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METHODS FOR CRYOSPHERE RESEARCH

RADIO-ECHO SOUNDING AND REFLECTION SEISMIC SURVEYS IN THE PIONERSKOE SUBGLACIAL LAKE AREA, EAST ANTARCTICA

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Radio-echo sounding and reflection seismic profiles have been collected in the area of Pionerskoe Subglacial Lake in East Antarctica during the austral summer field seasons of 2003–2006. The surveys were run by the Polar Marine Geosurvey Expedition with the Russian Antarctic Expedition and aimed at studying the subice surface topography and subglacial lakes. The ice thickness in the area varies from 1450 to 2450 m, and the bedrock elevations are between 300 and 1300 meters. A rose diagram based on the bedrock grid indicates six principal directions of landforms: 65–245°, 10–190°, 30–210°, 115–295°, 145–325° and 160–340°. According to refelction data, lake Pionerskoe is about 30 m deep and has ~300 m thick sediments.

Radio-echo sounding, reflection profiling, Pionerskoe Subglacial Lake, East Antarctica

INTRODUCTION

Systematic Russian studies of Antarctica began with launching the Mirny Observatory on 13 February 1956 on the Davis Sea coast. Early in the history of observations, scientific data were collected along logistic traverse routes. The first traverse started on 2 April 1956, from the Mirny station inland, to establish the first Soviet station in the interior of Antarctica, called *Pionerskaya*. The traverse was performed under the leadership of *Mikhail Mikhailovich Somov*, head of the First Soviet Antarctic Expedition; *Alexandre Mikhailovich Gusev* took on as head of the Pionerskaya station after 22 April. The traverse finished on 4 May 1956 having reached the point 370 km away from the coast, where the station was set up at 69°44,785′ S and 95°32,197′ E, according to the field situation. The station was opened on 27 May 1956, by raising the USSR national flag [*Tauber and Dolgin, 1959*], and was abandoned on 15 January 1959; currently it is fully buried under snow (Fig. 1, *a*).

Since that time on, multiple traverses as part of glaciological, geophysical, and other programs provided details of the ice sheet structure along regional profiles through the Pionerskaya station, as well as maps of ice thickness and bedrock elevations [*Tolstikov, 1966*]. Geophysical surveys for the structure of the ice sheet and the subice surface topography were completed in the early 1980-s [*Savatyugin and Preobrazhenskaya, 2000*] and resumed only two decades later.

Fig. 1. Pionerskaya station and Vityaz mobile geophysical laboratory.
a: photograph by A.A. Ekaykin, March 2005; *b*: photograph by S.V. Popov.

METHODS AND INSTRUMENTS

The Polar Marine Geosurvey Expedition, jointly with the Russian Antarctic Expedition (RAE), resumed scientific traverses in field season 44 (1998/99), after a long gap, to study the ice and subice structure by radio-echo soundings (RES). The work was inspired by the discovery of subglacial lake Vostok [*Ridley et al., 1993; Kapitsa et al., 1996*] and was originally confined to the lake limits. Later, since field season 49 (2003/04), the study territory was extended to the whole band between the Mirny and Vostok stations, where several traverses were undertaken [*Popov et al., 2007*].

The interest to the Pionerskaya station area was rekindled after the 2003/04 RAE campaign had revealed a subglacial water cavity (a lake) right beneath the site, within a ~2 km long profile segment along the traverse route. Ground-based RES surveys continued during field season 50 (2004/05), when eight profiles of a 29.9 km total length were collected. However, that survey failed to complete the task because the lake turned out to exceed its expected size [*Popov and Chernoglazov, 2006*]. The lake shape was constrained to a high resolution during RAE season 51 (2005/06) with a 17 × 22 km 2D network of profiles spaced at 2 km (Fig. 2) [*Popov et al., 2007; Popov and Masolov, 2007*]. The obtained evidence was used for reference to shoot one reflection profile with an optimal source-receiver configuration in season 53

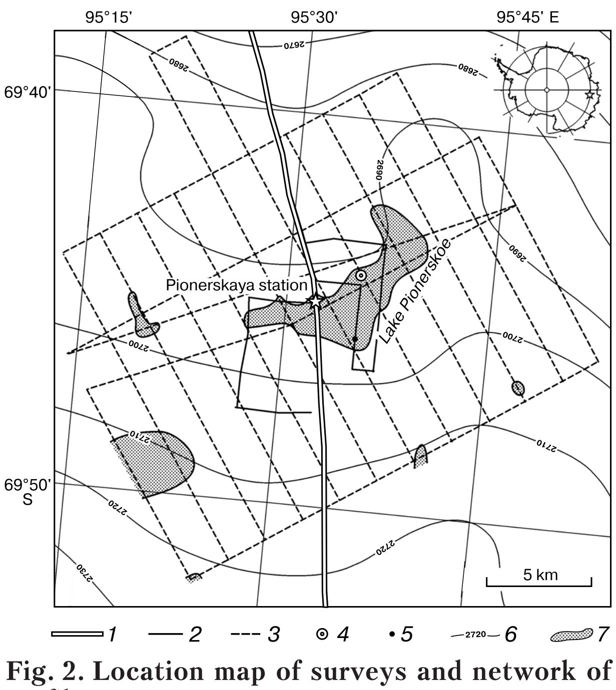

Fig. 2. Location map of surveys and network of profiles.

1 – RES line collected during season 49 along Mirny–Vostok traverse route; *2* – routes of season 50; *3* – routes of season 51; *4* – shot point; *5* – receiver point; *6* – elevation contour lines, m, spacing 10 m [*Rémy et al., 1999*]; *7* – subglacial lakes.

(2007/08), in order to estimate the lake depth and the thickness of sediments, if any.

The data were acquired with the RES-60-98 ice radar system, which was designed specially for ground-based radio-echo surveys in the area of lake Vostok and mounted inside the *Vityaz* mobile geophysical laboratory (Fig. 1, *b*). It was a 60 MHz ice radar with pulse repetition frequency 600 Hz, pulse length 0.6 μs, peak pulse power 60 kW, and dynamic range 180 Db; the reflected signals sampled at period 50 ns and rate 0.5 Hz were digitized by a 12 bit ADC. The shots and receivers were positioned with GPS [*Popov et al., 2001*], to an accuracy about 1 m relative to the design location. The elevation was estimated by satellite altimetry [*Rémy et al., 1999*]. Average survey speed was about 5 km/hr, corresponding to a receiver spacing about 3 m.

The seismic reflection profile was shot in late February 2008 when the traverse moved back from Vostok to the Progress station. The surveys followed the methods used to study Vostok subglacial lake, as the objective was the same [*Popkov et al., 1998, 1999; Masolov et al., 2006; Popov et al., 2007*]. Acoustic waves excited by detonation along two lines (40 g/m, 50 m long) placed on the snow surface were received by a 12-channel streamer of vertical geophones SV-20, with a ~3010 m offset to the first channel (Fig. 2).

RESULTS

Ice thickness and subice surface topography

Ice thickness was estimated from data collected in three field seasons. Times were converted to depths assuming radio-wave propagation in the ice sheet at 168 m/μs on average. The same velocity of electromagnetic waves, according to the data for the Antarctic ice sheet (Fig. 1 in [*Popov et al., 2003*]), was assumed in processing all records acquired during traverses between the Mirny and Vostok stations. The ice thickness (Fig. 3) varies approximately from 1450 to 2450 m, being the greatest in the valley which accommodates Pionerskoe lake and the smallest at the top of the Golitsyn subgalcial mountains. The ice thickness variations are due uniquely to the subglacial surface topography (Fig. 4).

The ~300 m deep NE-striking flat-bottomed (U-shaped) Pionerskaya valley is the dominant subglacial landform in the area. Its floor lies at an elevation about 400 m a.s.l., and the sides slope at more than 400 m/km (22°). The geometry of its transversal profile approaches a 12 × 9 km triangle. In the west, the valley forks into 1.5 to 3 km wide arms. The structure remains unconstrained, and its length is unknown.

There are four subglacial water cavities within the valley, lake Pionerskoye being the largest one. The flat valley floor, with slopes no more than 2°, makes thinking that the lakes are as shallow as a few tens of meters; the inference has been proven valid by further seismic surveys.

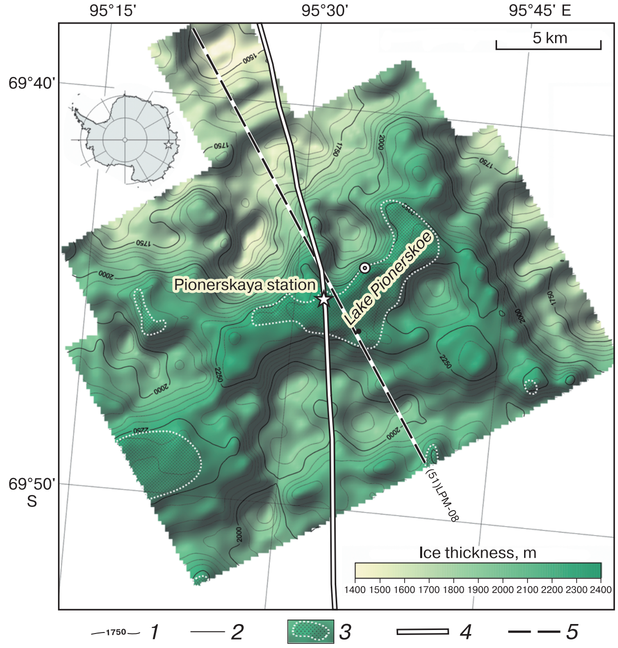

Fig. 3. Ice thickness in the area of Pionerskoe subglacial lake.

Ice thickness contour lines, m: *1* – main ice base contours, at 250 m spacing; *2* – additional ice base contours, spacing 50 m; *3* – subglacial lakes; *4* – Mirny–Vostok traverse route; *5* – profile (51)LPM-08.

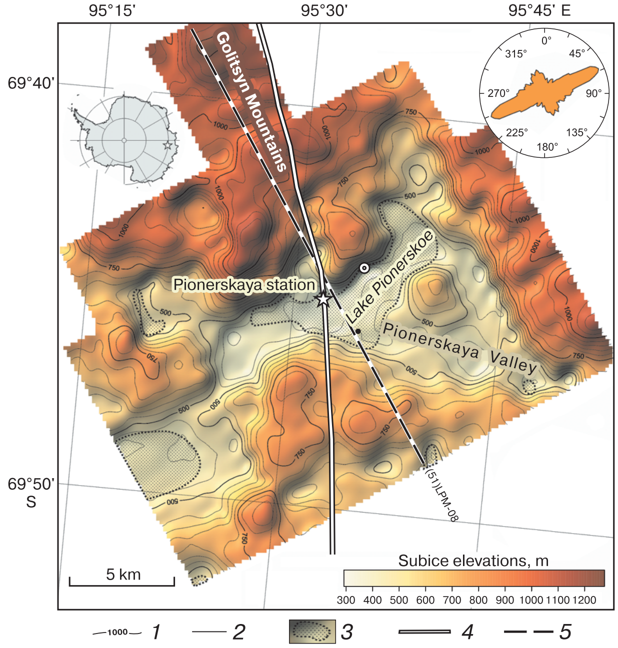

Fig. 4. Subglacial surface structure in the area of lake Pionerskoe.

Elevation contour lines, m: *1* – main elevation contours, at 250 m spacing; *2* – additional elevation contours, spacing 50 m; *3* – subglacial lakes; *4* – Mirny–Vostok traverse route; *5* – profile (51)LPM-08. Inset shows rose diagram of principal orientations of landforms.

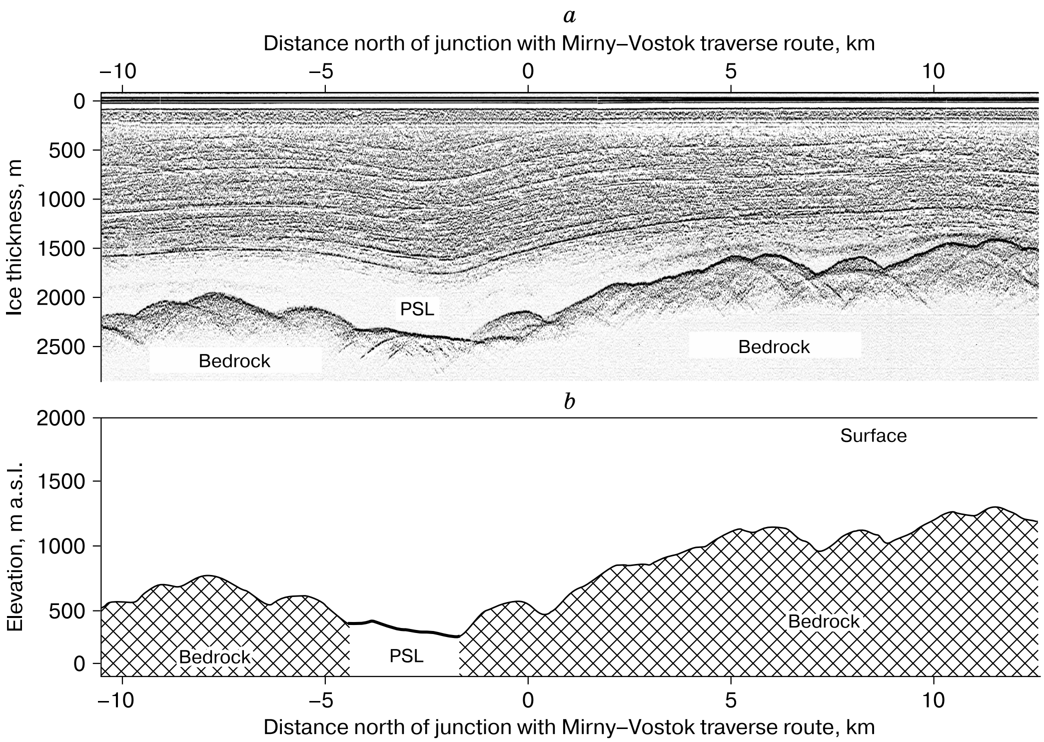

Fig. 5. Geophysical cross sections along profile (51)LPM-08.

a: RES time section; *b*: model of ice sheet. PSL is Pionerskoe subglacial lake.

The Pionerskaya valley has mountainous borders. A 3 × 3 km dome-shaped uplift rises about 200 m in the valley eastern part and flanks the lake in the northwest. Steep slopes exceeding 18°, from 150 m in the west to 500 m in the east, indicate a tectonic origin of the valley.

The mountains bordering the valley in the north and east are low, from 900 to 1250 m a.s.l., and have flat tops, with a height difference about 100 m and a slope to 10°. The southern border, a 2 km wide range, with flat tops and elevations 750 m a.s.l., is beyond the survey area in the west and east. A similar 4 × 2 km W–E landform occurs in the western part of the valley, between the two arms.

South and southwest of the range there are two valleys with two subglacial water cavities discovered within their limits. One valley has a smooth floor and lies at an elevation about 600 m, while the other is located at the boundary of the survey area, and most of it has not been mapped.

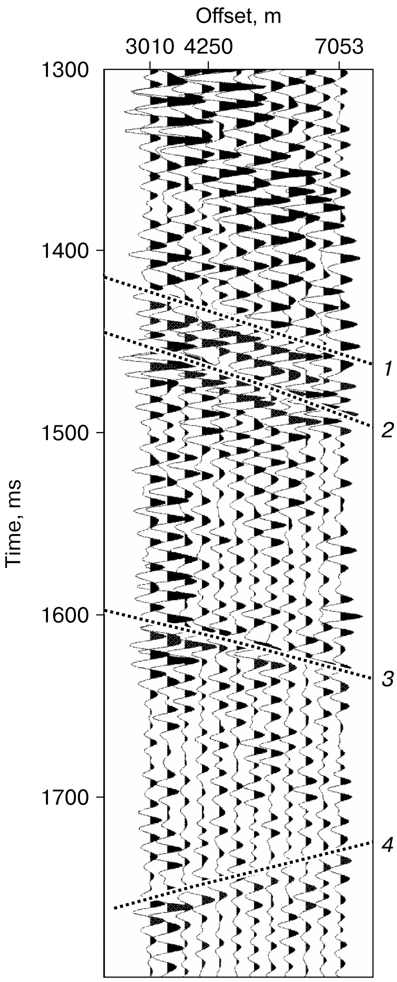

Fig. 6. Shot gather recorded in the area of Pionerskoe subglacial lake.

Reflection events: *1* – ice base; *2* – lake bed; *3* – bedrock surface; *4* – out-of-plane reflection (lateral wave).

The flat tops of the mountains record rapid glacial erosion by the ice sheet advance, at 20 m/yr in this area [*Salamatin et al., 1982*]).

The bedrock grid was used to calculate a rose diagram indicating six principal directions of geomorphic structures at 65–245°, 10–190°, 30–210°, 115–295°, 145–325° and 160–340° (Fig. 4). The first direction is especially well pronounced.

An RES time section and a cross section of the ice sheet along profile (51)LPM-08 are shown as an example in Fig. 5 (for the profile location see Figs. 3, 4).

Lake Pionerskoe depth

One reflection profile was shot during RAE field season 53 (2007/08) to estimate the depth of lake Pionerskoe (for survey configuration see Fig. 2). There are four events appearing in seismic responses (Fig. 6). However, identifying their origin and correlating them to specific interfaces is problematic because the survey method does not allow estimating effective velocities to reflectors and tracing the reflections continuously along the profile. At the current state of knowledge, the model can be only tentative, proceeding from the general idea of the region structure and inferred interfaces. The data were processed in *SeisWide 4.3*.

Early Russian seismic surveys along the Mirny–Pionerskaya profile [*Kondratiev et al., 1960; Kondratiev and Gamburtsev, 1963*] recorded *P*-, *S*-, and *PS*-wave data, as well as phases related to a moraine inside ice. Judging by the arrival times, the waves traced in the Pionerskaya station records are *P* reflections. Event *1* resolvable at 1.438 s against surface multiples within the ice is the ice base reflection. Event *2* traceable tentatively at 1.466 s may represent either the ice enclosing a moraine, or a layer of wet(?) sediments, or a ~30 m thick layer of water. The latter hypothesis appears to be the most realistic in the light of the available RES data.

Event *3*, with its arrival at 1.612 s, may come either from a sediment-bedrock interface or from the subice surface. Detailed analysis of the seismogram and inversion are in favor of the former interpretation.

Finally, event *4* recorded at 1.743 s, with a negative apparent velocity, is likely a response of the subice bedrock uplift in the northern part of the Pionerskaya valley.

Thus, the depth of lake Pionerskoe apparently reaches 30 m and Mesozoic-Cenozoic sediments on its bed may approach a thickness of 300 m.

CONCLUSIONS

The radio-echo sounding (RES) and seismic reflection surveys of 2003 through 2008 provided new evidence of the bedrock topography and the system of subglacial lakes in the area of the Golitsyn subglacial mountains. According to the survey results, lake Pionerskoe apparently reaches a depth about 30 m and has Mesozoic-Cenozoic sediments on its bed, possibly, about 300 m thick.

The data is of exceptional value, for two reasons: this part of Antarctica is almost unexplored and the lake depth has never been measured instrumentally before (Pionerskoye is second after lake Vostok, out of 414 subglacial lakes discovered in Antarctica [*Popov and Chernoglazov, 2006; Wright and Siegert, 2011*], where such measurements were undertaken). This is really an accomplishment, because reflection shooting from the ice surface is the only way to estimate the lake depths. However, all known Antarctic lakes, including Pionerskoe, are far from stations and field camps [*Wright and Siegert, 2011*], while the surveys are impossible without logistic support. The area is obviously of great scientific interest. According to the existing views [*Jamieson and Sugden, 2008; Miller et al., 2008; Jamieson et al., 2010*], the Golitsyn mountains are apparently a glaciation center in East Antarctica. Furthermore, the mountains are bounded by the poorly explored Gaussberg and Skott rifts [*Golynsky and Golynsky, 2009*], and the area is thus a keystone for understanding the deep structure and evolution of this part of the continent. Unfortunately, the investigations stopped after the transportation center for traverses had been moved from Mirny to Progress, which made the resuming of ground-based surveys very unlikely.

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