Morphology of the Subglacial Bed Relief of Lake Vostok Basin Area (Central East Antarctica) Based on RES and Seismic Data

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Abstract. During the austral summer field seasons of the 1995–2004 Polar Marine Geological Research Expedition (PMGRE) within the frame of the Russian Antarctic Expedition (RAE) carried out ground-based geophysical investigations in the sub-glacial Lake Vostok area in order to study the ice sheet and bed relief. Geomorphological analysis of the data allowed better understanding of sub-ice and sub-water structures. The most striking structure is the Vostok Basin which subdivides into five main substructures: lake plane, deep-water hollow, sub-water ridges, internal and external slopes. We detected six principal morphological substructures outside the Vostok Basin: lowlands, low hilly planes, high planes, ridged plane, Komsomolskiye Mountains and middle mountain land. A geomorphological chart has been produced.

Introduction

Russian investigations of the Lake Vostok area were started in 1995 by the Polar Marine Geological Research Expedition (PMGRE) within the frame of the Russian Antarctic Expedition (RAE). They were part of the scientific endeavour dedicated to the existence of the large subglacial lake named Vostok (Ridley et al. 1993; Kapitsa et al. 1996) and devoted to ice sheet and bed relief studies. The Russian field work (Fig. 3.6-1) included radio echo sounding (RES) and seismic reflection measurements (Masolov et al. 1999, 2001, 2002; Popov et al. 2001, 2003b, and others).

In 1999, airborne geophysical research (including RES) was carried out over the Lake Vostok region to determine the ice thickness, bedrock topography, lake shape, the amplitude of the bottom reflections and other characteristics (Tabacco et al. 2002). A good coverage of the lake area by the geophysical data was carried out by Americans during the field season of 2000. They collected airborne RES, magnetometric and gravimetric data on the regular network 7.5×11.25 km^2 (Studinger et al. 2003; and others). All the data allowed forming the first insights into the subglacial morphology and tectonics of the area (Masolov et al. 2001; Popov et al. 2002; Studinger et al. 2003).

It is necessary to note that the investigations of the Lake Vostok area are crucial for a number of Antarctic scientific fields. Analysis of the ice core data from the unique 5G-1 borehole (drilled in 1991–1998 at Vostok Station) enabled to reconstruct the climate history of our planet over the past 420 ka (Lipenkov et al. 2000; Petit et al. 1999). Besides, comparison of the ice core and RES data, tracing and dating of the radar layers allowed estimation of the features of the ice sheet formation (Mandrikova et al. in press; Siegert et al. 1998; Popov 2003). In this respect the region of Lake Vostok is the most convenient because of the availability of numerous RES lines. Another principle problem is the questions of the formation and existence of the subglacial lakes. Lake Vostok is the biggest and the best studied one by geophysical, glaciological and biological methods. Therefore, understanding of the processes occurring in the lake and in the ice sheet results in understanding the nature of other similar objects (Dowdeswell et al. 2003; Siegert et al. 2001).

The Lake Vostok area is characterized by a major fault system which can be extended for a long distance (Leitchenkov et al. 1998). In this respect, the understanding of the tectonics and geological history of this region is important for studying the East Antarctic deep structure. As a first step, the geomorphological analysis could be used being one of the best ways for bed relief study. The proposed sketch is one of the first of our attempts of geomorphologic analysis of the bed relief which is covered by a thick ice sheet (Popov et al. 2002).

Data and Methods

Russian geophysical investigations were directed to the bed relief and contouring of Lake Vostok. Mapping of the lake bottom was accomplished by seismic reflection work, while RES was applied for mapping of the bedrock topography outside the lake (Masolov et al. 2001, 2002; Popov et al. 2001, 2003b). Between 1995 and 2004, data from 196 seismic reflection shots were collected and about 3 250 km of the RES profiles were obtained. Position of the seismic shots and RES routes are shown in Fig. 3.6-1.

To get accurate seismic data it is necessary to measure the acoustic velocities in ice. Toward this end, during the austral summer field seasons of 1996–1998 we performed vertical seismic profiling in the 5G-1 borehole to define the acoustic velocities. Logging device was kindly provided by Prof. Heinz Miller (AWI, Bremerhaven). The measurements allowed calculating the acoustic velocity in pure

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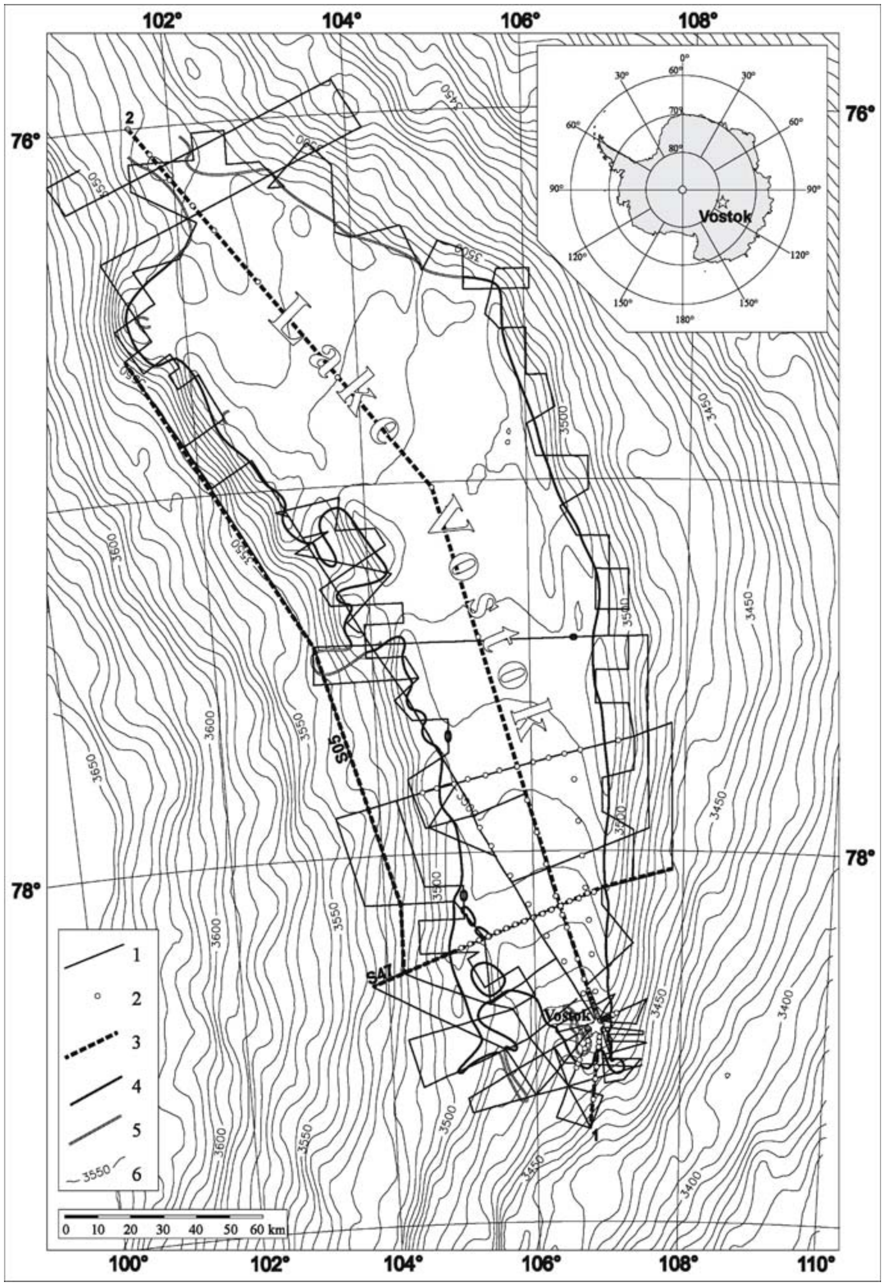

Fig. 3.6-1.
Location map of Lake Vostok area. *1:* Russian RES routes; *2:* sites of Russian reflection seismic soundings; *3:* location of the cross sections shown in Fig. 3.6-2; *4:* confidential Lake Vostok grounding line; *5:* supposed Lake Vostok grounding line; *6:* surface elevation contours (m)

ice using the direct wave. The velocity is 3 920 m s^{-1}. Averaged velocity from the ice surface to the ice base is 3 810 m s^{-1}. This value is used in all our investigations in the Lake Vostok area. Ice thickness in the 5G-1 borehole vicinity, defined using the direct and reflected waves from the ice base (3 750 m), is in good agreement with the RES data (Popov et al. 2003a). During the field season of 1999/2000 wide-angle seismic reflection measurements were performed in the vicinity of Vostok Station to measure the average velocity of the radio wave propagation in ice, which is 168.4 ±0.5 m μs^{-1} (Popov et al. 2003a).

Our geomorphological chart was based on the standard procedure for morphological classification. The boundaries between the regions are the following elements: Lines of maximal steepness of convex or concave forms (Lastochkin 1987, 1991; Spiridonov 1975). The space between the structural elements is genetic homogeneity for scale mapping. Specific features of the regions depend on such morphometric characteristics as relative and absolute height, displacement, gradient, shape and geological information. The last one is inaccessible because the bedrock is covered by ice.

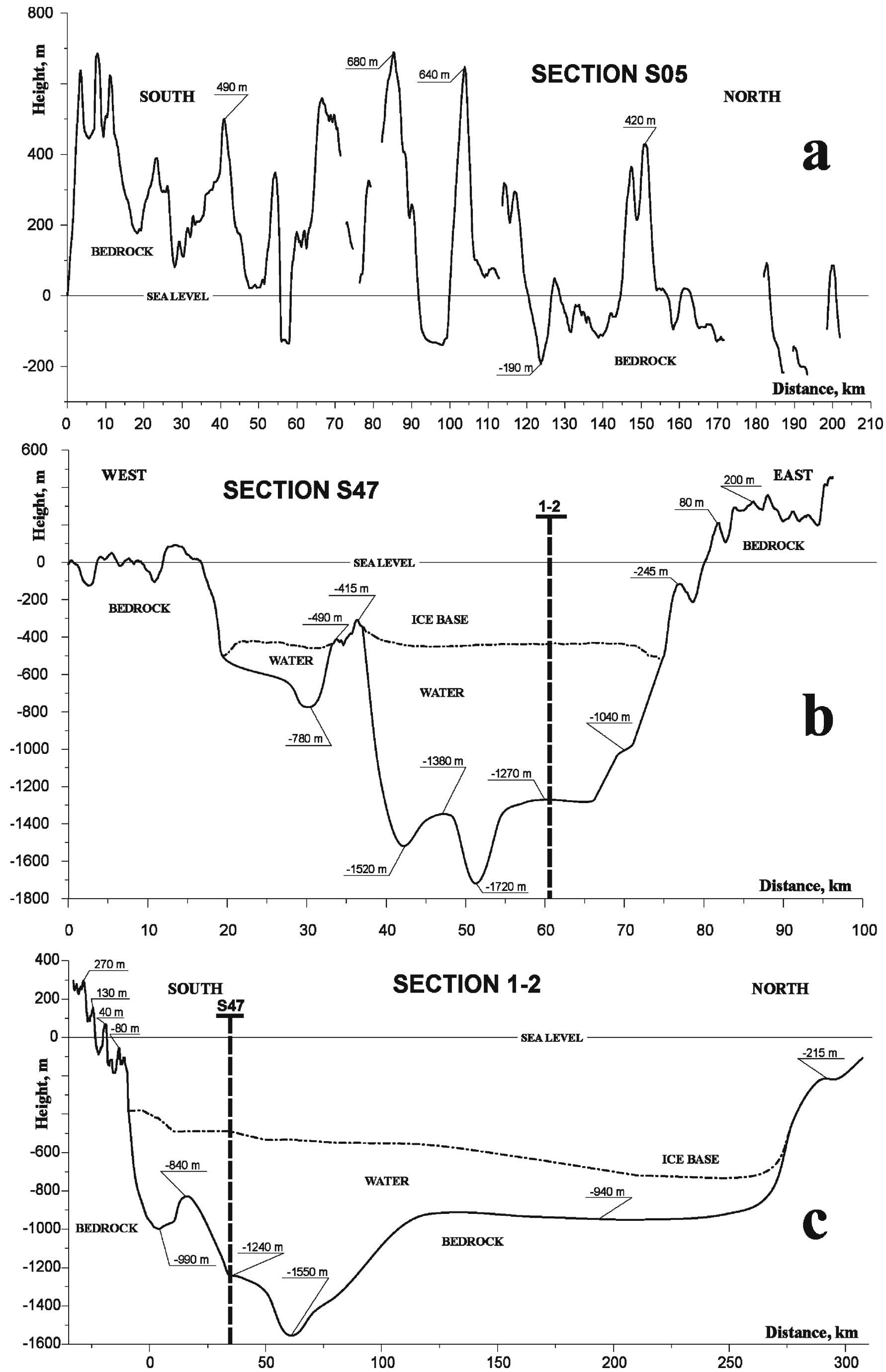

Fig. 3.6-2.
RES and seismic cross sections. The locations of the routes are shown in Fig. 3.6-1

It is necessary to note that the geomorphological chart derived is based on the RES and the seismic cross sections. Some examples are shown in Fig. 3.6-2. The use of the real cross sections is more correct than the use of the contour map since the process of contouring results in smoothing the data. Some smoothing is acceptable for producing and describing the geophysical data but inappropriate for geomorphological analysis.

Morphology

The reflection seismic and RES data show a dominating structure in the region that is the Vostok Basin (Fig. 3.6-3). Its size is approximately 270 × 80 km. The basin configuration is oval-shaped in S-N direction and complicated by a number of small-size structures located along the western side of the basin. The eastern side of the basin is mostly rectilinear south of 77°. The basin boundary is marked by edges of mountain ridges and other enveloped positive forms of the bed relief. The Vostok Basin is subdivided into five main substructures (Fig. 3.6-3): lake plane (LP), deep-water hollow (LD), sub-water ridges (LR), internal (BS) and external slopes (LS).

The lake plain is located in the northern part of the basin. It is possibly represented by sub-horizontal sub-water surface −940 m deep and approximately 150 km long. Our seismic data suggest that the depth variability is about ten meters. This result is based on only four seismic points Fig. 3.6-1, and 3.6-2). It is not enough to fully describe the mentioned large area. However, the randomly located measurements showed practically the same bedrock height. The deep-water hollow has a pear-shaped configuration with a depth from about −1 700 to −800 m. Its relative height is approximately 250 m with a normal slope of about 3° and the size is about 30 × 55 km (Fig. 3.6-2b and 3.6-2c). The relief of the deep-water hollow is complicated by sub-water ridges and valleys with N-W and S-E directions mostly. Their relative heights are from 150 up to 400 m. Sub-water ridges subdivide the southern part of the lake bottom into the deep-water and the shallow-water basins (Fig. 3.6-2b). Its absolute height varies from −780 up to −460 m. The ridge slopes are terraced. The

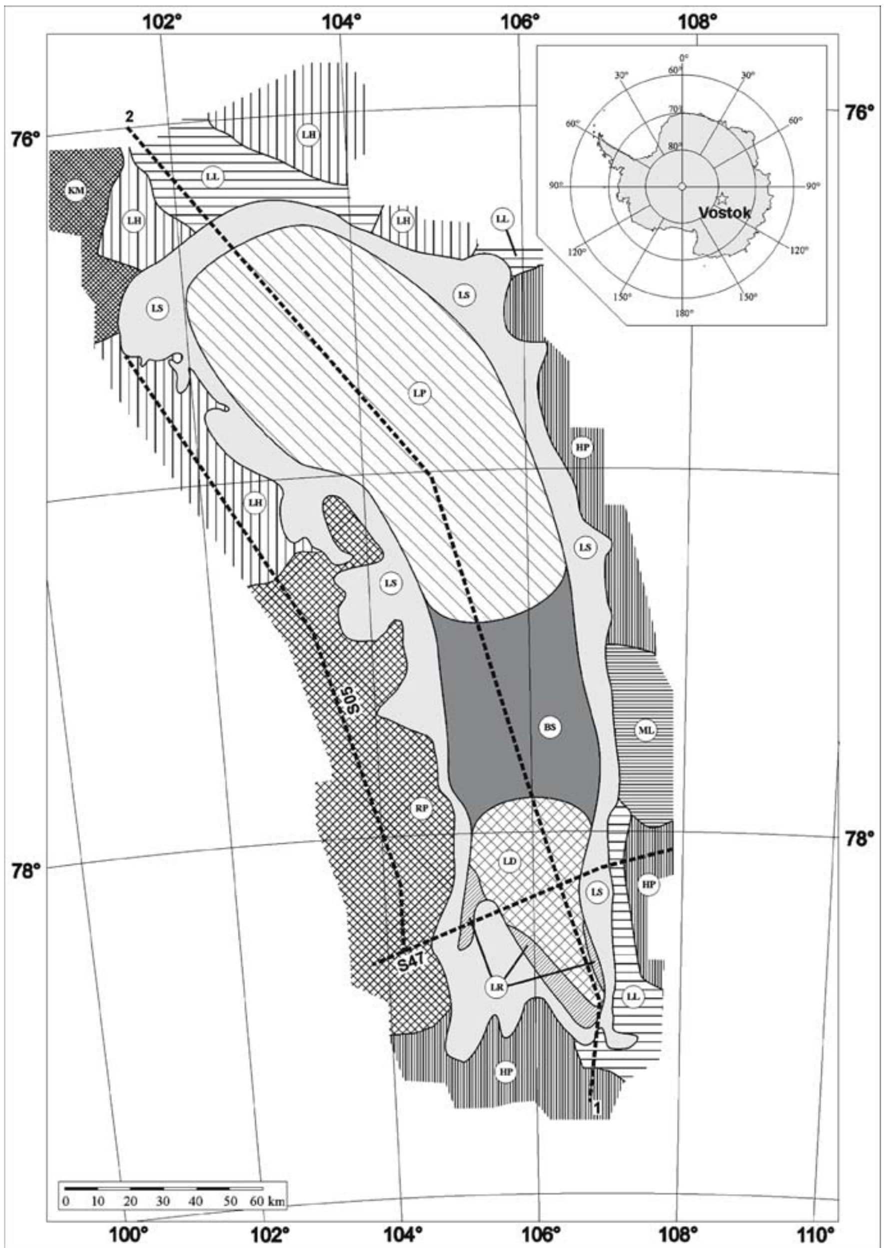

Fig. 3.6-3.
Geomorphological pattern of Lake Vostok area. *Dashed lines* show sections of Fig. 3.6-2; *LP:* lake plane; *LD:* deep-water hollow; *LR:* sub-water ridges; *BS:* internal slope; *LS:* external slope; *LL:* lowlands; *LH:* low hilly planes; *HP:* high planes; *RP:* ridged plane, *KM:* Komsomolskiye Mountains, *ML:* middle mountain land

terraces are located at the depths of about –1 380, –1 270, –940, –860, –600, –520, –480 and –460 m. They are characterized by different sizes from 1 up to 7 km long (Fig. 3.6-2b and 3.6-2c). The internal slope is positioned north of the deep basin between the deep-water (in the Vostok Station area) and shallow-water regions. Its depth varies from about –1 400 to –930 m with an angle app. 0.5° (Fig. 3.6-2c). The external slope of the Vostok Basin encircles all the mentioned substructures forming their external boundary. Its width changes from kilometres to several tens of kilometres. Elevation of the external slope varies from –1 300 to about 400 m. The slope angle is approximately 17–22° (Fig. 3.6-2b and 3.6-2c). Its structure is complicated by valleys and canyons app. 1.5 km in width and about 400 m in depth.

Subglacial relief of the area around the Vostok Basin is very different. We identified four principal morphologic substructures there (Fig. 3.6-3): lowlands (LL), low hilly planes (HP), high planes (HP), ridged plane (RP), Komsomolskiye Mountains (KM) and middle mountain land (ML).

The lowlands are located in the north and the south from the Vostok Basin. They are valleys that represent the prolongation of the main Vostok Basin. The absolute height of the lowlands is from about –300 up to sea level in the south and from about –500 m up to –300 m in the north. Its surface is characterized by the slope with the angle of approximately 1° to the Vostok Basin side. The low hilly planes are best expressed in the northern part of the Vostok Basin. Their absolute height is approximately from –100 m up to 100 m and complicated by single hollows and ridges of the W-E directions in the northwestern part and S-N directions in the northern part of the area (Fig. 3.6-2a). Its relative height is about 200 m in general. The ridges width is about 10 km. The high planes are located in the south and east of the Vostok Basin. Their absolute height is about 300 m mainly with several complicated ridges about 100 m in height. The ridged plane is located to the west from the Vostok Basin. Its principal feature is a number of ridges in W-E direction. Having more then 400 m in relative height difference and about 10 km in width, they are divided by a plane which is about 150 m in height. It could be spurs of Sovetskiye Mountains, which are hypothetically located between Lake Vostok and Sovetskaya Station (PMGRE archives, not published). Hypothetical Komsomolskiye Mountains are located between Lake Vostok and Komsomolskaya Station (not published). Their observed small part is about 800 m in height. The last region is the middle mountain land located east from the Vostok Basin. It is probably a fragment of a high ridge. Observed bedrock height is about from 400 up to 1 100 m.

This is one of the first attempts of a morphological analysis of the Lake Vostok bedrock. The authors hope to continue this work using new materials to come from the neighboring areas, which will result in better understanding the Lake Vostok formation.

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References

Dowdeswell JA, Siegert MJ (2003) The physiography of modern Antarctic subglacial lakes. In: Fard AM (ed) Subglacial lakes: a planetary perspective. Global Planet Change 35(3/4), pp 221–236

Kapitsa AP, Ridley JK, Robin G de Q, Siegert MJ, Zotikov I (1996) A large deep freshwater lake beneath the ice of central East Antarctica. Nature 381(6584):684–686

Lastochkin AN (1987) Morphodynamical analysis. Nedra, Leningrad, (in Russian)

Lastochkin AN (1991) Relief of the earth surface. Nedra, Leningrad, (in Russian)

Leitchenkov GL, Verkulich SR, Masolov VN (1998) Tectonic setting of lake Vostok and possible information contained in its bottom sediments. Lake Vostok study: Scientific objectives and technological requirements. Internat Workshop March 24–26, 1998, AARI, St. Petersburg, pp 62–65

Lipenkov VYa, Barkov NI, Salamatin AN (2000) History of Antarctic climate and glaciation from the study of the Vostok Station ice core. Probl Arktiki i Antarktiki 72:197–236, (in Russian)

Mandrikova DV, Lipenkov VYa, Popov SV (2003) Ice sheet structure in the subglacial Lake Vostok area (East Antarctic) based on RES data. Mater Glaciol Data, (in Russian)

Masolov VN, Kudryavtzev GA, Sheremetyev AN, et al. (1999) Earth science studies in the Lake Vostok region: existing data and proposals for future research. SCAR Internat Workshop on Subglacial Lake Exploration Report, Cambridge, pp 1–18

Masolov VN, Lukin VV, Sheremetyev AN, Popov SV (2001) Geophysical investigations of the subglacial lake Vostok in Eastern Antarctica. Doclady Earth Sci 379A(6):734–738

Masolov VN, Lukin VV, Popov SV, Popkov AM, Sheremet'ev AN, Kudryavtsev GA (2002) Main results of the seismic and radio echo sounding investigations of the subglacial lake Vostok. Razvedka i ohrana nedr 9:40–44, (in Russian)

Petit JR, Jouzel J, Raynaud D, Barkov NI, et al. (1999) Climate and atmospheric history of the past 420 000 years from the Vostok ice core, Antarctica. Nature 399(6735):429–436

Popov SV (2003) Application the radio echo sounding for the glaciological investigations. Trudy XX–XXI All-Russian sympos Radio echo sounding of the nature environments 3:57–64, (in Russian)

Popov SV, Mironov AV, Sheremetyev AN (2001) Result of ground RES researches of subice lake Vostok in 1998–2000. Mater Glaciol Data 89:129–133, (in Russian)

Popov SV, Lastochkin AN, Popkov AM, Masolov VN, Lukin VV (2002) Results of geomorphologic interpretation of the bed relief in the subglacial Lake Vostok area. EOS 83(19) Suppl., Abstract B22A-02

Popov SV, Sheremetyev AN, Masolov VN, et al. (2003a) Velocity of radio-wave propagation in ice at Vostok station, Antarctica. J Glaciol 49(165):179–183

Popov SV, Sheremetyev AN, Masolov VN, Lukin VV (2003b) Main results of the ground-based RES and glaciological observations in the subglacial Lake Vostok area (East Antarctica) in 1998–2002. Mater Glaciol Data 94:187–193, (in Russian)

Ridley JK, Cudlip W, Laxon W (1993) Identification of subglacial lakes using ERS-1 radar altimeter. J Glaciol 73(133) 625–634

Siegert MJ, Hodgkins R, Dowdeswell JA (1998) Internal radio-echo layering at Vostok station, Antarctica, as an independent stratigraphic control on the ice-core record. Annals Glaciol 27:360–364

Siegert MJ, Ellis-Evans JC, Tranter M, et al. (2001) Physical, chemical and biological processes in Lake Vostok and other Antarctic subglacial lakes. Nature 414:603–609

Spiridonov AI (1975) Geomorphologic mapping. Nedra, Moscow, (in Russian)

Studinger M, Bell R, Karner GD, et al. (2003) Ice cover, landscape setting and geological framework of Lake Vostok, East Antarctica. Earth Planet Sci Letters 205:195–210

Tabacco IE, Bianchi C, Zirizzotti A, Zuccheretti, Forieri A, Della Vedova A (2002) Airborne radar survey above Vostok region, East Central Antarctica: ice thickness and Lake Vostok geometry. J Glaciol 48:62–69