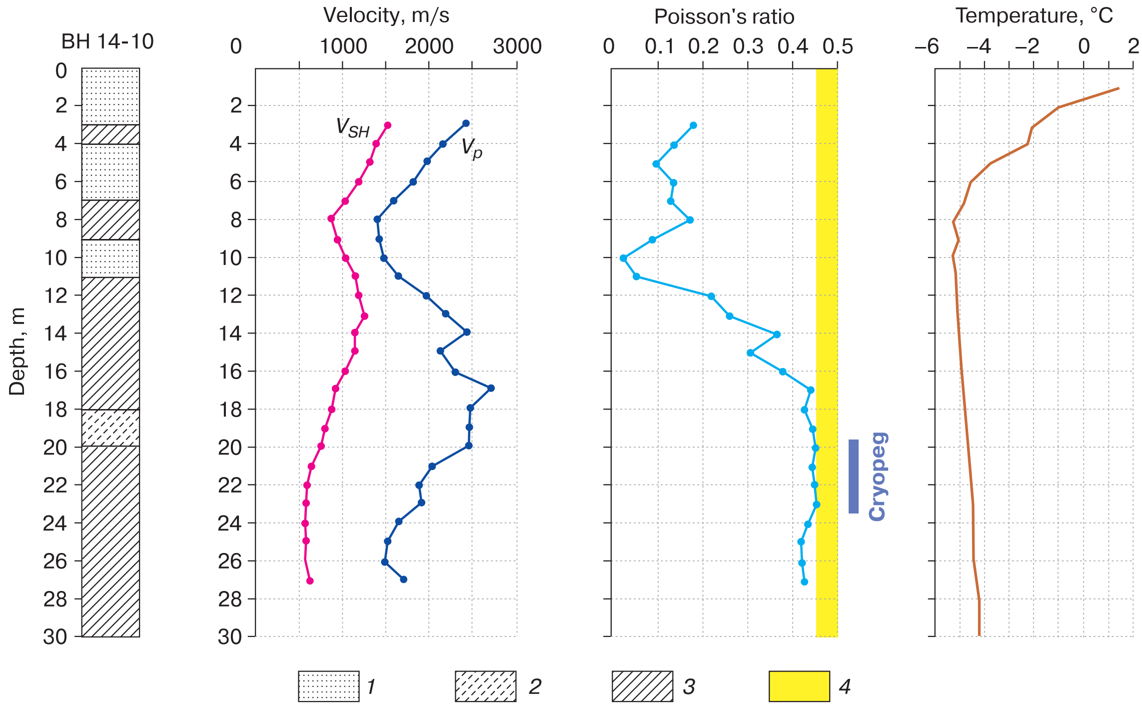

Fig. 5. VSP logs from borehole 14-10 at MarreSale permafrost monitoring site.

1 – sand; *2* – silt clay; *3* – clay; *4* – μ range in unfrozen water-saturated soil. V_p is *P* velocity; V_{SH} is *SH* velocity.

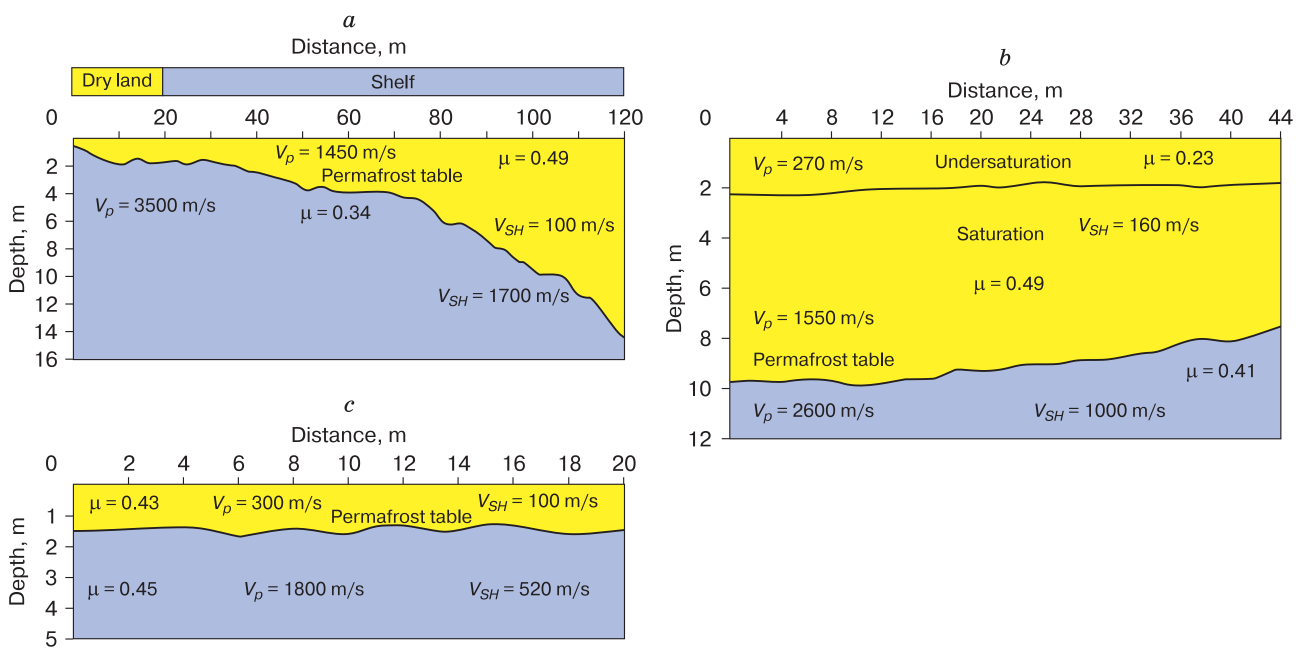

Fig. 6. Permafrost sections of coastal Ob Bay area (*a*), beach in Pechora delta (*b*) and beach in western Yamal (*c*), obtained from *P* and *SH* refractions.

a: Kamennyi Cape Village; *b*: Bolvansky monitoring site; *c*: MarreSale monitoring site.

CONCLUSIONS

The available published evidence and experimental results we collected for years in the areas of Arctic West Siberia and European North allow inferences about the use of Poisson's ratios as a tool to discriminate between unfrozen and frozen soils.

1. The conventional seismic criteria are not always workable as permafrost proxies.

2. We suggest to identify the frozen state of rocks using Poisson's ratio and provide theoretical and experimental grounds for this choice.

3. Experimental results prove that the ratios of $\mu > 0.46$ correspond to unfrozen water-saturated soils of sand to clay grain sizes, irrespective of their composition, temperature, and salinity, while frozen rocks have $\mu < 0.45$. The range 0.45–0.46 is a threshold that marks the transition between the unfrozen and frozen states.

4. The μ values can be lower or higher depending on the amount of unfrozen pore water, which additionally makes Poisson's ratio a proxy of permafrost sluggishness.

5. Being a reliable criterion for identifying permafrost, Poisson's ratio is especially effective in the case of frozen soils rich in plastic clay. Used jointly with other seismic criteria, it can improve the quality of seismic data from permafrost areas.

References

Drozdov, D.S., Skvortsov, A.G., 1998. Engineering-geological features of permafrost from integrated geological and geophysical well-log data (Urengoi oil-gas-condensate field), in: Problems of Geocryology (in Russian), Puschino Science Center, Puschino, pp. 59–61.

Dzhurik, V.I., 1988. Seismic hazard in frozen soil, in: Estimating the Effect of Ground Conditions on Seismic Hazard (in Russian). Nauka, Moscow, pp. 168–183.

Frolov, A.D., 1998. Electric and Elastic Properties of Frozen Ground and Ice (in Russian). Puschino Science Center, Puschino, 515 pp.

Goryainov, N.N. (Ed.), 1992. Seismoacoustics for Hydrogeology and Engineering Geology (in Russian). Nedra, Moscow, 264 pp.

Gurvich, I.I. (Ed.), 1970. Seismic Surveys (in Russian). 2nd Edition, Nedra, Moscow, 552 pp.

Gurvich, I.I., Nomokonov, V.P. (Eds.), 1981. Seismic Surveys. A Handbook for Geophysicists (in Russian). Nedra, Moscow, 464 pp.

Hobson, G.D., 1967. Hammer seismic investigation, Good Spirit Lake area. Pap. Geol. Surv. Can., No. 1, 37–41.

Melnikov, V.P., Skvortsov, A.G., Malkova, G.V., et al., 2010. Seismic studies of frozen ground in Arctic areas. Russian Geology and Geophysics, 51 (1), 134–142.

Neave, K.G., Sellmann, P.V., 1983. Seismic velocities and subsea permafrost in the Beafort Sea, Alaska. Proc., 4th International Conference on Permafrost, Fairbanks, USA, vol. 1, pp. 894–898.

Rogers, J.C., Morack, J.L., 1978. Geophysical investigation of offshore permafrost, Prudhoe Bay, Alaska. Proc., 3rd International Conference on Permafrost, Edmonton, Canada, vol. 1, pp. 560–566.

Sadurtdinov, M.R., Skvortsov, A.G., 2008. Permafrost conditions in the coast of the Pechora Bay, in: Geophysics for Engineering and Mineral Exploration. Proc., 4th International Workshop-2008 (in Russian), Gelendzhik, pp. 2 (On-line version).

Sadurtdinov, M.R., Skvortsov, A.G., Tsarev, A.M., 2009. Shallow-water submarine seismic surveys of shallow subsurface, in: Geophysics for Engineering and Mineral Exploration. Proc. 5th International Workshop, Gelendzhik (On-line version).

Sadurtdinov, M.R., Tsarev, A.M., Dubrovin, V.A., Skvortsov, A.G., 2010. An experience of studying engineering cryological conditions within shallow-water areas in the Yamal Peninsula, in: Integration of Geosciences for New Discoveries. Proc. International Conference & Exhibition, St. Petersburg–2010, St. Petersburg, pp. 2. (On-line version).

Sadurtdinov, M.R., Skvortsov, A.G., Tsarev, A.M., Malkova, G.V., 2012. Permafrost conditions in Kashin Island (Pechora Delta), from seismic profiling data, in: Resources and Risks of Permafrost Areas in a Changing World, Proc., Tenth International Conference on Permafrost, Book of Abstracts, Yekaterinburg, vol. 4/2, pp. 488–489.

Savich, A.I., 1979. Seismoacoustics for Studying Elastic Properties and Deformation in Rocks (in Russian). Nedra, Moscow, 214 pp.

Sedov, B.M., 1988. Seismic Surveys in Permafrost (in Russian). Nauka, Moscow, 180 pp.

Skvortsov, A.G., Tsarev, A.M., Sadurtdinov, M.R., 2011a. Engineering applications of seismic methods in permafrost, in: Proc. 4th Conference of Russian Geocryologists, Moscow, 7–9 June 2011 (in Russian), Universitetskaya Kniga, Moscow, vol. 1, pp. 225–232.

Skvortsov, A.G., Tsarev, A.M., Sadurtdinov, M.R., 2011b. Specificity of seismic studies in frozen ground. Kriosfera Zemli, XV (4), 110–113.

Skvortsov, A.G., Dubrovin, V.A., Sadurtdinov, M.R., Tsarev, A.M., 2012. Results of seismic surveys at the Marre-Sale permafrost monitoring station (Yamal), in: Resources and Risks of Permafrost Areas in a Changing World, Proc., Tenth International Conference on Permafrost (TICOP), Pechatnik, Tyumen', vol. 5, pp. 289–290.

Voronkov, O.K., 2009. Seismic Surveys for Engineering Applications in Permafrost: Studies of Structure and Properties of Frozen and Unfrozen Rocks (in Russian). B.E. Vedeneev Izd. OAO VNIIG, St. Petersburg, 401 pp.

Voronkov, O.K., Motorin, G.A., Mikhailovsky, G.V., Kuntsevich, S.P., 1997. Seismic-geological classification of permafrost soils. Kriosfera Zemli, I (3), 47–54.

Zykov, Yu.D., 2007. Geophysical Methods for Permafrost Studies. A Manual (in Russian), Moscow University Press, Moscow, Moscow, 272 pp.

Received
October 30, 2013