

A review of the nature and geophysical studies of the thick permafrost in Siberia: Relevance to exploration on Mars

Anatoly D. Frolov

Scientific Council on Earth Cryology, Russian Academy of Sciences, Moscow, Russia

Received 26 June 2002; revised 21 October 2002; accepted 30 January 2003; published 29 April 2003.

[1] In this paper we discuss the best Siberian permafrost analog of the Martian cryosphere in connection with the design of deep-sounding geophysical methods for the detection of liquid water beneath frozen formations on Mars. The peculiarities of the terrestrial cryolithozone and its unique thickness (up to 1.5 km) in the region under consideration (Western Yakutia) are described. The Russian experience in detecting the lower boundary of permafrost, by various geophysical methods, and suggestions regarding the most effective methods for the deep sounding of the Martian cryosphere are also briefly discussed. *INDEX TERMS*: 1823 Hydrology: Frozen ground; 0925 Exploration Geophysics: Magnetic and electrical methods; *KEYWORDS*: Permafrost, origin, thickness, geophysical studies

Citation: Frolov, A. D., A review of the nature and geophysical studies of the thick permafrost in Siberia: Relevance to exploration on Mars, *J. Geophys. Res.*, 108(E4), 8039, doi:10.1029/2002JE001881, 2003.

1. Introduction

[2] Systematic exploration of the Martian cryosphere using automated orbiters, landers, rovers and even human explorers requires careful assessment of the presumed approaches and geophysical methods. To optimise the chances of success, this assessment should be based on the experience gained from conducting similar studies on Earth under conditions analogous to those expected on Mars. According to common concepts [e.g., Clifford, 1993; Carr, 1996], the mean annual temperature of the Martian surface varies from ~ 220 K at the equator to ~ 155 K at the poles. The minimum winter temperature in the polar regions is about 140 K, while the summer maximum in the equatorial zone is ~ 295 K. These extreme climatic conditions are believed to have produced a cryolithozone which is estimated to be ~ 2 – 3 km thick in the equatorial region and up to 6–13 km thick at the poles.

[3] Environmentally, the closest terrestrial analog of the Martian cryolithozone is found in the inner mountain regions of Antarctica, where there is essentially no precipitation and the mean annual temperature is about 218 K. It is here, in the vicinity of the Russian Vostok research station, that the coldest spot on Earth is located. The lowest winter temperature ever registered there was equal to 184 K (July 1983) and the highest summer temperature was 259.4 K (January 1974). There are reasons to believe that some interior mountain areas, which have never been covered with an ice sheet, feature the oldest permafrost on the Earth (about 20 million years old), with a potential thickness in excess of 3 km [Vtyurin, 1998]. But the studies of this permafrost are still at their earliest stage, due to the remoteness and general inaccessibility of this region.

[4] A better studied (but somewhat poorer) analog to the Martian cryolithozone, is the cryolithozone of the central part of Western Yakutia, which lies in the northern part of Central Siberia. The climate of this region is extremely continental. The eastern part is the most dry (total annual precipitation amounts to ~ 200 mm) and cold (mean annual air temperature ~ 262 K). The coldest spot in the Northern Hemisphere is located just eastward in the Verkhoyansk and Oimyakon region. The mean annual temperature here is about 256 K and winter temperatures sink occasionally to 203 K. The cryolithozone here is often more than 1 km thick and has a maximum known thickness ~ 1.5 km. Long-term geocryological studies in the region have revealed many of the principal features of the cryolithozone's thickness and structure [Kondratieva, 1998]. This region is the only terrestrial analog of the Martian cryosphere that has been relatively well explored.

[5] In the section that follows, I discuss special features of this unique area of the cryolithozone, the Russian experience in the determining its lower boundary by using geophysical methods, and make some recommendations for the exploration of Mars based on these data.

2. Main Factors Controlling the Thickness of the Cryolithozone in the Western Yakutia Region of Siberia

[6] It is well known that the thickness of permafrost is controlled by zonal, regional and local factors, and their changes during the Quaternary, and in the Holocene in particular. The main zonal factor is the extremely cold continental climate that persisted through the whole of the Quaternary. It was distinguished by long (more than 200 day) winters with constantly low temperatures (from ~ 225 – 250 K, on average). This caused a progressive increase in permafrost thickness. The alternating episodes

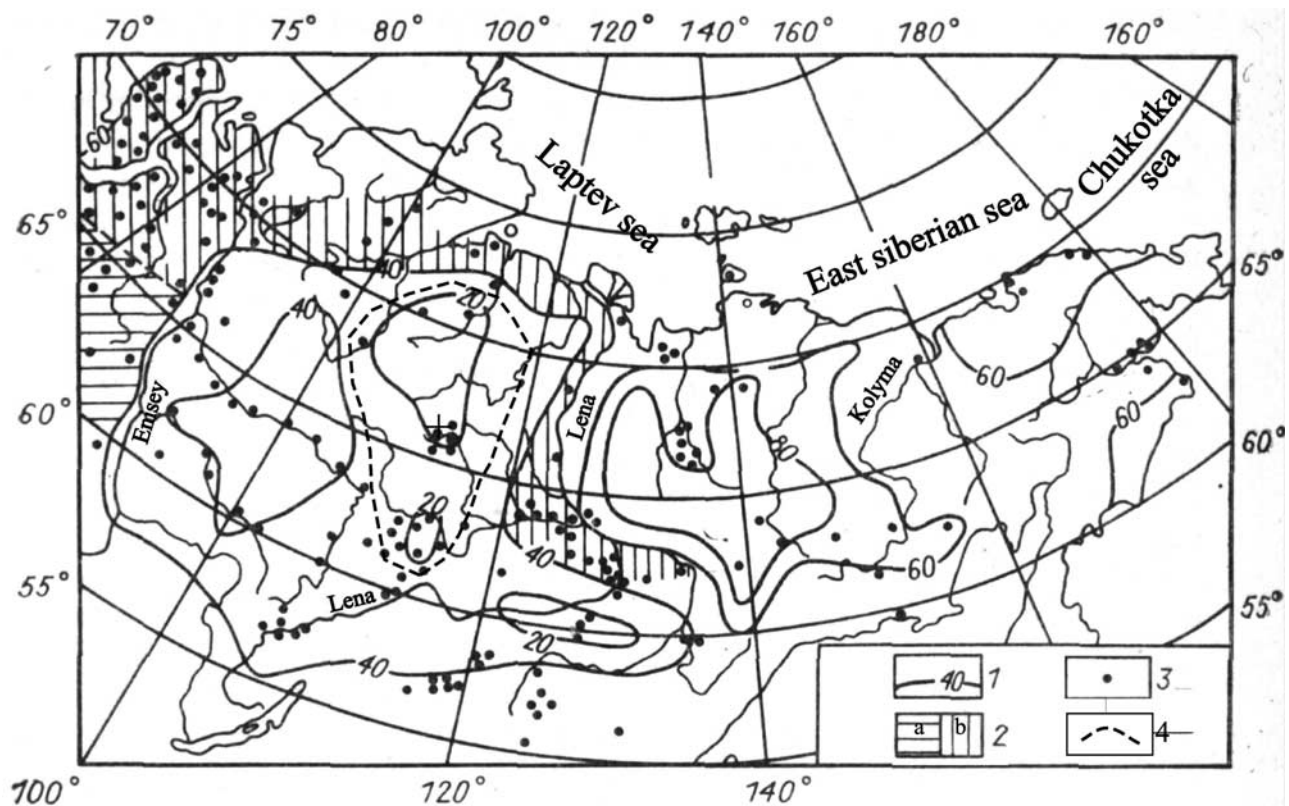


Figure 1. Map of the heat flow distribution in Siberia, by V. T. Balobaev and V. N. Devyatkin [Devyatkin, 1994]. 1, isolines of the heat flow density (mW/m^2); 2, heat flow in the nonstationary cryolithozonal: $Q^- = 0$ (a) and $Q^- < Q^+$ (b); 3, points of the heat flow measurements; 4, approximate disposition of the area with the most deep-rooted cryolithozone from Figure 2; cross is the location of boreholes from Figure 3.

of warming and cooling associated with the major glaciations did not tangibly affect the cryolithozone thickness in this region, although some fluctuations may have occurred.

[7] Both regional geothermal heat flow and geological structure are of paramount importance among the factors affecting cryolithozone formation. Of these, heat flow has the lesser effect, while the pre-existing permafrost thickness has the greater (all other factors being the same).

[8] An important factor is the relationship between the heat flow values in thawed (Q^+) and frozen (Q^-) formations at the base of the permafrost. The state of permafrost is stationary in the case where the two heat flow values are approximately equal ($Q^+ \approx Q^-$), and nonstationary when they are unequal. In the latter case, geothermal measurements would reveal this thermal state only if boreholes could penetrate the whole permafrost thickness and at least 200 m below it. To prove the nonstationary state, heat flow should be measured both above and below the permafrost lower boundary. Two principal types of unsteady permafrost are distinguished: aggrading permafrost (increasing in thickness) for conditions where $Q^+ < Q^-$, and degrading where $Q^+ > Q^-$ (and also in the special case of $Q^- \approx 0$). Many difficulties arise (lateral inhomogeneity of the thermal field, great distortions of permafrost temperature during borehole drilling, etc.) when we try to perform precise and reliable measurements of temperature in boreholes drilled through frozen formations, especially in nonstationary ones. The

experience of long-term geothermal studies in the cryolithozone has permitted us to gain an understanding of these difficulties and to develop approaches and measurement procedures for successively overcoming them [Devyatkin, 1993].

[9] As evident from a review of the data available on the geothermal heat flow distribution in Siberia (Figure 1) and from long-term geocryological investigations conducted over the northern part of Central Siberia (Figure 2), there is a good correspondence between the area of lowest heat flow ($\sim 13\text{--}20 \text{ mW}/\text{m}^2$) and the region of maximum permafrost thickness (i.e., compare Figures 1 and 2). The most extensively studied area is the Daldyn-Alakit diamond-bearing region in Western Yakutia (including the southern slope of the Anabar anticline and the northern part of Vilyuy plateau). The local permafrost thickness, as established by drilling and temperature measurements, is up to 1100 m in the region between the Lena, Vilyuy, Kaduy, and Khatanga rivers. But at the upper reaches of the river Markha, temperature measurements in two deep boreholes [Devyatkin, 1993] showed that the base of cryolithozone reaches a depth of $\sim 1500 \text{ m}$ (Figure 3). This region is part of a core area that experienced a deep continuous cooling of the lithosphere through the Late Neogene's - Quaternary. Hence the permafrost is about 2 million years old there. However, the local cryolithozone has a rather complicated structure, with cryopegs found both under and within

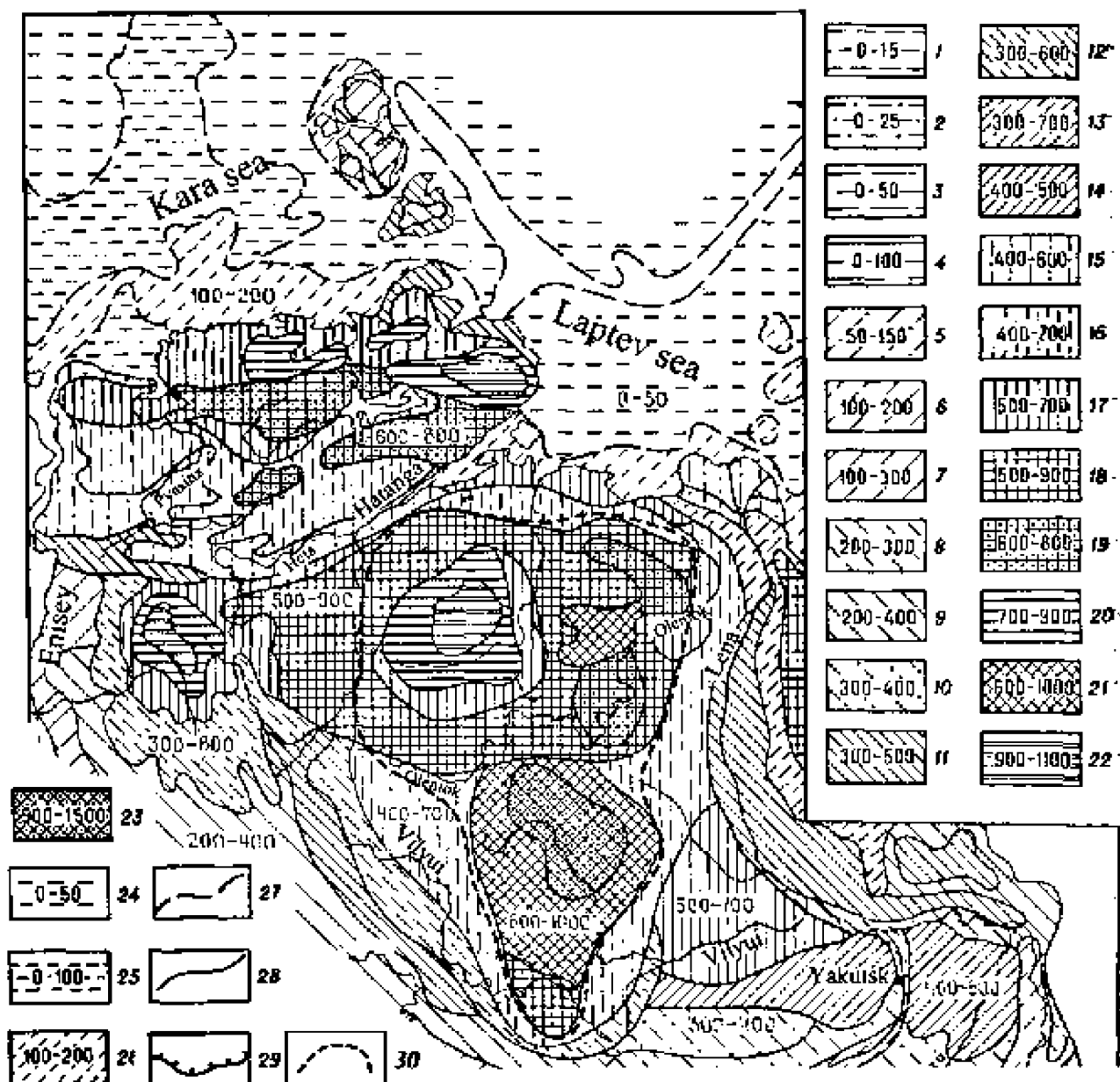


Figure 2. Map of the generalized cryolithozone thickness in the northern part (approximately between 85°–130°E longitude and 62°–75°N latitude) of Central Siberia [Kondratieva, 1989]. 1–26, various cryolithozone thickness (m); boundaries of the submarine (27) and subaerial (28) types of cryolithozone; 29 is the area with the most deep-rooted cryolithozonal.

frozen formations. The pore solutions, which are often of chloride composition here, show variable concentration up to 150–200 g/l. Heat flows are usually $Q^- \approx Q^+$, so the base of the local cryolithozone may be regarded as stationary (see Figure 1). Geologically, the northern part of Central Siberia is a rather inactive block of the Siberian platform. It consists of old Palaeozoic saliferous and calcareous formations (limestones, dolomites) that possess a high thermal conductivity. The presence of soluble salts causes cryopeg development. Other important local factors, that can influence the frozen formation thickness and its lateral changeability, are variations in ice content, salinity,

fissure density, lithology, tectonic events, and the local surface heat balance.

3. Determination of the Permafrost Lower Boundary Using Geophysical Methods

[10] Among the numerous geocryological problems that can be solved with the use of geophysical methods, the determination of the permafrost lower boundary is one of the most difficult and less studied. This may be attributed, firstly, to the heterogeneous and varying electrical and mechanical properties of the given frozen formation, and to the general

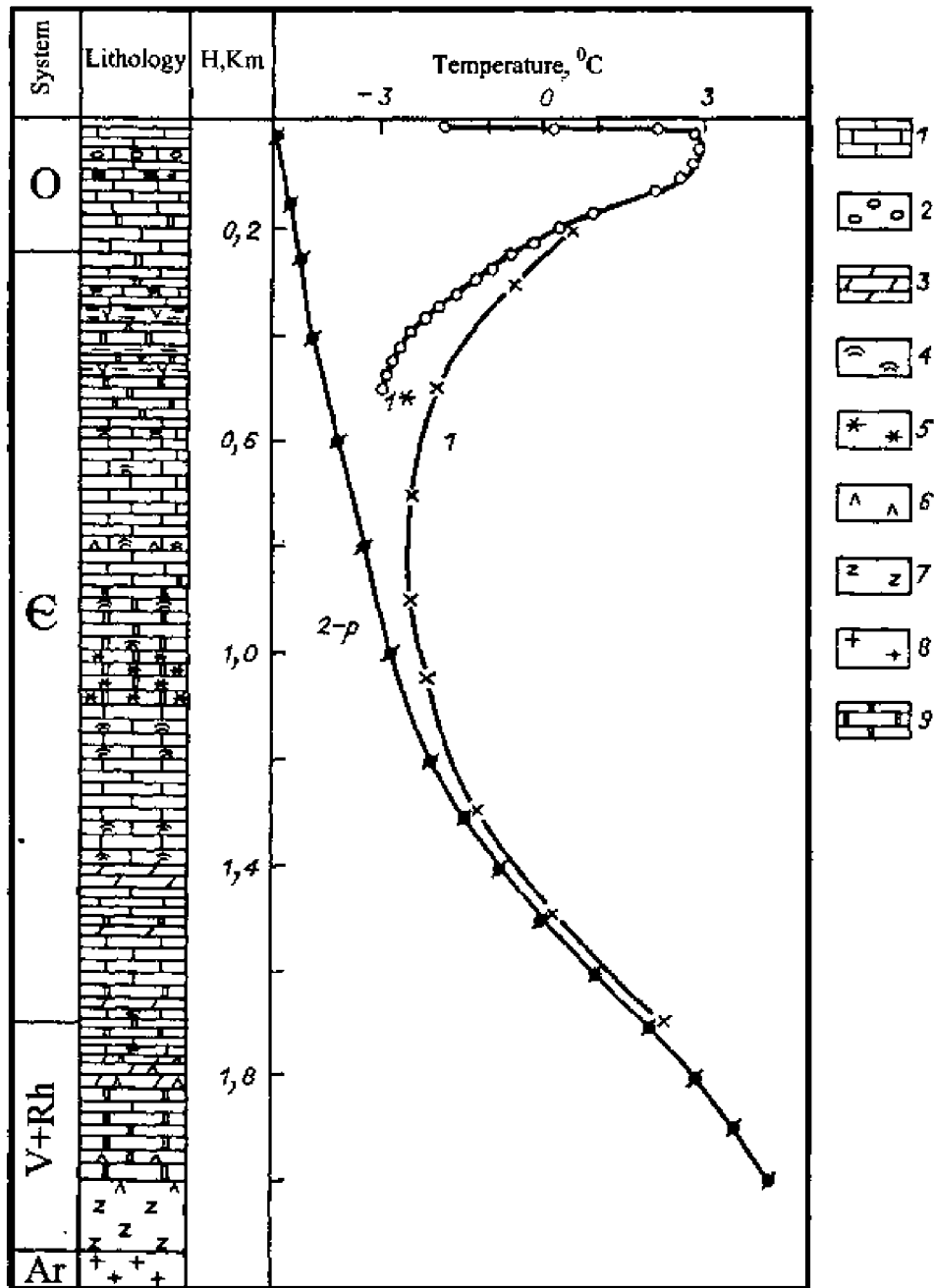


Figure 3. Temperature in two deep boreholes at the site Markhinsky (Western Yakutia, near North Polar circle, approximately 111°E long. and 66°N lat.) where the greatest depth on Earth to the lower boundary of the cryolithozone has been measured (~1.5 km). 1–6, various limestones, contained: pebbles, water-plants, quartz, anhydrite; 7, gabbro-diorit; 8, intrusive rocks; 9, dolomite; 1 and 1*, results of temperature measurements in the same borehole in February 1964 and August 1971, 2-p curve by measurements in June 1965 and August 1981 in one other borehole then 1 but at this same area.

characteristics of electromagnetic and elastic wave propagation within permafrost, which differ greatly from the more regular properties known for corresponding unfrozen formations [Frolov, 1998]. Secondly, it may be due to the fact that the lower boundary of the permafrost does not occur as a sharp and flat plane - a consequence of the spatial variability (both vertical and lateral) of physical properties, which is frequently observed in permafrost areas. Thirdly, the dispo-

sition of the permafrost lower boundary is generally not of practical interest in comparison to most other problems of engineering, construction, mining, etc., which typically relate to the upper layers of the cryolithozone. These and some other reasons [Frolov, 1998] explain why there is only a limited amount of experience in determining the permafrost lower boundary by either geophysical sounding (from the surface) or by borehole logging.

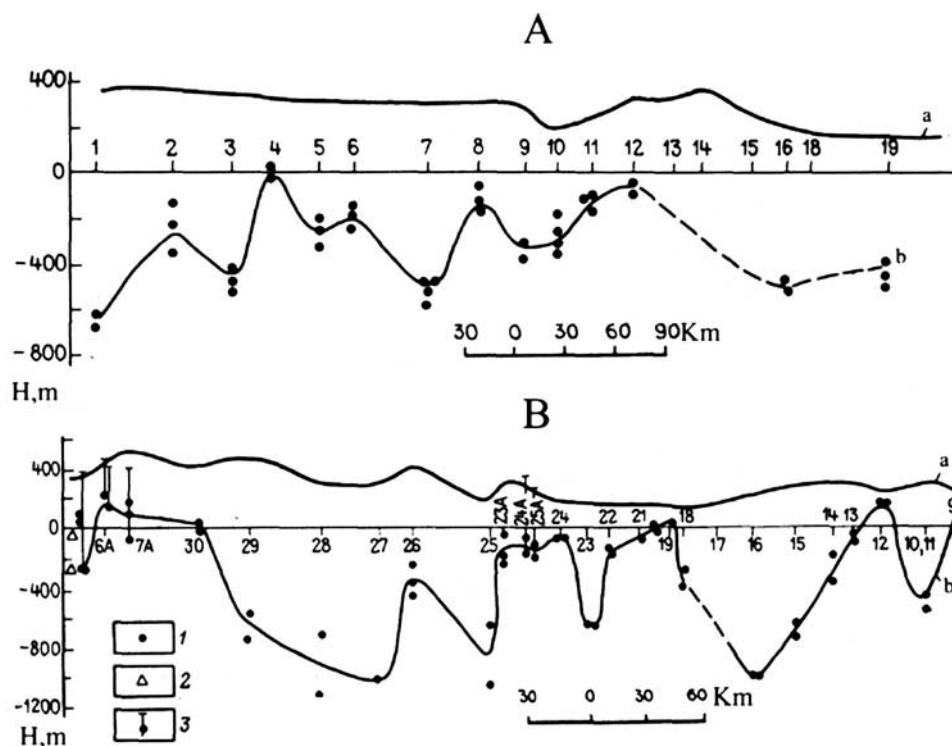


Figure 4. Examples of the results of geophysical deep soundings of cryolithozonal by VES using direct current. 1, points of disposition of the permafrost lower boundary; a, relief; b, generalized position of lower boundary of cryolithozone in the same part of Western Yakutia as Figure 3.

[11] However, because of the record thickness of permafrost discovered in the Anabar region, many soundings of the lower boundary have been performed using vertical electric sounding (VES) by direct or quasi direct current [Yakupov and Kalinin, 1989]. Figure 4 displays some typical results. As seen from the profiles, this region is characterized by great changes in the permafrost thickness from one site to another. In the author's opinion, it may be due to local changes in the mineralization of subpermafrost cryopegs (concentration of pore solutions vary from 50 to 200 g/l and more). The permafrost thickness may also be considerably reduced at large fault zones because the heat flow there may be increased due to ascending flows of deep water. Deviations in permafrost thickness may also be attributed to temporal changes in heat exchange during the Quaternary. In any case, variations in permafrost thickness within comparatively small distances (a few tens of kilometres) have been confirmed for this region by geothermal studies in boreholes [Devyatkin, 1993]. Considerable increases in the permafrost thickness and lower heat flows ($\sim 13\text{--}19\text{ mW/m}^2$) have also been established within and near kimberlitic pipes.

[12] Besides VES, other geophysical methods have been used in the mapping of thick permafrost — primarily transient electromagnetic soundings (TEMS) and, less frequently, seismic sounding and well logging. Figure 5 gives an example of a TEMS investigation that was successfully employed to obtain the thickness of clastic deposits with high ice content. The measurements were performed with coincident $100 \times 100\text{ m}$ loops centered 1 km apart along the profile. To interpret the results, the

parameters S_T , H_T and ρ_T , (plate conductance, depth and resistivity) were calculated and used for every sounding [Nim et al., 1994]. As seen in Figure 5, the TEMS data agrees quite well with the results of a subsequent gravimetric survey.

[13] Seismic surveys often meet with difficulties resulting from a complicated pattern of wave fields within the cryolithozone (due to distortions of seismic rays and time-distance curve shape, large discrepancies between mean and effective wave velocities, etc. [Frolov, 1998]). Only occasionally, under favorable conditions, may the position of the permafrost base be located using reflected or refracted waves [Akimov et al., 1979; Brent and Harrison, 1998]. Among borehole geophysical methods, the most efficient for finding the lower permafrost boundary has been PS (spontaneous polarization) logging [Akimov et al., 1979].

4. Geophysical Methods Suitable for Martian Cryosphere Studies

[14] Recent works [e.g., Kuzmin and Zabalueva, 1998] indicate a high probability of unfrozen solutions in the Martian cryosphere. It seems possible therefore, that cryopegs may exist both within and under frozen formations and occupy a sizable portion of its predicted cryosphere thickness. If so, the situation may be like that found in the northern part of the Central Siberian cryolithozone, where frozen formations are inhomogeneous in structure and possess an uneven, nonplanar, low-contrast lower boundary. This potential variant of Martian cryosphere structure

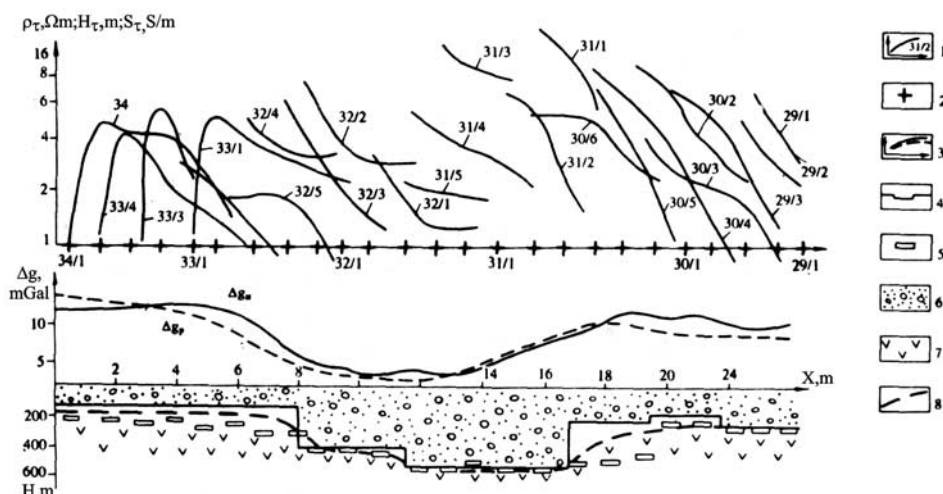


Figure 5. Example of the results of transient electromagnetic soundings (TEMS) of permafrost in Eastern Siberia (longitudinal conductance, effective depth and apparent resistivity) jointly with gravimetric survey data: 1, curves according to the TEMS data; 2, an origin of coordinate of TEMS point ($\rho = 10^3 \Omega\text{m}$, $t = 1\text{ms}$); 3, curves of Δg (dotted line, calculated values); 4, interpretation gravimetric model; 5, depth according to TEMS interpretation; 6, ice reached frozen sandy-clayey soils; 7, volcanic rocks; 8, supposed boundary.

would greatly complicate sounding investigations aimed at the identification of the permafrost base (at depths of 3–5 km) and any subpermafrost groundwater that may lie beneath.

[15] Under such conditions, the most suitable geophysical methods for the deep sounding of the Martian crust would be low frequency electromagnetic pulse methods (utilizing magnetic exciting and receiving loop dipoles). It is now possible to conduct TEMS investigations with precise measurements of magnetic components with quantum magnetometers. Other related techniques may also be of use. For these methods one should consider the highly peculiar electrical characteristics of frozen soils, especially the saline ones at low frequencies, which exhibit strong and complicated frequency and temperature dispersion of the complex dielectric permittivity [Frolov, 1998] and probably a superparamagnetic effect as well. Some seismic techniques may also be of use for deep soundings of the Martian cryosphere [Apraia et al., 2001]. But in this case, as discussed above, geophysicists must take into account the features of seismic-cryological cross-sections and particularities of wave propagation parameters established for terrestrial frozen soils and ice [Frolov, 1998].

[16] Finally, let us take a brief look at the possibilities of ground penetrating radar (GPR) or radio echo sounding (RES) use for a deep sounding of the Martian cryosphere, which was the subject of many ardent discussions during the Conference on the Geophysical Detection of Subsurface Water on Mars that was held in Houston, August 2001. Extrapolating from the experience in Russia and in the United States concerning the use of RES in the terrestrial cryolithozone, it appears extraordinarily unlikely that this method will prove useful in determining the great ($\sim\text{km}$) thickness of frozen ground on Mars. Radar soundings have determined Antarctic cold glacier thicknesses exceeding 3 km and subpolar temperate and warm glaciers

to a depth $\sim 0.5\text{--}0.7$ km. But contrary to freshwater ice, frozen soils and fissured rocks are considerably less homogeneous. Within frozen formations, variations in constitutional ice and unfrozen liquid phase content, soil granulometric and mineralogical composition, cryotexture, etc., can produce strong scattering and absorption, resulting in significant radio wave energy losses. Laboratory and field data on radio wave propagation velocity and absorption coefficient (in the range of 1 to 100 MHz) obtained for frozen soils of different composition and temperature [Frolov, 1998] show that even under the most favourable conditions (frozen homogeneous nonsaline sands at 258–263 K) the depth of radar sounding may be, at most, $\sim 100\text{--}150$ m — an estimate that assumes a frequency range of 1–10 MHz, the use of the most powerful and modern equipment with measurements of soil electric and magnetic characteristics, aperture synthesis, and special signal filtering and processing. Indeed, the best sounding performance achieved so far in investigations of terrestrial permafrost is that of Arcone et al [2002], who reached a depth of ~ 80 m in the Dry Valleys of the Antarctic. Elsewhere, in frozen and slightly saline sandy-clayey soils, the maximum sounding depth does not exceed ~ 30 m and, in more saline clayey deposits, the maximum depth may not exceed a few meters. Therefore, the practical application of GPR or RES on Mars may be limited to studies of only the shallow subsurface. Even in this case, to interpret the data with any confidence will require in situ measurements of the effective dielectric permittivity and electrical conductivity of the regolith (in the range of sounding frequencies that will be used), as these properties may vary noticeably from one site to another and may differ from values measured in samples obtained at other landing sites. In Russia, special equipment and techniques have been developed to conduct such radio wave measurements in boreholes [Istratov and Frolov, 2003].

5. Conclusions

[17] The northern part of Central Siberia (Western Yakutia) is a unique region of the terrestrial cryolithozone that may be one of the best and most accessible analogs of the Martian cryosphere. It would be worthwhile to use this region as a proving ground to test and certify any geophysical equipment and techniques designed to study the cryosphere of Mars.

[18] The most suitable geophysical methods to detect subpermafrost liquid water on Mars are low frequency electromagnetic and pulse methods (using transient processes) as well as some kinds of seismic methods. Based on terrestrial experience, the use GPR is likely to provide information only on the characteristics of the upper part (depth $\leq 100\text{--}150$ m) of the Martian cryosphere.

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A. D. Frolov, Scientific Council on Earth Cryology, Russian Academy of Sciences, Fersman Street 11, Moscow, 117312, Russia. (ipquis@redline.ru)