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New 3D bathymetry and sediment distribution in Lake Vostok: Implication for pre-glacial origin and numerical modeling of the internal processes within the lake

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ABSTRACT

A new distribution of water and unconsolidated sediments in subglacial Lake Vostok, East Antarctica was developed via inversion of airborne gravity data constrained by 60 seismic soundings. A model was developed for host rock with a density of 2550 kg/m^3 that was inferred from prior 2D modeling. Our 3D bathymetry model of Lake Vostok corresponds better with seismic data (RMS of 125 m) than two previous models based on the same gravity dataset. The good match in both water and sediment thicknesses between the gravity model and seismic measurements confirms two major facts about Lake Vostok: (1) the lake is hosted by sedimentary rocks, and (2) the bottom of the lake is covered with a layer of unconsolidated sediments that does not exceed 300 m in the southern basin and thickens almost to 400 m in the northern basin. Our new bathymetry model suggests much shallower water thicknesses (up to twice the previous estimates) in the middle and northern parts of the lake, while the water layer is thicker in the southern basin. Numerical modeling of the internal processes in the lake reveals the relevance of our new bathymetry model to the basal mass balance. A significant decrease in transport is observed in the shallower northern basin, as well as a decrease of 33% in the turbulent kinetic energy. However, only minor differences were observed in the distribution of the calculated freezing and melting zones compared to previous models. Estimates for the sedimentation rates for six possible mechanisms were made. Possible sedimentation mechanisms are: (1) fluvial and periglacial, i.e. those that are active prior to the establishment of a large subglacial lake; (2) deposition due to overlying ice sheet, including melting out of the ice, as well as bulldozering by the overriding ice; and (3) suspended sediments from subglacial water flow including those deposited by periodical subglacial outbursts. The estimates for these mechanisms show that unconsolidated sediments of the observed thickness are most consistent with a lake that existed before glaciation.

1. Introduction

The largest known subglacial lake – Lake Vostok – is located beneath Russian Station Vostok in East Antarctica. This large fresh-water lake, covered with approximately 4 km of ice, attracts much attention from the scientific community due to its uniqueness and possibly life-supporting environment. The north-dipping lake ceiling causes the temperature/pressure conditions to vary across different parts of the lake (Kapitsa et al., 1996; Siegert et al., 2000; Studinger et al., 2003). Those differences trigger melting at the ice–water interface in the northern part of the lake but freezing of the lake water onto the bottom of the ice sheet in the southern part of the lake. Such a distribution of melting/freezing patterns, in turn, is responsible for generating water circulation within the lake (Siegert, 2005; Thoma et al., 2007a, 2008a). Both the melt/freeze and coupled water circulation processes within Lake Vostok are subject to numerical modeling, as in Williams (2001), Mayer et al. (2003), and Thoma et al. (2007a, 2008a). The key ‘a priori’ information for such modeling is the 3D geometry of the lake, which infers both spatial and depth distribution of water as well as unconsolidated sediments at the bottom of the lake. The lake's coast line is well mapped by radar sounding data (Fig. 1), providing the spatial constraints for both water and sedimentary layers.

The precise knowledge of the lake's bathymetry is a necessary component of the numerical modeling of water circulation and mixing in the lake, as well as the interaction between the lake and the overlying ice sheet. The earliest 3D bathymetry model was proposed by

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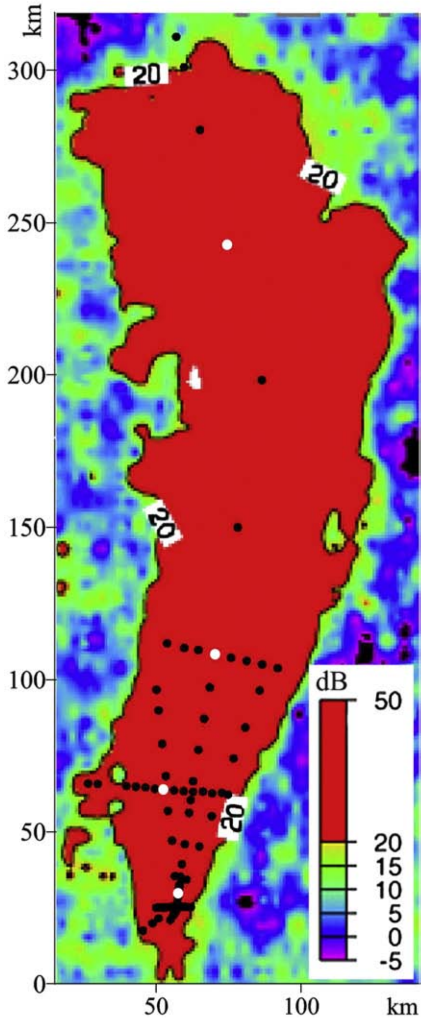

Fig. 1. Radar sounding bed echo strength map of the Lake Vostok area (Sasha Carter — personal communication); the lake is assumed to be the region of high echo strength. Black dots indicate seismic soundings used in this study (Masolov et al., 1999 and 2006; Item CEP 4c, 2002). Open circles show the seismic points with sediment thickness available from Filina et al., 2007.

Williams (2001) based only on a seismic water measurement beneath Vostok station. Two other 3D models of the Lake Vostok bathymetry (Studinger et al., 2004; Roy et al., 2005) are based on airborne geophysical data, collected by the University of Texas Institute for Geophysics (UTIG) during 2000–2001 field season (Richter et al., 2001; Studinger et al., 2003; Holt et al., 2006), constrained with seismic data available at the time. The bathymetry model developed by Studinger et al. (2004) was used as a boundary condition in the numerical modeling of the internal processes within the lake performed by Thoma et al. (2007a,b, 2008a,b). These model results gave deep insights into the flow regime and the tracer dispersion within Lake Vostok as well as reasonable values for the basal processes like freezing/melting and the total mass (im-)balance at the ice–water interface.

Unconsolidated sediments beneath most of Lake Vostok were identified based on early interpretation of seismic data (Masolov et al., 1999; Item CEP 4c, 2002). This sedimentary layer was believed to be up to 350 m thick in the southern part beneath Vostok Station and becoming thinner, up to 50 m, in the northern part of the lake. On the other hand, a more recent publication (Masolov et al., 2006) suggested that the lake's water overlies the acoustic basement, implying that there is no sedimentary layer at the bottom of Lake Vostok. However, a reinterpretation of these seismic data (Filina et al., 2007) revealed the existence of up to 270 m of unconsolidated sediments in the southern part of the lake and 350–380 m in the northern basin. Nevertheless, the detailed distribution of sediments and their implication for lake evolution have remained unknown.

Whether Lake Vostok existed before the current glaciation is unknown. Kapitsa et al. (1996) proposed that the melting of the overlying ice is the source of the water in Lake Vostok, inferring that the lake was formed after the current ice sheet covered the lake. Duxbury et al. (2001) applied a 1D thermodynamical model and concluded that a pre-glacial lake would have survived the glaciation without being frozen to the bottom if the water thickness in the lake exceeded about 50 m. This hypothesis is criticized by Siegert (2004, 2005), proposing that even if the lake existed before the glacial advance, it would be completely frozen during the onset period of glaciation, which again is rebutted by numerical modeling by Pattyn (2004). Thus, the question of whether the lake existed before glaciation is still a matter for debate.

The objectives of this paper are (1) to present a new model of the lake's bathymetry along with the distribution of unconsolidated sediments at the bottom of the lake, based on 3D inversion of the same gravity dataset used in Roy et al. (2005) and Studinger et al. (2004), constrained with seismic soundings available to date, (2) to compare and contrast the new model with previous models, (3) to evaluate the impact of the updated bathymetry on the numerically modeled flow and basal mass balance within Lake Vostok, and (4) to estimate sedimentation rates and times for various possible mechanisms capable of depositing unconsolidated sediments at the bottom of the lake in order to reveal the age of the lake.

2. Bathymetric models

2.1. Available data

The airborne geophysical data were collected on a regular grid with 7.5 km spaced east–west lines and 11.25 and 22.5 km spaced north–south tie lines. The flight elevation was 3.96 km above mean sea level (msl). The reduction of the gravity data used in Roy et al. (2005) and this study was performed at UTIG (Holt et al., 2006) with a reported RMS of the differences at the crossover points for the gravity grid after leveling of 1.2 mGal (1 Gal = 0.01 m/s^2). Studinger et al. (2004) uses the reduction algorithm based on Childers et al. (1999) and reports the standard deviation of the adjusted crossover error of 2.7 mGal.

There are more than 100 sparse seismic soundings over the lake (Masolov et al., 1999, 2006; Item CEP4c, 2002; Fig. 1), mostly located in the southern part of the lake. Seismic data suggests that the lake is deeper in the southern part with the maximal water thickness of 1200 m (Profile S47 in Fig. 1; Masolov et al., 2006); the water thickness decreases up to 250 m to the north of the lake. The most dense seismic coverage is available near Vostok station, where the seismic soundings are several hundred meters apart, revealing the presence of a relatively small (about 5 km across and 690 m deep) basin filled with 350 m of sediment (Masolov et al., 1999) beneath Vostok station.

2.2. Previous 3D bathymetry and sediment distribution models

The earliest 3D bathymetry model, developed by Williams (2001), was based on the single seismic water column measurement available by then. A few years later Roy et al. (2005, submitted in 2003) developed a bathymetry model for both water and sediment layers based on the inversion of airborne gravity data, showing the deepest lake bottom at ~1550 m below sea level (corresponding to ~800 m of water thickness) and sediment thickness of 300 m in the northern basin. In the Roy et al. (2005) model, the ice and water were considered to be one layer due to their similar densities. Different densities of the host rocks were used (2600 kg/m^3 for the lake's cavity area, 2800 kg/m^3 east of the lake) to represent the presence of the thrust fault suggested by Studinger et al. (2003). Roy et al. (2005) used the sediment density of 2000 kg/m^3. They chose the regional trend, required to calculate the residual anomaly before inversion, to be linear. The inversion was performed using a Very Fast Simulating Annealing algorithm (VFSA; Sen and Stoffa, 1995). This model has significant discrepancy with seismic data, as well as spatial divergence with the coastline obtained from radar sounding data.

Another model by Studinger et al. (2004) was composed for the water layer only. Since the sedimentary layer was believed to be thin it was ignored. This model uses the coastline constraint from radar sounding data; it shows a maximum water thickness in the lake of 800 m in the southern basin and about 450 m in the northern basin. Their comparison with seismic data at 19 points (RMS of 250 m) shows a better agreement than the model of Roy et al. (2005). Studinger et al.'s (2004) model was developed for a density of the host rock of 2670 kg/m^3. A regional trend of the second order was calculated based on "the misfit between the regional bedrock topography inverted from gravity and the bedrock topography from radar data" (Studinger et al., 2004).

Although the bathymetry models of Roy et al. (2005) and Studinger et al. (2004) are superior to Williams' (2001) model, they still have some discrepancy between seismic and gravity derived water thicknesses. In the southern basin, the maximal water thickness recorded by seismic data is 1200 m, while in the northern basin the water layer does not exceed 250 m.

2.3. New 3D bathymetry and sediments distribution model for Lake Vostok and comparison with previous models

All available airborne data were interpolated into a regular grid with 5 km cells, which is smaller than an estimated resolution of gravity data for the survey parameters used (~7.2 km based on Childers et al., 1999; Holt et al., 2006). Before inversion, the gravity effects of all known sources (the ice layer with density 920 kg/m^3 and rocks above msl) were calculated and removed from the observed free-air anomaly. This reduced anomaly increases rapidly over the lake by about 70 mGal — from the western edge to the eastern edge of the lake basin. The regional trend, representing the gravity effect of deeper geological structures, needs be removed before shallow gravity modeling. This regional trend should possess the following qualities: (1) it should coincide with the residual anomaly outside of the lake area, (2) it should be as close as possible to the linear over the lake, and (3) it should consist of only low frequencies due to deep sources. To accommodate all of those, the anomaly outside of the lake was complemented by 2D trends found by cubic spline interpolation along several profiles spaced by 50 km. The resultant regional trend was found by interpolation over the entire lake region, followed by low-pass filtering with the 50 km wide window. The residual anomaly, found by subtraction of the regional trend from the reduced gravity anomaly, was used as model input (Fig. 2).

The gravity anomaly is a function of the anomalous mass geometry and its density contrast with the host rock. The proposed model for Lake Vostok consists of water and unconsolidated sedimentary layers overlying the host rock. The water density of 1000 kg/m^3 was used in this study. The densities of unconsolidated sediments and the host rocks should be properly chosen and fixed during inversion. In this study, sediments at the bottom of the lake were chosen to have density of 1850 kg/m^3, which is a typical value for water-filled unconsolidated sediments. Previous 2D gravity modeling of Lake Vostok showed the best agreement between water thicknesses derived from seismic soundings and from gravity inversion if the density of 2550 kg/m^3 was used for host rocks (Filina et al., 2006). The chosen density of 2550 kg/m^3, typical for consolidated sedimentary rocks, is also consistent with the observed sedimentary rock inclusions trapped in the ice beneath Vostok Station (Leitchenkov et al., 2007), as well as with the model of Studinger et al. (2003), where the presence of a sedimentary basin beneath Lake Vostok was suggested.

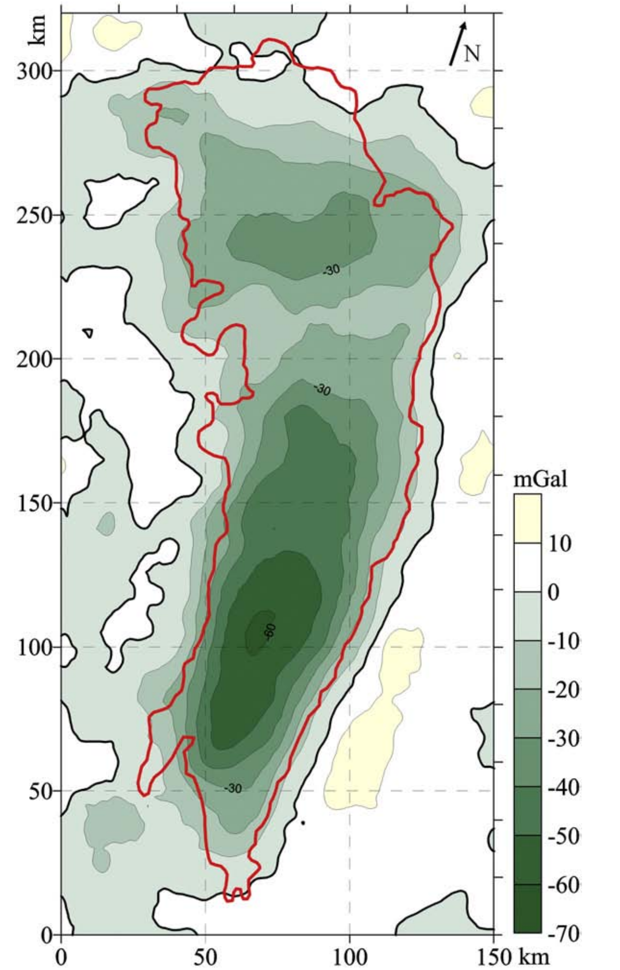

Fig. 2. The residual gravity anomaly over Lake Vostok; contour interval is 10 mGal. The thick black line corresponds to zero mGal. Red line shows the lake's coastline from radar data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The forward problem was solved based on the equation of Parker (1973). The inversion was performed using a conjugate gradient method for both water and sedimentary layers (Tarantola, 1987). The inversion was also performed using a VFSA algorithm (Sen and Stoffa, 1995) as in Roy et al. (2005). The results of inversions with conjugate gradient and VFSA algorithms correlate very well with the mean value of the difference between the two results being less than 3 m for both water and sedimentary layers. Such a good match infers that the global minimum was achieved during the inversion.

The new bathymetry model of Lake Vostok (Fig. 3A) has a maximal water thickness of 1100 m in the southern basin, showing very good correlation with seismic data (Fig. 4). Since many seismic soundings are located near Vostok Station at distances up to several hundred meters from each other, only 60 points located at least 5 km apart (red dots in Fig. 4) were used to constrain the model. The RMS of the difference between water thicknesses derived from seismic data and gravity modeling is 125 m. In the northern basin the water depth is 280 m. The lake bathymetry being shallow in the central part of the lake is also consistent with the results of Gorman and Siegert (1999). The thickness of the inverted layer of unconsolidated sediments (Fig. 3B) is up to 300 m in the southern basin and 400 m in the northern one, which is also consistent with seismic data (Filina et al., 2007).

Possible errors in the results of gravity inversion include the uncertainty in the gravity data, errors in the ice thickness and density assumption. The estimated error in water layer due to data uncertainty

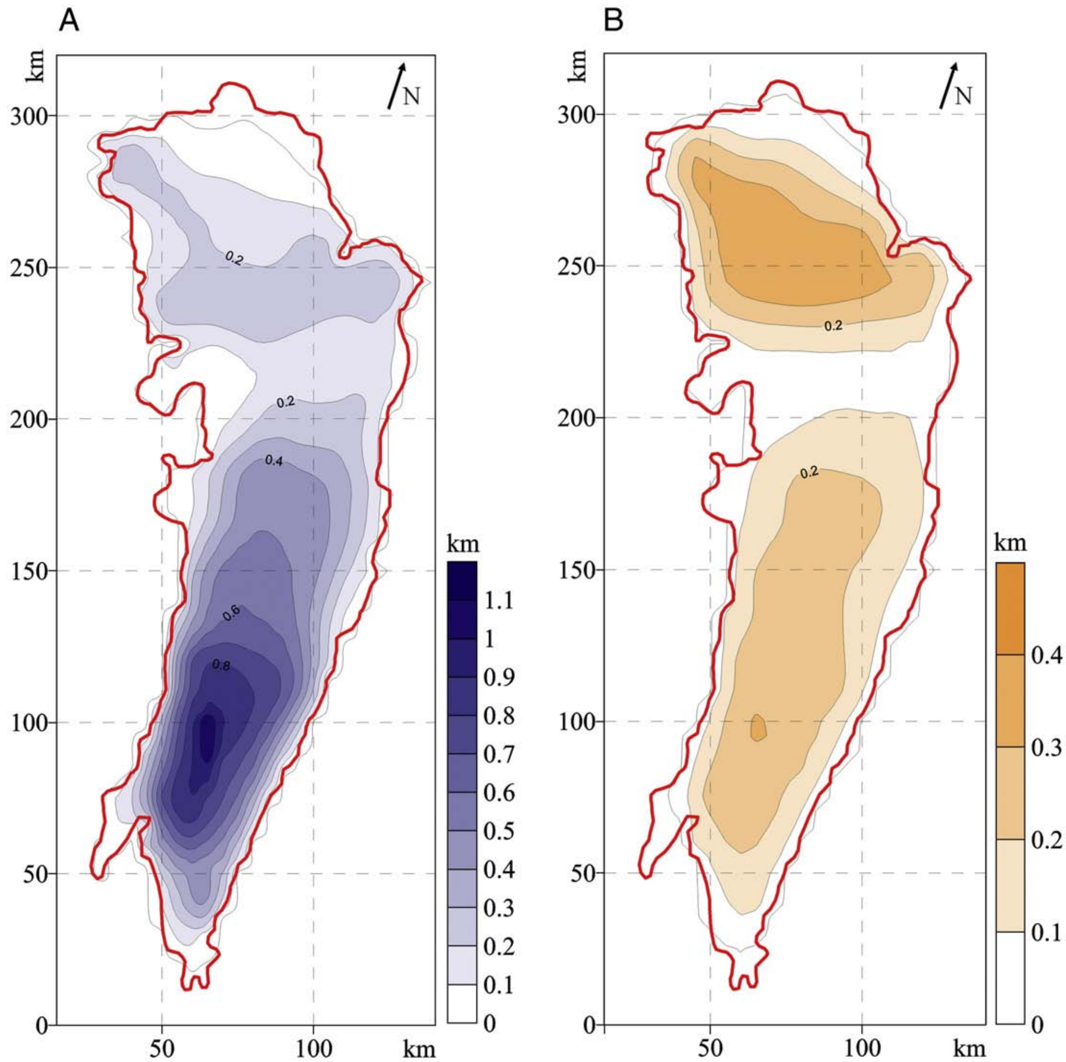

Fig. 3. The results of the revised inversion of airborne gravity data. Red line shows the lake's coastline from radar data. (A) The water thickness in km derived from gravity inversion (contour interval is 0.1 km). (B) The sediment thickness in km (contour interval is 0.1 km). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of 1.2 mGal is 19 m. The RMS of the differences at the crossover points for the ice thickness dataset over the lake is 11 m (D. Young — personal communication), that corresponds to the error in gravity data less than 1 mGal. If the density of 2670 kg/m^3 is used during modeling, the lake's depth decreases by about 200 m. This is one of the possible explanations for the lake appearing to be shallower (up to 800 m) in the Studinger et al. (2004) model than it actually is (up to 1200 m based on seismic soundings), since Studinger et al. (2004) utilizes density of 2670 kg/m^3 for the host rock. The new estimated water volume for Lake Vostok is 5000±950 km^3 in contrast to 5400±1600 km^3 estimated by Studinger et al. (2004). In spite of the new bathymetry model's indication of a thicker water layer in the southern basin, the total water volume in the lake decreases by about 8% due to much shallower water thicknesses (up to twice the previous estimates) in the middle and northern parts of the lake.

Another reason for the discrepancy in water thickness derived from the Studinger et al. (2004) gravity inversion and seismic soundings is the omission of a layer of unconsolidated sediments. Based on the seismic soundings, the layer of unconsolidated sediments in the northern basin appears to be thicker than the water layer (350–380 m of sediments vs. 250 m of water). Those sediments are responsible for a gravity effect up to 8 mGal, which exceeds the accuracy of the gravity data by several times. That is why the sedimentary layer cannot be ignored during modeling. The model of Roy et al. (2005) includes the presence of the sediments at the bottom of the lake, although its thickness was constrained based on the distribution reported in Masolov et al. (1999). The most probable reason for the disagreement of inverted water thickness with seismic data in Roy et al.'s (2005) model is the use of a linear regional trend. This also resulted in a spatial discrepancy with the lake's coastline.

A comparison of 3D bathymetry/sediment models for Lake Vostok is shown in Table 1. Only the seismic model represents the small basin beneath Vostok station, which is up to 690 m deep, about 20 km long and 5 km wide. The dimension of this basin is smaller than the resolution of this airborne gravity dataset (Childers et al., 1999; Holt et al., 2006) and clearly demonstrates the resolution limits of gravity derived bathymetry models.

3. Numerical modeling of water circulation and mass exchange at the ice–water interface

This section describes the results of the numerical modeling of subglacial processes within Lake Vostok. The modeling was performed with ROMBAX, an established numerical flow model for subglacial studies (Thoma et al., 2007a, 2008a,b). This three-dimensional fluid dynamics model calculates the basal mass balance at the ice–water

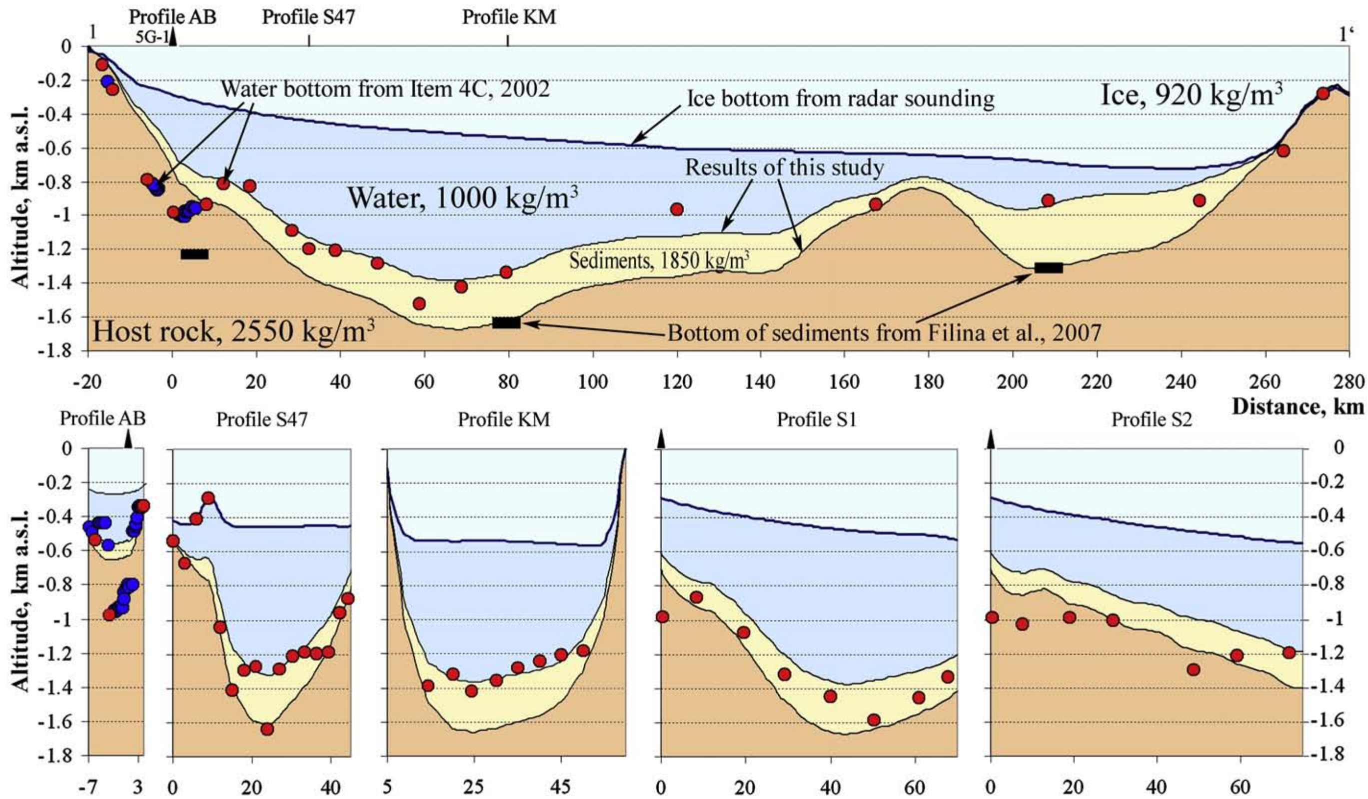

Fig. 4. Comparison of presented model with seismic data (for location see Fig. 1). Red dots show the bottom of the lake form seismic data used to constrain the model and to calculate the RMS of the difference between gravity derived water thickness and seismic data; blue dots are seismic data that were ignored since they are less than 5 km apart. Black rectangles on the profile along the lake show the bottom of sedimentary layer from Filina et al., 2007; black triangles are 5G-1 borehole at Vostok station. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interface, as well as the mass transport inside the lake. The required boundary conditions for this modeling include the geometry of the ice–water interface (ice draft) and the lake's bathymetry. The precise knowledge of the above interfaces is crucial to model the flow regime and the basal mass balance of subglacial lakes, as it was noted by Williams (2001) and Thoma et al. (2007a). Here we describe the impact of our new bathymetry model on these parameters with respect to earlier studies, based on the bathymetry model of Studinger et al. (2004). For our numerical flow modeling we use the very same ice draft as in previous studies, but our new water column thickness described in the previous section. About 7% of grid nodes at Lake Vostok's edges had to be removed, because of the inconsistency arising from merging two models with slightly different grounding lines; thereby the model's volume decreases by less than 5%, which was neglected.

The impact of the new water column thickness on the flow regime is indicated by changes in the vertically integrated mass transport stream function, shown in Fig. 5 (to be compared with Thoma et al., 2007a) and the meridional overturning rate, shown in Fig. 6. In the shallower northern basin, we observe a significant decrease in transport. The cyclonic (clockwise rotating) gyre in the center of the lake is also slightly decreased and it follows the bathymetry southward; its center is now located about 55 km more to the south. Consequently, the size and intensity of the anticyclonic gyre in Lake Vostok's southern tip is widely reduced; zonally averaged it is even nearly completely dissolved compared to the results shown in Thoma et al. (2007a). In terms of the turbulent kinetic energy a 33% decrease is observed.

Comparing the distribution of the calculated freezing and melting zones between our new bathymetry (Fig. 7) and the one presented in Thoma et al. (2007a), depicts only minor differences. This proves that this pattern is closely related to the ice draft as expected. However, the updated averaged melt and freeze rates are about 20% lower. Due to the reduced flow, lesser warm water is transported from the lake's bottom to the lake–ice interface and hence, less ice is melted. If less ice is melted, the amount of supercooled water with the potential to freeze is reduced and the freeze rates decrease, too. In addition to this, the reduced transport allows diffusive processes to blur temperature gradients, necessary for melting and freezing. Differences in the total mass balance, which is mainly determined by the ratio between the geothermal heat and the heat flux into the ice (Thoma et al., 2008a), can be neglected as they fall below the changes in lake area.

Table 1
Comparison of 3D bathymetry/sediment models for Lake Vostok

	Water thickness in the southern basin	Water thickness in the northern basin	Sediment thickness	Number of seismic points used and RMS
Seismic data	1200 m	250 m	Up to 380 m	–
Williams (2001)	510 m	Not existent	Not included in the model	–
Roy et al. (2005)	~1000 m	~800 m	Up to 250 m	Not reported
Studinger et al. (2004)	~800 m	~450 m	Not included in the model	19 points, 250 m
This study	1100 m	280 m	Up to 400 m	60 points, 125 m

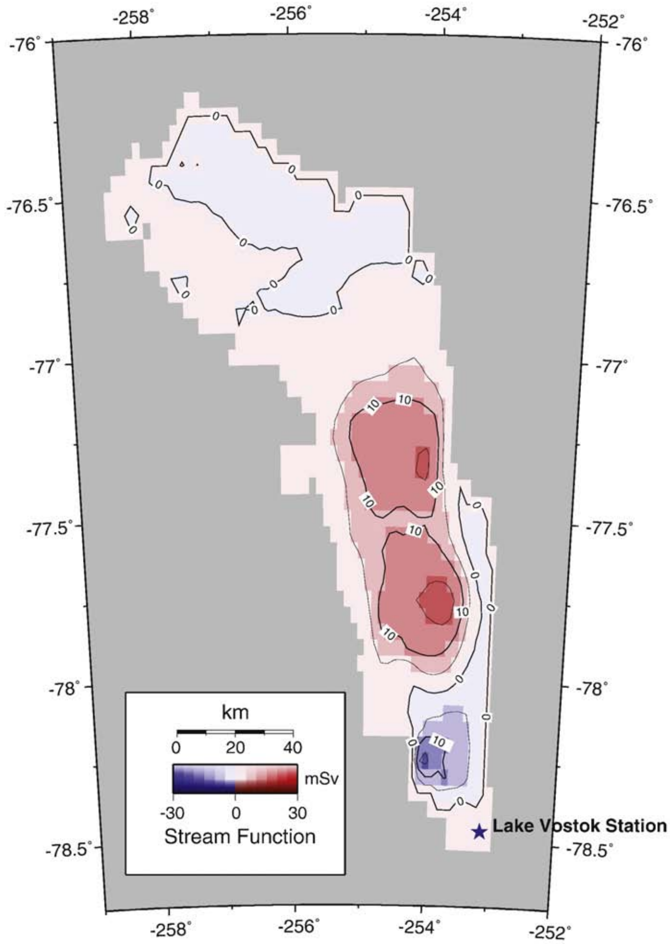

Fig. 5. Vertically integrated mass transport stream function (1 mSv = 10^3 m^3/s).

Based on different signatures of reflection signals from ice-penetrating radar measurements, Studinger et al. (2004) derived a map, showing melting only in the lake's northern basin, while freezing dominates the southern basin. This apparent contradiction can be resolved, keeping in mind that the signature in the reflection radar signal indicates the presence of accreted ice rather than the process of freezing or melting. Hence, indications of accreted ice across the southern basin can be a result of ice advection across the lake and so not necessarily indicative of widespread freezing. Taking the ice flow above the lake into account (Tikku et al., 2004), the massive freezing at the lake's western (upstream) edge, driven by the shape of the ice draft, results in a very thick layer of accreted ice. The subsequent melting is not sufficient to disintegrate this layer completely and hence, accreted ice can be observed in most parts of the southern basin (Thoma et al., 2008b).

4. Sedimentation processes in Lake Vostok

Our bathymetry/sediment model confirms the presence of a layer of unconsolidated sediments at the bottom of Lake Vostok revealed from seismic data (Filina et al., 2007). The total volume of sediments is estimated to be 2600 km^3. Our inversion of gravity data shows that sediments are not equally distributed over the lake's bottom (Fig. 3b). The larger and deeper southern basin with an estimated area of 10,000 km^2 holds ~1400 km^3 of sediments (up to 300 m thick layer), while ~1200 km^3 of sediments (up to 400 m thick) are located in the smaller and shallower northern basin with a surface area of approximately 7000 km^2.

Possible sedimentation mechanisms are: (1) fluvial and periglacial, i.e. those that are active prior to the establishment of a large subglacial lake; (2) deposition due to overlying ice sheet, including sediments melted out of the ice, as well as those scoured from rocks beneath the ice, transported and deposited into the lake by the overriding ice; and (3) suspended sediments from subglacial water flow including those deposited by periodical subglacial outbursts. The six possible mechanisms and their sedimentation rates and times (described below) are summarized in Table 2.

The fluvial/periglacial mechanisms assume that the lake existed before glaciation, and all of the observed sediments were deposited before the ice sheet came. For the first possible mechanism – due to subaerial fluvial processes – the sedimentation with the rate of 0.035 cm/yr as in subaerial Lake Baikal (Edgington et al., 1991) may be assumed, which is also consistent with the sedimentation rates observed in Lake Michigan (Robbins, 1975). This suggests that the lake should have existed 500 kyr before glaciation. For periglacial deposition a rate of about 10 cm/yr, as for the fast-moving temperate valley glaciers of southeast Alaska (Hallet et al., 1996) is most appropriate. Periglacial mechanism would take 1.8 kyr to deposit all the observed sediments at the onset of the glacial advance.

If Lake Vostok existed before glaciation, some of the sediments, but not all of them, may be deposited pre-glacially by the mechanisms described above. After the lake was covered with ice, the currently observed pattern of freezing at the south and melting at the north of the lake was developed. The accreted ice layer is 210 m thick (Jouzel et al., 1999) with the maximum sediment concentration observed in the first meters and no inclusions below the top 70 m. Because this sediment-rich accreted ice is preserved as it traverses the lake, no sediment input is likely to occur through meltout in the southern basin. In contrast, stronger melting in the northern basin (Fig. 7) eliminates any accreted ice from the western edge swiftly and sediment input into the lake occurs. The mechanism considered for meltout during glaciation will therefore operate in the northern basin as long as the distribution of ice

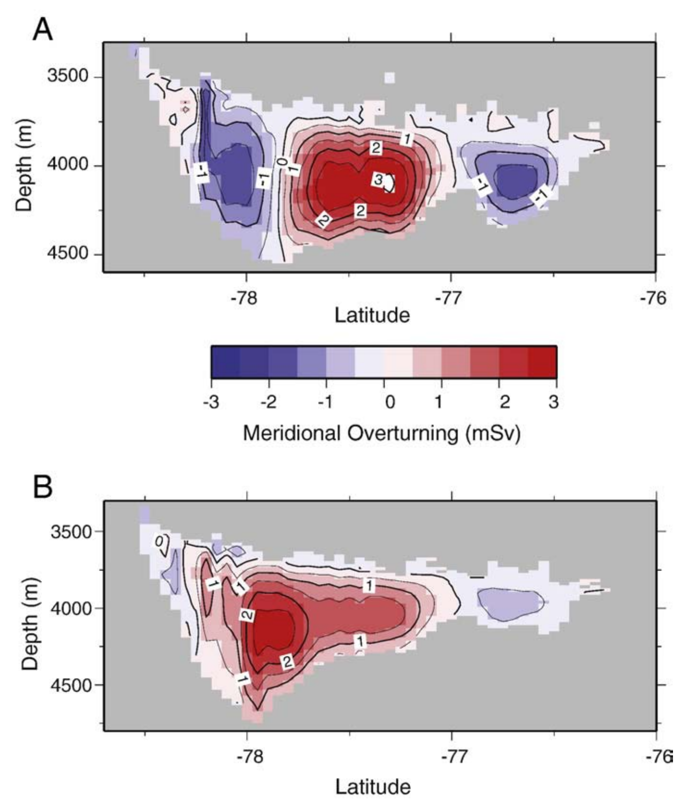

Fig. 6. Zonally averaged mass transport stream function, indicating the meridional overturning rate for (A) bathymetry model from Studinger et al. (2004) as in Thoma et al., 2007a, and (B) our new bathymetry.

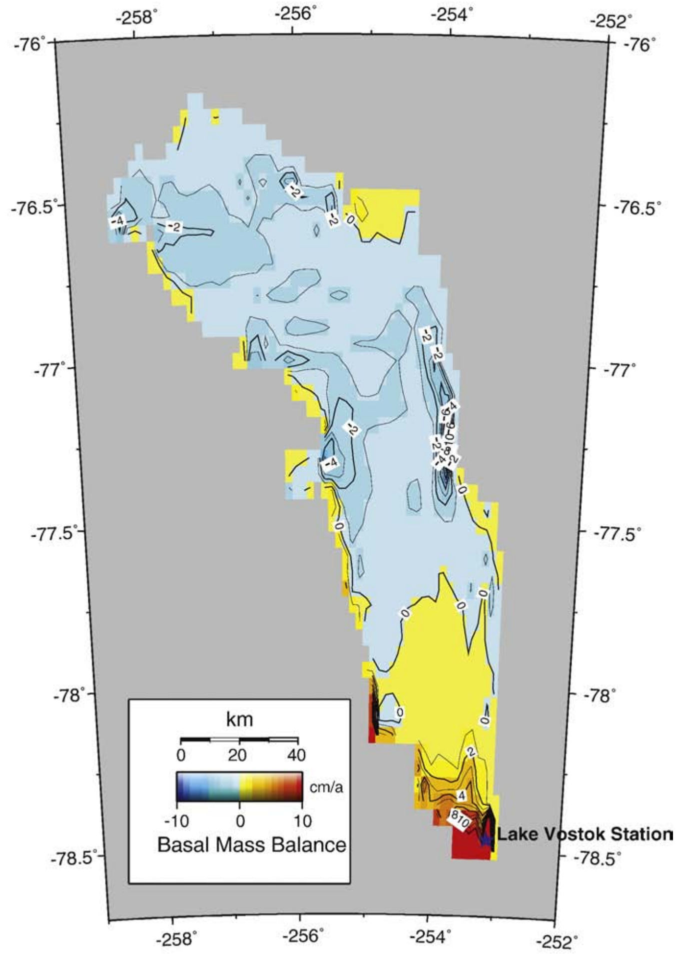

Fig. 7. Modeled basal mass balance at the ice–water interface. Negative values (blue/green) indicate melting, positive (yellow/red) values indicate freezing. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

draft is similar to that observed today. Our calculations for this meltout deposition mechanism assume that a uniform layer of 300 m (i.e. the southern basin observation) was deposited at the bottom of Lake Vostok before glaciation, and the sedimentation has been occurring in the northern basin since the lake was covered with ice, which is assumed to be within the last 30 Myr (Duxbury et al., 2001). In this case only 300 km^3 of sediments (equivalent to a 100 m thick layer of sediments in the northern basin) should be deposited. The estimate was made with the following assumptions: (a) the total amount of sediment that melts out from the overriding ice sheet may be estimated based on the average concentration of sediments in the top 70 m of the accreted ice observed in the ice core drilled at Vostok Station (Jouzel et al., 1999); (b) each visible inclusion grain was assumed to be a sphere of 2 mm diameter; and (c) the melting rate in the northern basin has been constant since the beginning of the glacial period and is constant for the entire basin with the value of 2 cm/yr (Siegert et al., 2000), which is also consistent with our calculated melting rates in Fig. 7. Assumptions (a) and (b) give an estimated average concentration of sediments in the top 70 m of the accreted ice of $3.6 \cdot 10^{-6}$. If it is conservatively assumed that the glacial period lasted 30 Myr (Duxbury et al., 2001), the sedimentation rate needs to be $140 \cdot 10^{-6}$ cm/yr to deposit a 100 m thick layer of sediments in the northern basin. The estimated sedimentation rates for the meltout mechanism is $7.2 \cdot 10^{-6}$ cm/yr, suggesting that it is not capable of depositing even a 100 m thick layer of unconsolidated sediments in the northern basin during glaciation.

The estimate for the deposition rate for the sediments that were scoured, transported and dumped in the lake by the overriding ice is more tenuous. It was assumed that in the southern basin all of the sediments that are brought with the moving ice and dumped in the lake, get quickly frozen at the ice bottom largely over the shallow water adjacent to the coast upstream of Vostok ice core, as in Leitchenkov et al. (2007). In contrast, in the northern basin it was assumed that the same amount of sediments is brought with the moving ice and dumped in the lake, but instead of being frozen to the ice bottom those sediments get deposited at the bottom of the lake. The sedimentation rate due to this mechanism was estimated based on the following assumptions: (a) the amount of sediments dumped in the lake by the overriding ice is equal to the maximal number of inclusions observed in the ice core drilled at Vostok Station (30 inclusions with an assumed diameter of 2 mm (as above) over 1 m of ice core; Jouzel et al., 1999), which corresponds to a sediment concentration of $16 \cdot 10^{-6}$; (b) the approximate length of the margin along which the deposition is occurring is 100 km; and (c) the current velocity of the ice sheet observed at Vostok station (2 m/yr, Bell et al., 2002, Wendt et al., 2006) is constant for the entire lake region as well as having been constant during the entire period of glaciation. The estimated sedimentation rate for this mechanism is $0.05 \cdot 10^{-6}$ cm/yr, which is insufficient to supply even the 100 m of sediments in the northern basin. This estimate above is based on two major assumptions; i.e., (i) sediment transport at the bottom of the ice is the same for both lake basins, and (ii) all sediments that are dumped in the lake in the southwestern portion get frozen at the bottom of the ice. Both of those assumptions are vague; however, the estimated sedimentation rate of $0.05 \cdot 10^{-6}$ cm/yr suggests that the amount of the sediments brought with the ice needs to be at least three orders of magnitude higher for this mechanism to deposit a 100 m thick layer of sediments in the northern basin over 30 Myr.

Two other possibilities for depositing sediments under glacial conditions include deposition of suspended sediments from a subglacial hydrological network as suggested in Exploration of Antarctic Subglacial Aquatic Environments (2007), or as a result of numerous subglacial outbursts as suggested in Wingham et al. (2006). Both of those mechanisms may deposit sediments in both of the lake's basins, so the estimates for those two were made for the entire 2600 km^3 of sediments observed at the bottom of Lake Vostok. If the glaciation is assumed to last the entire 30 Myr, the sedimentation rate needs to be $510 \cdot 10^{-6}$ cm/yr.

In the assumption that the sediment precipitates from the suspended load of the subglacial water system, the total volume of the

Table 2
The estimated sedimentation rates and times for different mechanisms depositing unconsolidated sediments at the bottom of Lake Vostok

Sedimentation mechanism	Timing of sedimentation with respect to glaciation		
	Before	Partially after[a]	After
Sediments brought with fluvial system(s)	0.035 cm/yr 500 kyr	–	–
Sediment deposited as a result of periglacial processes	10 cm/yr 1.8 kyr	–	–
Sediments melt out from the overlying ice sheet	–	$7.2 \cdot 10^{-6}$ cm/yr 635 Myr	–
Sediments are brought with the moving ice	–	$0.05 \cdot 10^{-6}$ cm/yr 101 Byr	–
Suspended sediment transported and deposited by water flowing into the lake	–	$350 \cdot 10^{-6}$ cm/yr 5 Myr	44 Myr
Suspended sediments deposited by periodical subglacial outbursts	–	$9400 \cdot 10^{-6}$ cm/yr every 27 yr 5 Myr	44 Myr

[a] In this scenario the uniform layer of 300 m was assumed to be deposited before the glaciation, while the remaining 100 m of sediments in the northern basin was deposited under the glacial conditions.

subglacial water available upstream of Lake Vostok needs to be estimated. The lake is located at a distance of ~200 km from Ridge B, so the catchment area may be conservatively estimated as a product of that distance and the lake's length (~300 km) perpendicular to the ice flow from that ridge. If bottom melting of 1 mm/yr is assumed (Kapitsa et al., 1996) for the entire catchment area, the estimated water flux through Lake Vostok is 0.06 km^3/yr or 1.9 m^3/s. This water flux is almost twice as large as the one assumed in Chapter 2 of Exploration of Antarctic Subglacial Aquatic Environments (2007), which suggested water flux of 1 m^3/s for Lake Vostok with most of it attributed to roof melting. If the sediment concentration of 0.001 by volume is assumed as in Exploration of Antarctic Subglacial Aquatic Environments (2007), the sedimentation rate for the flux of 1.9 m^3/s is $350 \cdot 10^{-6}$ cm/yr and it takes 44 Myr to fill Lake Vostok with the observed 2600 km^3 of sediments.

If deposition through a series of subglacial outbursts is assumed, a discharge rate of 50 m^3/s and a duration of each event of one year may be assumed as in Wingham et al. (2006), suggesting that 1.6 km^3 of water flows through Lake Vostok during one outburst event. Averaged over time, water is produced through basal melting in the catchment region upstream of the lake (as above) with the estimated surface area of 60,000 km^2 and an annual water volume available of 0.06 km^3. This melted water should induce an outburst event somewhere in the catchment approximately every 27 yr. Because the overall water flux is conserved, it would, again, take 44 Myr to fill out the observed volume of unconsolidated sediments assuming a sediment concentration in the water of 0.001 by volume (estimated sedimentation rate is $9400 \cdot 10^{-6}$ cm/yr for each outburst event). However, as these outbursts occurred, an increase in the ice elevation over one year of approximately 11 cm over the entire lake area should be observed. Such a significant change in ice surface altitude every few decades would probably not be missed since regular metrological and geophysical observations have been conducted at Vostok Station since the station opening in 1957.

In summary, although the two subglacial water flow/flood mechanisms have the fastest estimated sedimentation rates, they are still not be able to fill the lake with the amount of unconsolidated sediments observed by this study during the glacial period. Overall, the estimated sedimentation rates and required times for all of the subglacial mechanisms considered here (Table 2) suggest that Lake Vostok is older than the last glaciation, which is assumed to be within the last 30 Myr.

5. Conclusions

We present a new 3D bathymetry/sediment distribution for subglacial Lake Vostok, East Antarctica. This model was derived as a result of joint interpretation of airborne gravity data and seismic soundings available at the time. Our model shows a better agreement between the gravity derived water thickness and the one from the seismic observation (RMS of 125 m in 60 points) than previous models. Such a good agreement between gravity and seismic bathymetry models was achieved assuming that the lake is hosted by sedimentary rocks, which is confirmed with the analyses of the inclusions from the ice core at Vostok Station (Leitchenkov et al., 2007). We used our improved bathymetry as the geometric boundary condition for numerical flow model of internal processes within the lake. The results show a reduced circulation of water masses compared to earlier studies (Thoma et al., 2007a,b, 2008a), in particular in the much shallower northern basin. This leads to reduced average freeze and melt rates. Nevertheless, the total basal mass loss, primarily driven by the imbalance of geothermal heat and the heat flux into the overlying ice sheet, is mainly unaffected. Our gravity inversion also confirms the presence of unconsolidated sediments at the bottom of the lake, previously revealed from the analysis of seismic data in four different locations over the lake (Filina et al., 2007). The sedimentary layer is not uniform throughout the lake: the deeper southern basin holds up to 300 m of unconsolidated sediments, which thicken up to 400 m in the shallower northern basin. We also considered six different sedimentation mechanisms for deposition of unconsolidated sediments at the bottom of Lake Vostok. The estimates of sedimentation rates under glacial conditions show that those mechanisms are not capable of supplying the observed amount of sediments to the lake, revealing a pre-glacial origin for Lake Vostok.

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