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Earth Sciences

Modelling of geomechanical processes of interaction of the ice cover with subglacial Lake Vostok in Antarctica

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Abstract

As a result of analysis of the ice cover, geological structure and tectonics of the underlying rocks in the Lake Vostok area of Antarctica, a layered sub-horizontal structure of the ice cover and a distribution of the parameters of the ice composition were established. The physical and mechanical properties of the underlying rocks were determined experimentally. Complex tectonics revealed an increase in geothermal flow in the Vostok Basin region, which plays a role in the evolution of the Earth's crust and in shaping the morphology of its physical properties. A three-dimensional geomechanical model of the unified system 'glacier-Lake Vostok-bedrock ' was constructed and investigated. Regularities in the changes to the stress-strain state were revealed. Zones of development of plastic deformation in the ice cover along the perimeter of Lake Vostok and their distribution over the lake were established, which were confirmed by results from field observations. Modelling of geomechanical processes shows that the change in the mechanical state of the Earth's crust, taking into account the creep deformation of the ice sheet, relates more to nonlinear dynamic systems, which are characterized by unstable changes and should be considered as fractal systems.

Key words: Antarctica, fractal systems, geomechanical model, numerical modelling, stress-strain state, subglacial Lake Vostok

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Introduction

The determination of upward conductive heat flow, one of the mechanisms of intra-terrestrial heat release, occupies a special place in the study of subglacial Lake Vostok in Antarctica. It is important not only for determining the genesis of the lake and the associated evolution of life on Earth, but also for reliably determining the heat flow from the Earth's interior, which plays a role in the evolution of the Antarctic crust and the formation of its morphology and physical properties. In real-world conditions, the presence of a global heterogeneous ice sheet with creep deformation, as well as structural and thermophysical inhomogeneities in the Earth's crust (Yang & Song 2023), affects the geomechanical processes occurring under the influence of natural causes, which can be considered as a nonlinear dynamic system (close to fractal system). This is a process with non-constant and non-periodic variable trajectories. To establish the pattern of deformation of the ice sheet and its deflection in the area of Vostok Station, we used the obtained physical and mechanical properties of rocks of East Antarctica and elastic-plastic models of the medium, taking into account creep deformation for the ice sheet. Modelling of the geomechanical processes of the impacts of the glacial cover was considered over time as a linear dynamic system.

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Study of the ice sheet and subglacial Lake Vostok in Antarctica has been undertaken using seismic and radar methods since 1960, when seismic sounding by the reflected wave method and determination of the glacier thickness and subglacial relief were carried out (Savatyugin & Preobrazhenskaya 1999, Savatyugin *et al.* 2003, Popov *et al.* 2012, Popov 2021).

The native relief and depths of Lake Vostok, which is a depression in the form of a lowered block of the Earth's crust in an extended sub-meridional region of lithospheric destruction measuring ~310 × 100 km, have been established (Fig. 1; Savatyugin *et al.* 2003, Popov & Lunev 2012, Popov 2021). Eleven islands with a total area of 365 km^2 have been identified in the water area. The area of the largest of them is 175 km^2 (Popov *et al.* 2012).

Lake Vostok is an isolated water body with a water table area of 15 790 km^2 and a water body volume of 6100 km^3. Its altitude position varies from 600 to 150 m (Popov *et al.* 2011, 2012, Popov & Lunev 2012). The average depth of the lake is ~400 m. In the master plan of the lake, the southern part of the lake, measuring 70 × 30 km, is the deepest, with an average depth of ~900 m and a maximum depth in the central part of up to 1200 m (Savatyugin *et al.* 2003). The northern part of the lake, measuring 150 × 70 km, has an average depth of ~300 m and a maximum depth of up to 600 m (Popov *et al.* 2011, Popov & Lunev 2012). The concentration of dissolved oxygen in the lake water is estimated at 27–1300 mg/l, which is 2–90 times higher than the oxygen content in water under normal conditions (Arapov *et al.* 2005).

The bottom of the part of Lake Vostok, which has been studied using seismic measurements, has the shape of a step-like bend

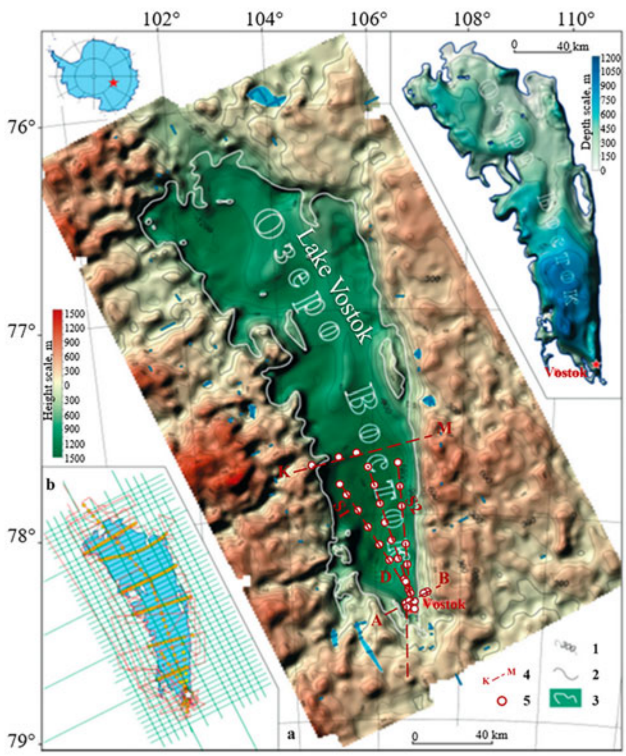

Figure 1. Native relief and subglacial water bodies in the area of Lake Vostok: 1 = isohypses of native relief, cross-section of isolines at 150 m; 2 = sea level; 3 = shoreline of the lake; 4 = seismic profiles; 5 = shot points of the seismic reflection survey of the 46th Russian Antarctic Expedition (RAE). The bottom-left inset shows the layout of the used geophysical data; blue colour shows subglacial water bodies; domestic radar routes are shown in red colour (Popov & Lunev 2012).

with bottom depths of 4310–5040 m from the ice surface, where the eastern step (depth 4310 m) is raised relative to the western one by 140 m.

The greatest thickness of the water layer (1200 m) is found in the central part of profile S1 (Fig. 1; Masolov *et al.* 2010). The bottom of the lake in the upper part is seemingly covered with loose sediments with a thickness of 40–300 m (Leitchenkov *et al.* 2016).

The water area of Lake Vostok is represented by a hilly underwater plain. In the western area of Lake Vostok there is a mainly mountainous landscape with elevations of up to 1580 m, and in the eastern area there is hilly and flat terrain with elevation differences of 100 m on average (Popov & Lunev 2012). The crustal thickness is 34 km to the west of the Vostok trench and 36 km to the east (Popov *et al.* 2012).

At depths of 55–60 km below Lake Vostok a local geospatial region with increased geothermal flow along a transcrustal fault into the Earth's crust was presumed to have been identified (Isanina *et al.* 2009). The Vostok Basin may be reefogenic in nature, as the fault zones have not been traced above the basement, and it is possible that the 'eastern ' block is in a stretched state and the 'western ' block is in a compressed state (Isanina *et al.* 2009). At the same time, an increase in geothermal flow is possible in the area of the Vostok Basin and to the east of it (Popov *et al.* 2012).

In the 'western ' block, the upper boundary of the basement is located at a depth of 3500 ± 200 m. It is rough but not stratified (Isanina *et al.* 2009). The thickness of the bottom sediments varies, ranging from 40 to 300 m (Leitchenkov *et al.* 2016).

The thickness of the sedimentary rocks varies from 400 m in the north to 1000 m in the south. Below this boundary, a crystalline basement lies at depths of 3.8–5.0 km (Isanina *et al.* 2009). The sedimentary stratum consists of sediments from the Upper Proterozoic to the Jurassic inclusive and represents deposits of glacial and glacial-marine genesis, with the presence of siltstone-clay sediments with inclusions of coarse-grained material (diamectites; Grikurov *et al.* 2003).

The crystalline basement is composed of a magmatized and granitized complex of gneisses and crystalline schists with a total thickness of 15–20 km.

Precambrian and Lower Palaeozoic intrusions of gabbroic-anorthosites and charnockite and Early Mesozoic intrusions of nepheline syenites are widespread in the crystalline basement (Pandey *et al.* 2023).

When opening the congelation ice layer with borehole 5G, small (0.1–1.0 cm) mineral inclusions captured by the glacier during its movement through the western shallow part of the lake were detected (Leitchenkov *et al.* 2016). Lake water samples (Lipenkov *et al.* 2017) obtained during the first opening of Lake Vostok on 5 February 2012 were studied previously (Litvinenko 2020).

Most of the bottom sediments accumulated in Lake Vostok and captured during the accretion of the lower ice layer in the form of small inclusions came from the western shore of the lake due to the exaration of the native glacier bed. These inclusions contain indirect information about its geological structure.

Studies of the core collected from borehole 5 G (Savatyugin *et al.* 2003) showed that at a depth of 3538 m at the base of the glacial strata there is a 200 m-thick layer of accretion ice formed as a result of lake water freezing over the base of a slowly moving (3 m/year) glacier. The upper part of this layer (from 3538 to 3608 m) is saturated with solid (mineral), irregularly distributed (from 2 to 25 per 1 m of core) inclusions of 1–2 mm in size, which were captured during its formation, when the glacier crossed the shallow coastal area of the lake located to the north-west of the borehole (Savatyugin *et al.* 2003). They actually reflect the composition of its bottom sediments, being carriers of unique information about the geological structure of the subglacial environment.

It was found that mineral inclusions are agglomerates formed as a result of coagulation of clay-mica minerals (0.3–0.5 μm in size). Illite and chlorite predominate among the clay minerals, with fragments (usually subrounded and angular) of rock-forming and accessory minerals present. Quartz of 10–100 μm, tourmaline (~70 μm), epidote, zircon and hornblende (50–100 μm) and rutile, dolomite and iron hydroxides were reliably identified. It was found that the general dimensionality of the substance composing the solid inclusions corresponds to the pelite-siltstone fraction of sediments. There is a large gravity anomaly near the lake. The presence of this anomaly and clay particles in the ice suggests that this part is composed of sedimentary rocks, possibly of Permian-Triassic age (Leitchenkov *et al.* 2016).

The angular shape of the quartz and accessory minerals testifies to glacial transport of fragmental material. Through the discovery of zircon it was possible to determine the age of the rocks subjected to exaration, which are 1.74 billion years old, corresponding to the time of formation of metamorphic complexes of the Proterozoic mobile belt of the Antarctic crystalline shield.

Russian studies and studies conducted by other nations have shown good agreement regarding water and sediment thicknesses between the gravity model and seismic measurements, which confirms two basic facts about Lake Vostok: the lake consists of sedimentary rocks and the lake bottom is covered with a layer of unconsolidated sediment that does not exceed 300 m in the southern basin and thickens to almost 400 m in the northern basin.

The ice cover above the lake has a layered, sub-horizontal structure of the distribution of the parameters of material composition, petrophysical and petrographic properties and the velocity and direction of flow of ice masses (Fig. 2). Up to a depth of 3539 m, the ice cover is composed of ice of atmospheric origin, but deeper than 3539 m and down to the contact of the glacier with the surface of lake water at a depth of 3769.3 m, the glacial cover is composed of congelation (lake) ice formed from the water of the subglacial reservoir (Fig. 2).

Ice is not an absolutely solid body. Even at low pressure it exhibits plastic properties. This means that it changes its shape or flows without turning into a liquid. Experimental and calculated data of the physical properties of ice (Epifanov 2007, Tsyganova *et al.* 2010, Vasilev *et al.* 2016) are shown in Table I.

The mechanical properties of ice depend on its structure, porosity, salinity and temperature (Higashi *et al.* 1964, Jones & Glen, 1969a,b, Michel & Ramseier 1971, Nanthikesan & Shyam Sunder 1994).

Structural transformations in the Antarctic glacier strata were studied as a result of analysis of a core from borehole 5 G at a depth of 3769.3 m (Lipenkov *et al.* 2007, 2011). A general tendency of ice crystal size to increase with depth was established (Fig. 3). The sizes of the crystals do not exceed 5 mm up to a depth of 2500 m, and then significant growth in is observed. At the same time, the orientation of the main axes of the crystals also changes.

Experimental studies have shown that the limit to ice fluidity also increases with decreasing temperature: as the temperature drops from -1.7°C to -20°C, the limit to ice fluidity increases by more than 200%, and down to -30°C it increases by 300%. The deformation curve has an elastic-plastic form with a pronounced yield area (Glazovsky *et al.* 2008).

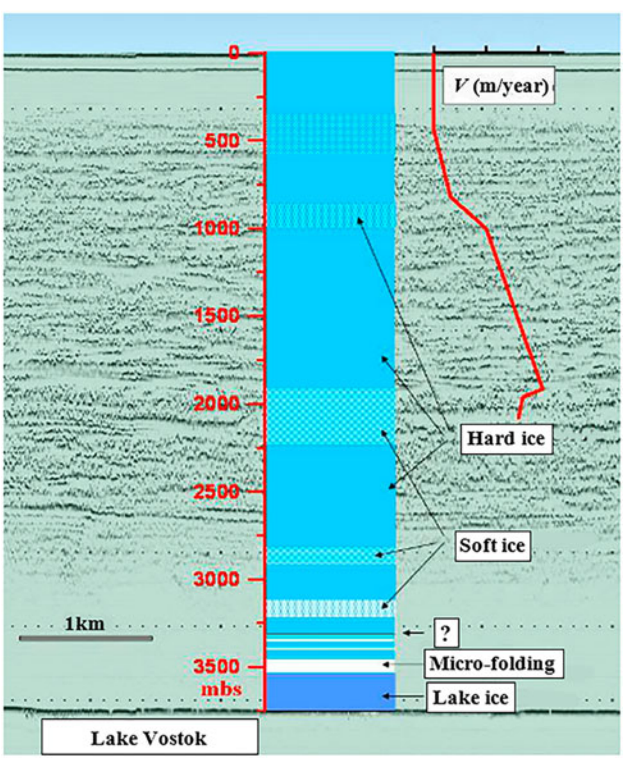

Figure 2. Layers of ice with different rheological properties in the ice-sheet section in the area of Vostok Station. The profile of ice velocity *V* relative to the surface is plotted based on the data from geophysical studies of a deep borehole.

Table I. Average physical and mechanical characteristics of ice.

Parameter	Value
Density of pure ice, ρ_0, kg/m^3	920
Porosity of surface snow, c_s	0.69
Compaction value, γ_s, m^{-1}	0.021
Creep index α in Glenn's law	3.0
Geothermal flow q_0, W/m^2	0.054
Melting point of ice (at a depth of 3700 m), T_f, °C	-2.7
Present-day rate of ice accumulation, b_0, cm/year	2.15
Young's modulus, E, Pa	9.33×10^9
Bulk deformation modulus, B, Pa	8.90×10^9
Shear modulus, G, Pa	3.52×10^9
Poisson's ratio, ν	0.35

Methodology

On the basis of published and experimental data on the ice cover and underlying rock, the native relief and the depths of the subglacial Lake Vostok (Ravich & Kamenev 1972, Grikurov *et al.* 2003, Savatyugin & Preobrazhenskaya 1999, Arapov *et al.* 2005, Popov *et al.* 2011, Popov & Lunev 2012), a three-dimensional model has been built, in which an elastic model of medium deformation and an elastic-plastic model of medium deformation based on the modified von Mises yield criterion have been used in

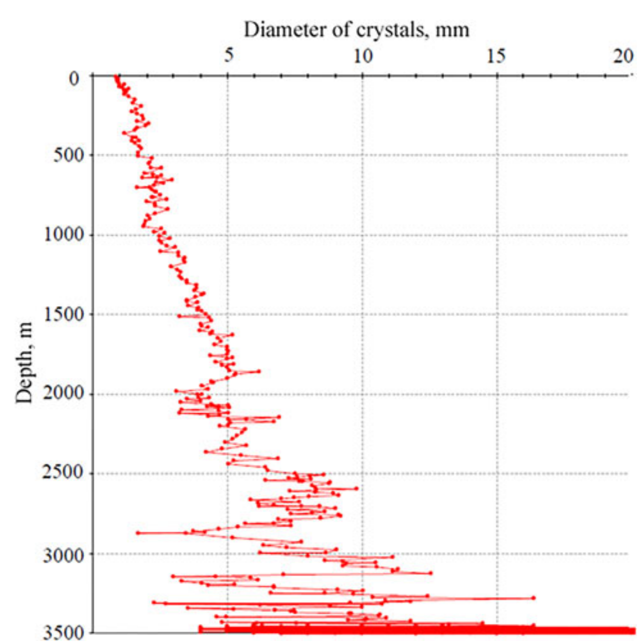

Figure 3. Change in ice-grain size with depth (Lipenkov *et al.* 2007).

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Table II. Physical and mechanical characteristics of the materials. The indicators are taken approximately and will be clarified based on the results of laboratory tests. The numerators show the instantaneous values of the indicators and the denominators show long-term values.

Name of the material	Density, kg/m^3	Stress-strain modulus, MPa	Bulk modulus, MPa	Shear-strain rate	Compressive strength, MPa	Tensile strength, MPa
Ice sheet	920	$\frac{9000}{1000}$	-	$\frac{0.350}{0.495}$	10	1
Lake Vostok water	1000	-	2100	0.499	-	-
Underlying rocks	2600	10 000	-	0.230	-	-

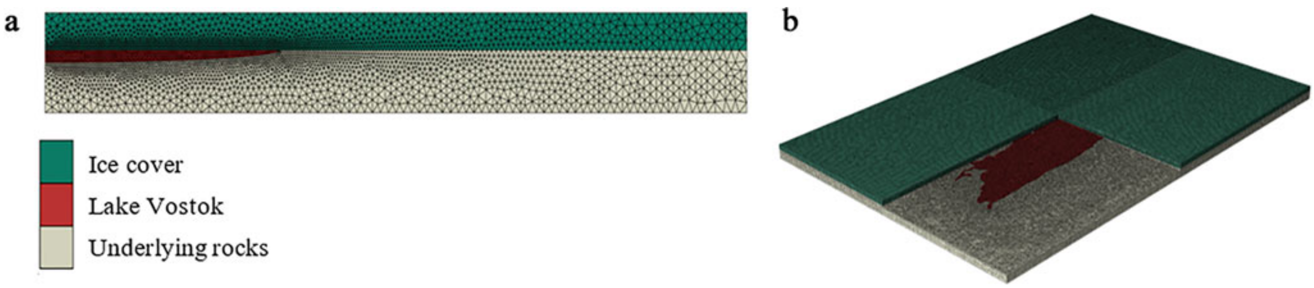

Figure 4. a. Planar and **b.** special finite-element models for forecasting the stress-strain state of the ice cover in Lake Vostok waters and the underlying rocks.

Table III. Brief description of the selected samples.

Sample number	Sampling location	Sample description
51101	Eastern edge of Amery Glacier, Mousinho Island	Fine- to short-grained charnockitoid (Cambrian metamorphosed intrusions)
51101-1	Eastern edge of Amery Glacier, Mousinho Island	Veined, medium- to coarse-grained granitoid gneiss (Cambrian metamorphosed intrusions)
52338-1	Fisher Massif, central part	Serpentinized ultrabasite (Mesoproterozoic metamorphosed intrusions)
52826-3	Fisher Massif, south-eastern rocks	Coarse-grained quartz monzogabbro (Mesoproterozoic metamorphosed intrusions)
52908-1	Prince Charles Mountains, Beaver Lake area	Polymictic gravelite (Permo-Triassic sediments)
52908-6	Prince Charles Mountains, Beaver Lake area	Polymictic conglomerate (Permo-Triassic sediments)
52910-1	Prince Charles Mountains, Beaver Lake area	Medium-grained gravelly sandstone (Permo-Triassic sediments)
53431-3	Prydz Bay, Bellingen Island	Fine-grained biotite-garnet gneiss (Neoproterozoic metamorphosed sediments)
54427-2Б	Prince Charles Mountains, MacLaud Massif, west shore of Radok Lake	Coarse-grained microcline granite (Neoproterozoic intrusions)
5410 (54427-2Б)	Prince Charles Mountains, MacLaud Massif, west shore of Radok Lake	Fine- to medium-grained orthogneiss of average composition (Meso-Neoproterozoic primary magmatic formations)

the numerical modelling of the stress-strain state of the ice cover, Lake Vostok waters and the underlying rock. The substantiation of long-term deformation characteristics of the ice has been performed on the basis of the adopted rheological model (Ashby & Duval 1985, Shyam Sunder & Wu 1990).

In the elastic model of medium deformation, the relationship between deformations $\boldsymbol{\varepsilon}$ and stresses $\boldsymbol{\sigma}$ (Eq. 1) is written through the elasticity matrix [**D**], which includes a set of coefficients determining the behaviour of the medium:

$$\boldsymbol{\sigma} = [\mathbf{D}]\boldsymbol{\varepsilon}. \tag{1}$$

The elasticity matrix for an isotropic linear-deformation medium is written in the following form (Eq. 2):

$$[\mathbf{D}] = \frac{E_y}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix}, \tag{2}$$

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Table IV. Results of testing the irregularly shaped samples with spherical indenters and their statistical processing.

Sample number	Sample	σ_p, MPa	$\sigma_{сж}$, MPa	$K_{хр}$	C_0, MPa	φ_0, °	C, MPa	φ, °	τ_{max}	μ	σ_R, MPa	$E_y \times 10^4$, MPa
1	521101	38.30772[a]	280.0981	7.463779	66.46047	54.32151	78.10359	31.05589	535.3268	0.294752	21.26	4.9
		5.230771[b]	63.19991	2.180692	7.177906	6.396274	11.14079	4.706684	319.4989	0.118624	3.59	0.41
		13.65461[c]	22.56349	29.21699	10.80026	11.77484	14.26412	15.15553	59.68297	40.2454	16.88617	8.367347
		4[d]	4	4	4	4	4	4	4	4	4	4
2	51101-1 perpendicular	7.730005	53.74231	6.964979	13.14289	53.70193	15.28877	30.47448	87.88383	0.298178	5.24	1.2
		3.057001	23.17355	1.058411	5.401421	3.622346	6.374545	2.58813	44.24567	0.072146	1.94	0.2
		39.54721	43.11975	15.19619	41.09766	6.745281	41.69429	8.492779	50.34563	24.19549	37.0229	16.66667
		5	5	5	5	5	5	5	5	5	5	5
2	51101-1 parallel	10.65343	53.88671	5.13884	15.41279	46.5601	17.0541	25.50567	54.76203	0.452151	24.52	–
		3.059592	12.65147	0.510185	4.001538	2.488361	4.292722	1.66136	10.68128	0.060165	4.64	–
		28.71931	23.47791	9.928022	25.96245	5.344407	25.1712	6.51369	19.50491	13.3064	18.92333	–
		5	5	5	5	5	5	5	5	5	5	–
3	52338-1	43.11024	247.8883	5.768515	66.51789	49.47749	75.06432	27.47218	306.1374	0.383523	24.526	6.5
		8.033813	52.08783	0.698329	12.61762	3.01989	14.59549	2.06379	100.1864	0.067915	4.640046	2.5
		18.63551	21.01262	12.10588	18.96876	6.103563	19.44397	7.51229	32.72595	17.7083	18.91889	38.46154
		5	5	5	5	5	5	5	5	5	5	5
4	52826-3	17.66563	121.0857	6.989387	29.77686	53.55363	34.57335	30.39909	198.0854	0.303142	9.82625	2.7
		7.548924	55.39224	1.308642	12.96187	4.262734	15.24687	3.076626	114.7121	0.082596	4.193549	0.32
		42.73227	45.74632	18.72327	43.53002	7.959748	44.10005	10.12078	57.91043	27.24654	42.67701	11.85185
		8	8	8	8	8	8	8	8	8	8	6
5	52908-1	8.475596	47.56542	5.670496	12.90471	48.84137	14.513	27.06607	57.71404	0.40072	4.85	3.4
		1.985592	10.11841	0.962914	2.669237	4.13745	2.975296	2.828671	21.81659	0.093363	1.2	0.54
		23.42717	21.27261	16.98112	20.68421	8.471199	20.5009	10.45098	37.80119	23.2987	24.74227	15.88235
		4	4	4	4	4	4	4	4	4	4	4
6	52908-6	8.885295	59.16962	7.062955	14.72893	53.54988	17.03179	30.42855	95.71384	0.305382	4.97	1.5
		3.489844	14.01227	1.639988	4.405751	5.037831	4.676626	3.662253	31.94282	0.097257	2.09	0.19
		39.27663	23.68153	23.21958	29.91222	9.407734	27.45821	12.03558	33.37326	31.84769	42.05231	12.66667
		6	6	6	6	6	6	6	6	6	6	5
7	52910-1	5.800909	33.8511	5.882291	9.015565	49.89674	10.1982	27.76757	42.94855	0.374847	3.29	1.3
		1.922801	10.79403	0.810901	2.871862	3.3046	3.234003	2.281191	17.02848	0.072663	1.11	0.01
		33.14655	31.88678	13.78546	31.85449	6.622877	31.71152	8.215309	39.64857	19.38471	33.7386	0.769231

(*Continued*)

Table IV. (*Continued.*)

Sample number	Sample	σ_p, MPa	$\sigma_{cж}$, MPa	K_{xp}	C_0, MPa	φ_0, °	C, MPa	φ, °	τ_{max}	μ	σ_R, MPa	$E_y \times 10^4$, MPa
		5	5	5	5	5	5	5	5	5	5	2
8	53431-3	24.12385	179.2449	7.628907	42.17863	54.75762	49.70744	31.37848	354.0061	0.286513	13.37	3.6
		4.537201	41.7168	2.308339	5.600976	6.327778	7.815362	4.698811	229.754	0.116121	2.96	0.73
		18.80794	23.27363	30.25779	13.27918	11.55598	15.72272	14.97463	64.90116	40.52916	22.13912	20.27778
		4	4	4	4	4	4	4	4	4	4	4
9	54427-2B	24.75456	166.9738	6.887386	41.36243	53.23575	47.90744	30.16733	269.032	0.309094	13.8	2.4
		6.186016	40.03593	1.400078	9.148416	4.582923	10.65471	3.306678	120.8175	0.088692	3.63	0.22
		24.9894	23.97737	20.32815	22.11769	8.608732	22.2402	10.96112	44.90824	28.69409	26.30435	9.166667
		4	4	4	4	4	4	4	4	4	4	4
10	5410-1	22.86534	156.1108	7.019673	38.52449	53.98698	44.67762	30.66284	247.9634	0.291178	12.69	4.4
		10.29432	63.87992	0.932596	16.36949	2.895051	18.70434	2.113176	101.2884	0.054044	5.81	0.4
		45.02151	40.91959	13.28546	42.49112	5.362498	41.86512	6.891652	40.84811	18.56064	45.78408	9.090909
		5	5	5	5	5	5	5	5	5	5	5

[a]The average values of the indicators.
[b]Root mean square deviations of the indicators.
[c]Coefficients of variation (%).
[d]Number of determinations.

where E_y is the modulus of elasticity and ν is Poisson's ratio.

The elastic-plastic model of medium deformation based on the modified von Mises yield criterion is written in the following form (Eq. 3):

$$\sigma_y = q, \tag{3}$$

where σ_y is the boundary value of tensile stresses corresponding to the true limit to the fluidity of the ice and q is the normal stress intensity.

For volumetric stress conditions (Eq. 4):

$$q = \frac{\sqrt{2}}{2}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}. \tag{4}$$

To describe the rheological processes in the ice cover, the double power law model is used, which provides the most complete description of the development of long-term deformations characteristic of the second stage of creep (i.e. the stage of steady-state creep).

The model makes it possible to take into account the influence of the intensity of tangential stresses on the rate of development of creep deformations, as well as the influence of temperature. For ice, the dependence of the creep strain rate on its state is transformed to the following form (Eq. 5; Protosenya & Katerova 2023):

$$\dot{\varepsilon}^{vp} = A_1 exp\left(-\frac{B_1}{\theta - \theta_Z}\right)\left(\frac{q_k}{\sigma_o}\right)^{C_1} + A_2 exp\left(-\frac{B_2}{\theta - \theta_Z}\right) \times \left(\frac{q_k}{\sigma_o}\right)^{C_2}, \tag{5}$$

where A_1, A_2, B_1, B_2, C_1 and C_2 are rheological model parameters determined experimentally, θ is ice temperature, θ_z is absolute zero temperature, σ_0 is a control parameter (taken to be equal to 1 MPa) and q_k is the intensity of tangential stress.

The parameters of the accepted models of material deformation are presented in Table II.

The described models are implemented in the *SIMULIA Abaqus CAE* software package.

Two finite-element models in planar-strain (Fig. 4a) and spatial (Fig. 4b) settings have been built to predict the stress-strain state of the ice sheet, Lake Vostok waters and the underlying rocks. The construction of the geometry of the models was carried out on the basis of geophysical survey data with some simplifications, which would not have a significant impact on the results of the prediction of the stress-strain state.

The problem has been solved in a gravitational setting with the following boundary conditions: displacements along the lower boundary of the model are prohibited in all directions; displacements along the lateral boundaries of the model are prohibited in the direction normal to these boundaries; and displacements along the upper boundary of the model are not limited.

The planar model dimensions are: width = 90 km and height = 10 km. The geometry is divided into triangular quadratic finite elements. The dimensions of the spatial model are: length = 2360 km, width = 2360 km and height = 10 km. The geometry is divided into tetrahedral quadratic finite elements.

Numerical modelling of the stress-strain state forecast of the considered system has been performed in the following sequence:

formation of the initial stress state before the formation of the ice cover; and formation of the stress state of the considered system in the process of ice-cover formation.

Determination of rock properties

In the study of the physical and mechanical properties of rocks, due to the limited volume of the samples taken and their non-standard shape, methods of testing samples of regular (cylindrical) and irregular shapes with spherical indenters have been used.

The research has been carried out according to the standard methodology (GOST 24941-81) and supplemented with data for determining the complex of mechanical parameters according to the improved methodology developed in the laboratory of physical and mechanical properties of St Petersburg Mining University. Elastic-wave velocities were measured in the samples beforehand and then tested in controlled deformation mode.

The following indicators of physical and mechanical characteristics of the samples have been determined: density of regular-shaped samples (volume density), propagation velocities of elastic longitudinal (VP) and transverse waves (VS), strength limits for uniaxial

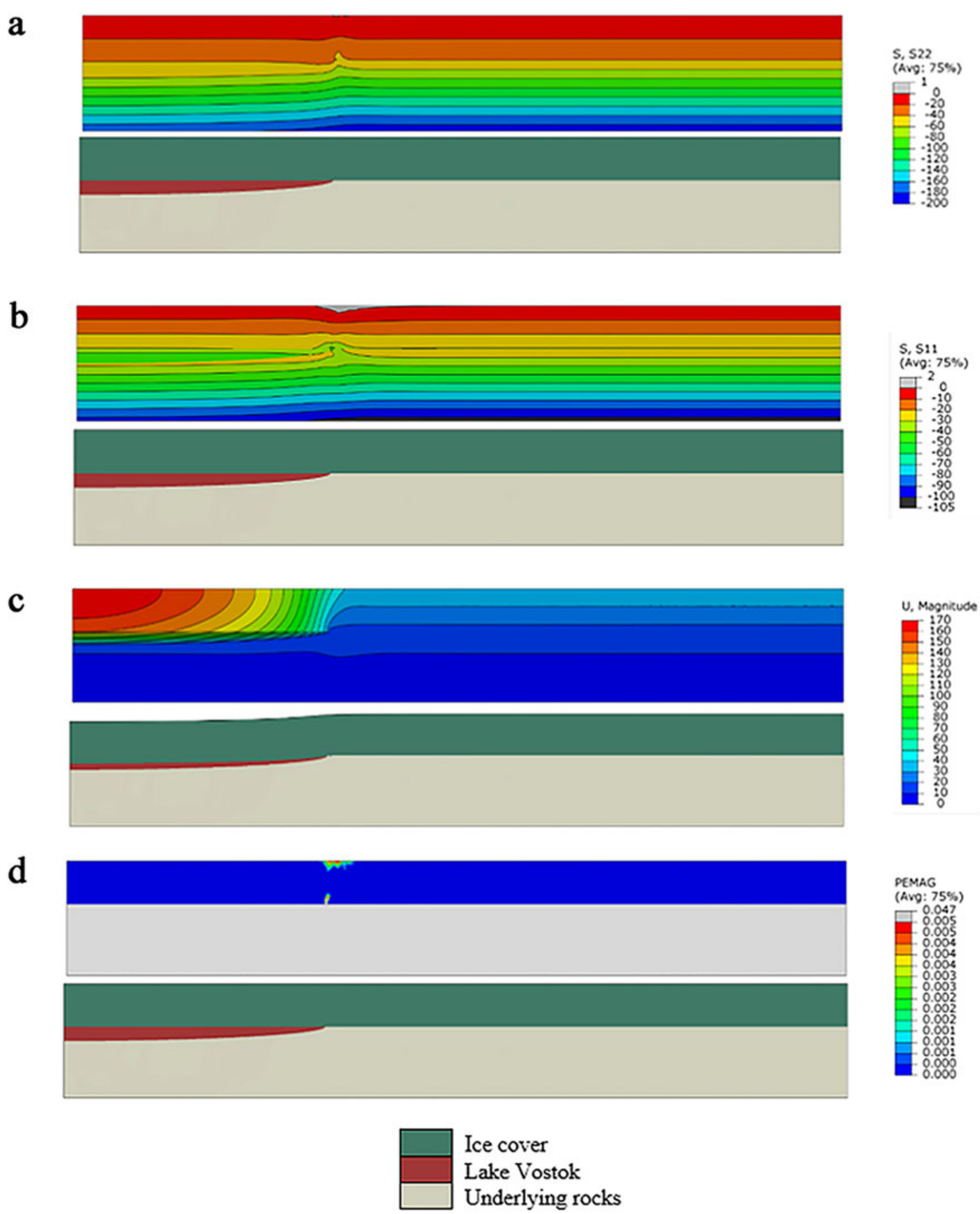

Figure 5. Distribution pattern in the planar deformation setting in the ice cover of the waters of Lake Vostok and underlying rocks: **a.** vertical stress (MPa), **b.** horizontal stress (MPa), **c.** resultant absolute deformation (m) and **d.** plastic deformations (fractions of a unit).

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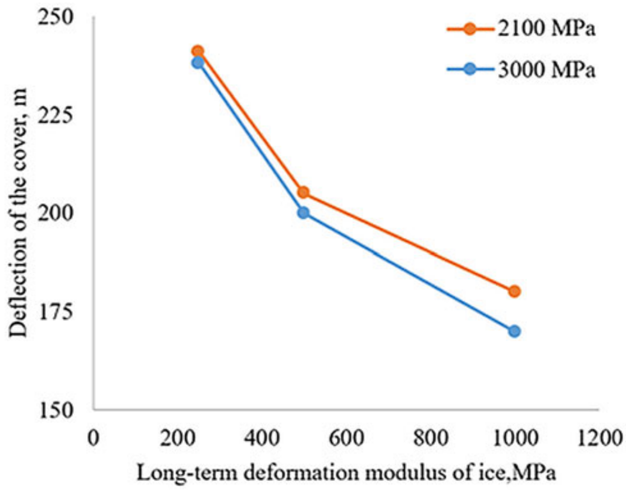

Figure 6. Variation of the maximum value of the ice-cover deflection depending on the long-term deformation modulus of ice and bulk modulus of water in Lake Vostok.

compression (σcj) and tension (σp), brittleness index (Bi), cohesion (C) in volumetric compression and the corresponding angle of internal friction (φ) and deformation characteristics - moduli of total deformation and elasticity, transverse deformation coefficients, modulus of bearing capacity decline and residual strength. Statistical processing of the test results has been performed.

Sample descriptions are given in Table III.

Results

As a result of laboratory studies of 10 samples of bedrock from East Antarctica, new information on lithologic differences of the basement has been obtained, and the presence of Permo-Triassic sedimentary deposits in the synrift complex has been established.

The test results from the 10 samples represented by magmatic, metamorphic and sedimentary rocks collected in East Antarctica (Prince Charles Mountains region) are shown in Table IV. The complex of the physical and mechanical parameters of the rocks determined from the results of tests of irregularly shaped specimens with spherical indenters is presented: strength limits under uniaxial tension (σp) and compression (σcj), brittleness index (Bi), ultimate shear strength without normal stresses (cohesion; C_0) and the corresponding angle of internal friction (φ_0), cohesion (C) under volumetric compression and the corresponding angle of internal friction (φ), modulus of elasticity (E_y) and Poisson's ratio (μ) and residual strength under uniaxial compression (σ_R). Statistical data processing has been performed.

The results of calculations and of predicting the stress-strain state of the system 'ice sheet-lake-underlying rocks' are presented in the form of diagrams of the distribution of vertical and horizontal stresses, as well as in the form of diagrams of the resultant absolute deformations and diagrams of plastic deformations.

The results of calculations in the planar-deformation setting (Fig. 5) allow us to make a judgement about the character of the ice-cover deflection over Lake Vostok and changes in the stress state of the water in the lake. It has been established that the potential deflection of the ice cover can reach 250 m with the accepted mechanical characteristics of ice and water bulk modules.

The influence of changes in the long-term ice deformation modulus in the range of 250–1000 MPa and the water bulk modulus range of 2100–3000 MPa is described by a non-linear relationship, with increasing ice-cover deflection values as the deformation modulus decreases (Fig. 6).

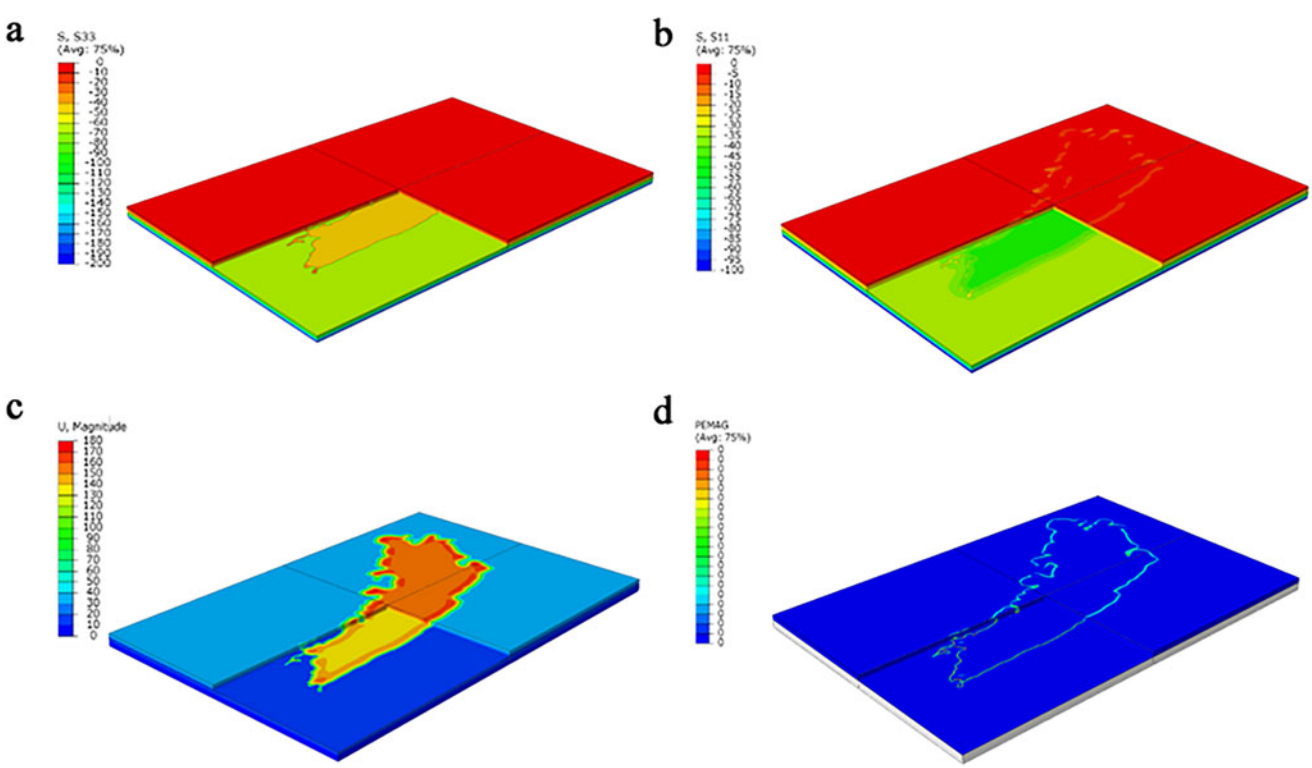

Figure 7. Spatial distribution patterns in the ice cover of the Lake Vostok waters and underlying rocks: **a.** vertical stress (MPa), **b.** horizontal stress (MPa), **c.** resultant absolute deformation (m) and **d.** plastic deformations (fractions of a unit).

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The largest deflection is observed above the centre of Lake Vostok. The stress distribution patterns suggest a complex character of stress distribution in the system under consideration in the vicinity of the lake. The plastic deformation zone is formed at the edge areas of the lake, and, as the results show, it does not extend to the entire height of the ice cover.

The results of calculations performed in the spatial setting are presented in the form of profiles of vertical and horizontal stress distribution and resulting absolute and plastic deformations (Fig. 7). Taking into account the complex geometry of Lake Vostok allowed us to clarify the character of formation of the stress-strain state of the ice cover. In general, it is possible to note qualitative and quantitative convergence of the modelling results in planar and spatial settings.

Discussion

To verify the reliability and correctness of the results of the numerical modelling, the geomechanical model has been verified using the data from experimental tests of bedrock samples and field observations in borehole 5G, drilled to a depth of 3769.3 m to the surface of Lake Vostok.

The geometric dimensions of the spatial model were chosen to achieve a calculation error of no more than 1% at the model boundaries.

The averaged rheological parameters that take into account the influence of the maximum creep strain rate (A_1 and A_2), the non-linear dependence between the initial velocity and stresses (C_1 and C_2) and the dependence of the creep strain rate on temperature (B_1 and B_2) are selected with the necessary accuracy to describe the ice sheet deformation process based on field observations in borehole 5G.

The stress values at the contact of the glacier with the lake according to the results of numerical modelling have been determined in the range of 32.0–35.0 MPa, and in the area of borehole 5 G to be 34.60 MPa, which satisfactorily correlates with the experimental data regarding the glacier pressure at the contact with the lake of 33.78 ± 0.05 MPa obtained from the results of measuring the ice-core density from borehole 5 G (Lipenkov *et al.* 2021).The slight discrepancy in the results is due to the averaging in the model of the rheological properties of ice by layer, as well as the fractal properties of ice crystals and changes in temperature along the depth of the ice cover.

Conclusions

A new three-dimensional geomechanical model of the system 'glacier-subglacial lake-bedrock ' has been developed, which allows for modelling changes in the stress-strain state of the system, taking into account the drilling of deep boreholes.

For the first time a set of physical and mechanical characteristics of the rocks of East Antarctica (the region of Prince Charles Mountains), including volume density, propagation velocities of elastic longitudinal and transverse waves, ultimate strength under uniaxial compression and tension, brittleness coefficient, cohesion under bulk compression and the corresponding angle of internal friction, as well as deformation characteristics (modules of general strain and elasticity, coefficients of transverse deformation, modulus of bearing capacity decline and residual strength), have been experimentally determined.

Numerical modelling has shown that the deflection of the ice cover at given ice characteristics can reach a value of 250 m or more. Changes in the mechanical characteristics of the ice cover can significantly affect this value.

It has been noted that the stresses in the waters of Lake Vostok are distributed according to the hydrostatic law, while the stresses in the ice cover are distributed according to a law similar to the hydrostatic law. The zones of development of plastic deformations of the ice cover over Lake Vostok have been determined. It is shown that plastic deformations in the ice cover are localized in the areas along the perimeter of the lake, and the maximum intensity of their distribution is confined to the lower and upper layers of the ice cover.

The data obtained provide satisfactory convergence with the results of *in situ* observations obtained during drilling of the ultra-deep borehole and penetration into the subglacial Lake Vostok at a depth of 3769.3 m.

The established regularities of stress-strain state formation in the elements of the system under consideration can be used as input data for modelling borehole drilling processes, as well as for forecasting the main parameters of the natural environment in the subglacial Lake Vostok and the underlying rock necessary for the design and effective operation of unique research equipment and instrumentation.

In further studies it is planned to experimentally specify the structure and strength-deformation characteristics of the ice cover, as well as the underlying rocks, and to reveal the influence of deep geothermal flows, which will make it possible to improve the three-dimensional geomechanical model of the system 'glacier-subglacial lake-bedrock ' and to consider it as a dynamic non-linear system in the large-scale study of the subglacial Lake Vostok.

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Competing interests. The authors declare none.

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