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GEOLOGY

Ice Cover of Lake Baikal as a Model for Studying Tectonic Processes in the Earth's Crust

Academician of the RAS N. L. Dobretsov[a], S. G. Psakh'e[b], V. V. Ruzhich[c], V. L. Popov[d], E. V. Shil'ko[b], N. G. Granin[e], V. Yu. Timofeev[f], S. V. Astafurov[b], A. V. Dimaki[b], and Ya. Starchevich[d]

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Investigation of real geological media faces significant difficulties related to the scale of objects (e.g., the length of fractures ranges from tens to thousands of kilometers) and significant durations of geological processes (long-term observations are needed to obtain reliable information about peculiarities of the response of fractures to forcing). Strains are accumulated over tens and even hundreds of years [1–3]. Therefore, physical modeling using simplified and smaller-scale block schemes is a promising field in the study of tectonic processes in the Earth's crust. The rheological characteristics, structural pattern, and forcing dynamics in such schemes can be considered similar to those in the Earth's crust [4–5]. The present paper is dedicated to study of the implication of the fracture-block system of ice cover in Lake Baikal and dynamics of its loading as an object for modeling geotectonic and seismogeological processes in the lithosphere. Investigations and observations were carried out during expeditions of the Siberian Division of the Russian Academy of Sciences in 2005–2006 with the participation of scientists from the Berlin Technical University (Germany).

Visual examination of the ice cover in Lake Baikal shows that it is a classic representative of a hierarchic fault-block medium. It consists of different sized blocks divided by fractures. The fractures penetrating the entire ice cover are actually boundaries between blocks (interfaces), which ensure the dominating sector of the deformation ability of ice floes and play a role similar to the tectonic fracture zones between plates or blocks in the lithosphere. Hierarchic organization of the block structure of ice cover in Lake Baikal determines one of its advantages as a model medium, namely the possibility to choose characteristic block sizes in a wide interval of scales (from a few meters to many kilometers). The relatively short duration of the characteristic processes of deformation and breaking (usually not exceeding a few days or weeks) is an important advantage of the model system considered here.

The rheology of ice is an important factor that provides similarity of the ice cover in Lake Baikal to lithospheric fragments. At typical winter temperatures, the ice in Lake Baikal is a brittle polycrystalline material, with an irreversible deformation zone comparable in length with the elasticity zone [6–8]. At the same time, when the ice temperature approaches the melting point (0°C), the ice becomes plastic. This is accompanied by a decrease in Young's modulus and the limits of fluidity and strength. Therefore, when comparing the Earth's crust and ice cover of Lake Baikal, it is important to note the general character of temperature variation with depth. For example, with increasing distance from the surface, the ice temperature increases from the value corresponding to the air temperature (from –15 to –30°C) to the water temperature (approximately 0°C). We note that the lithosphere has similar conditions, since the temperature of its surface corresponds to the air temperature (i.e., significantly lower than the melting temperature), while the temperature at the lower boundary is close to the temperature of the asthenosphere (i.e., close to the melting temperature of the corresponding geomaterials) [1, 9]. A similar type of temperature variation of mechanical properties of ice and the lithosphere ensures qualitative similarity of the variations in the rheology of the ice cover in Lake Baikal and the lithosphere. It is also noteworthy that both the ice cover

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[a] *Presidium of the Siberian Division, Russian Academy of Sciences, pr. akademika Lavrent'eva 17, Novosibirsk, 630090 Russia; e-mail: dobr@sbras.nsc.ru*

[b] *Institute of Strength Physics and Materials Sciences, Siberian Division, Russian Academy of Sciences, Akademicheskii pr. 2/1, Tomsk, 634021 Russia*

[c] *Institute of the Earth's Crust, Siberian Division, Russian Academy of Sciences, ul. Lermontova 128, Irkutsk, 664033 Russia*

[d] *Berlin Technical University, Sekr. C 8–4, Gebaude M, Strasse des 17 Juni 135, Berlin, 10623 Germany*

[e] *Institute of Limnology, Siberian Division, Russian Academy of Sciences, ul. Ulan-Batorskaya 3, Irkutsk, 664033 Russia*

[f] *Trofimuk Institute of Oil and Gas Geology and Geophysics, Siberian Division, Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090 Russia*

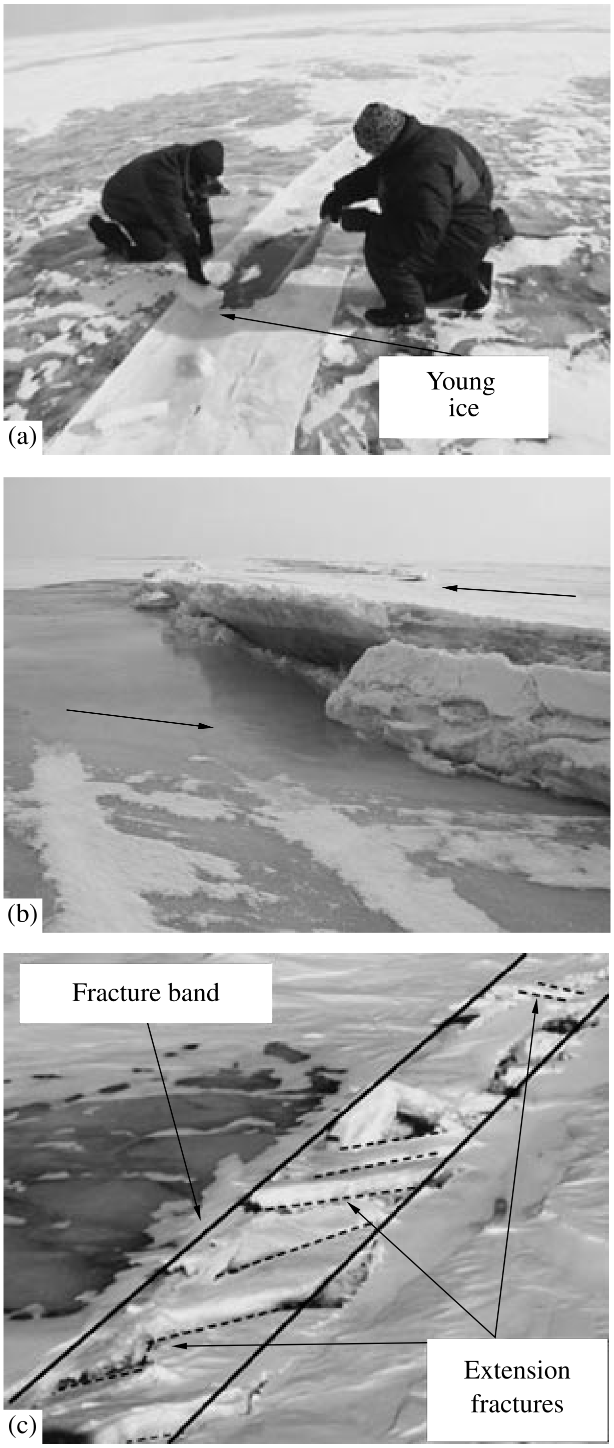

Fig. 1. Examples of structure formation of (a) spreading, (b) subduction, and (c) pull-apart types in the ice cover of Lake Baikal.

and the lithosphere are located over a melted (in the case of the lithosphere, viscous and partly melted) substrate, which is an important factor ensuring the qualitative similarity of the conditions at the lower boundaries of the media considered here. This determines in many respects the general regularities of their mechanical behavior.

The stressed state of the ice cover is an important factor of its hierarchic-block structure. This state appears as the result of interaction of the newly formed or moving (under the forcing of wind and currents) ice cover with coasts. It is clear that owing to the morphological diversity of coasts in Lake Baikal, the stress–strain state of the ice cover is complicated and nonuniform. Therefore, the ice cover can include elements of extension, compression, shear, and bending.

The coastal topography determines the intervals marked by the creation of the most favorable conditions for the formation of fractures. The fractures crosscut the ice cover in both longitudinal and transversal directions into separate ice flows. They are characterized by a regular distribution pattern, which is repeated every year [10]. It is important to note that the main factors that influence the ice cover and determine the variation in the stressed state of the system, are a priori temperature fluctuations of the air related to solar insulation, snow cover, wind stress, currents under ice, and temperature convection of the water. However, it is rather difficult to estimate the role of each of these factors due to the overlapping of multiple factors and other reasons.

The results of investigations and observations carried out during expeditions demonstrated that some mechanisms of deformation of the fault-block ice cover of Lake Baikal can be correlated with the effects known in geodynamics, such as spreading, subduction, pull-apart, and others [1, 11–13]. Figure 1 shows particular examples of the formation of such structures in the ice cover.

During the expedition, we carried out not only general investigation of the character and peculiarities of the behavior of the ice cover in Lake Baikal, which is located in a complex constrained state of stress, but also detailed instrumental study of the strain regime of its fragment related to one of the active major fractures. Figure 2 presents a schematic chart of the investigated sector of this interface boundary.

This fracture represents an echelon of smaller ruptures (oriented at an angle of ~35° to the latitudinal line), which serves as a common interface. The length of each rupture reaches a few kilometers. Each subsequent rupture (off the coast) is located southeast of the previous one, which points to the dextral character of the shear component of displacements along the general fracture. The distance between the edges of the neighboring ruptures is approximately the same and reaches a few tens of meters. Moreover, their edges are connected by blind or nonfrozen fractures. Such a morphogenetic scheme of the major fracture reflects the kinematics of its growth and can be considered as a scaled model of the formation of a seismogenerating general tectonic fault (Fig. 3).

During the expedition in 2006, we carried out instrumental measurements of relative normal and

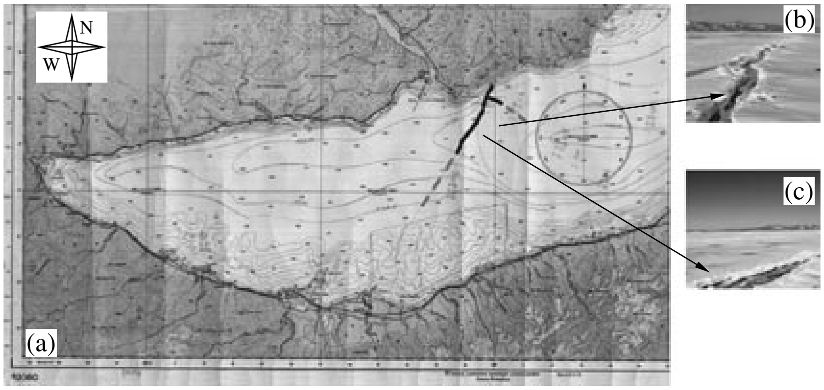

Fig. 2. Chart of the southern sector of Lake Baikal. The solid line denotes visually examined sectors of the active fracture; the dashed line, approximate directions of the further propagation of the studied active fractures.

shear displacements of the edges of fractures dividing ice blocks. The equipment used in the study made it possible to perform measurements accurate to a few micrometers. The results of measurements indicate that active deformations took place in the observed fragment of the block medium during the entire observation period. This is manifested, in particular, in widening of the studied interface. The rate of increase and widening increases with the distance from the coast (Fig. 3). For example, the total extension over a period of 6 days was equal to 12 mm near the site of intersection of fracture B with transversal active fracture B1 (which appeared much later than fracture B) and was as much as ~0.5 m at a few kilometers from the coast. Fragments of these fracture sectors are shown in Figs. 2b and 2c, respectively. It should be noted that the apparent width of the active band (i.e., the band of ice-free water or a thin layer of young ice) decreases and does not exceed a few centimeters when we trace along fracture B from the site of intersection with fracture B1 in the direction to the coast (i.e., upward in Fig. 3). Hence, it is likely that the main deformations during the observation period in the studied fragment of the ice cover are related to the formation of the block limited by fractures A, B, and B1.

As seen in Fig. 3, the shear component of relative displacements along fracture zone A–B is small (no more than a few millimeters). At the same time, both the normal and tangential relative displacements increase at the site of intersection with fracture B1 by one order of magnitude. This confirms the existence of the rotational deformation mode, which is manifested in the rotation of the ice block bounded by fractures A, B, and B1. Such signs of rotational behavior of the lithospheric plate are characteristic of geodynamics. This relative motion of the ice block is explained by the action of flexural stress of the ice block medium related to the constrained shear-type strain (the main shear is likely to be directed along the coastline) in the study region. The action of local flexure stresses also explains the fragmentation of the studied fragment of the ice cover due to the formation of latitudinal fracture B1 (and younger smaller accommodation fractures B2 and B3).

Deformations associated with the relative displacement of ice blocks are manifested irregularly as a sequence of stages (phases) of the relatively rapid increase in displacements divided by time intervals, during which the rate of displacements are slowed down. During these intervals, the edges of fractures can congeal and ice plates can consolidate. This process is similar to the geological process of healing of fractures. Therefore, the stages of rapid growth of the major fracture after the freezing phase frequently begin with a dynamic shock and rapid displacement along the frac-

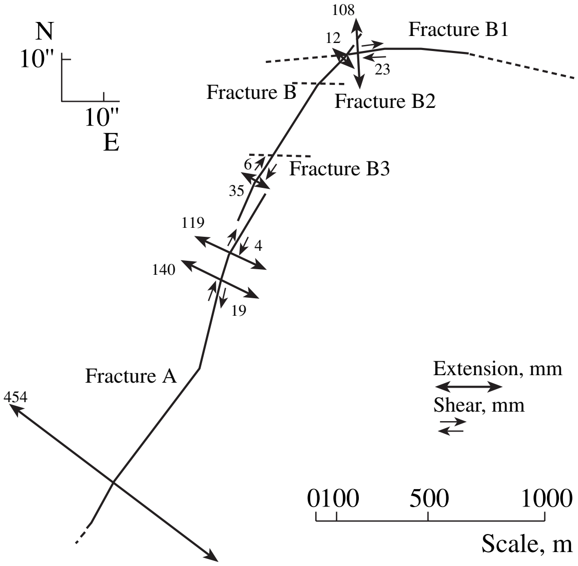

Fig. 3. Schematic chart of instrumentally studied sector of the line of the active boundary between ice blocks. Solid lines show fractures plotted on the basis of GPS data; dashed lines, approximate directions of the spreading of fractures; arrows, the direction of relative normal and shear displacements of fracture edges for six days; numerals near the arrows, displacements (in mm).

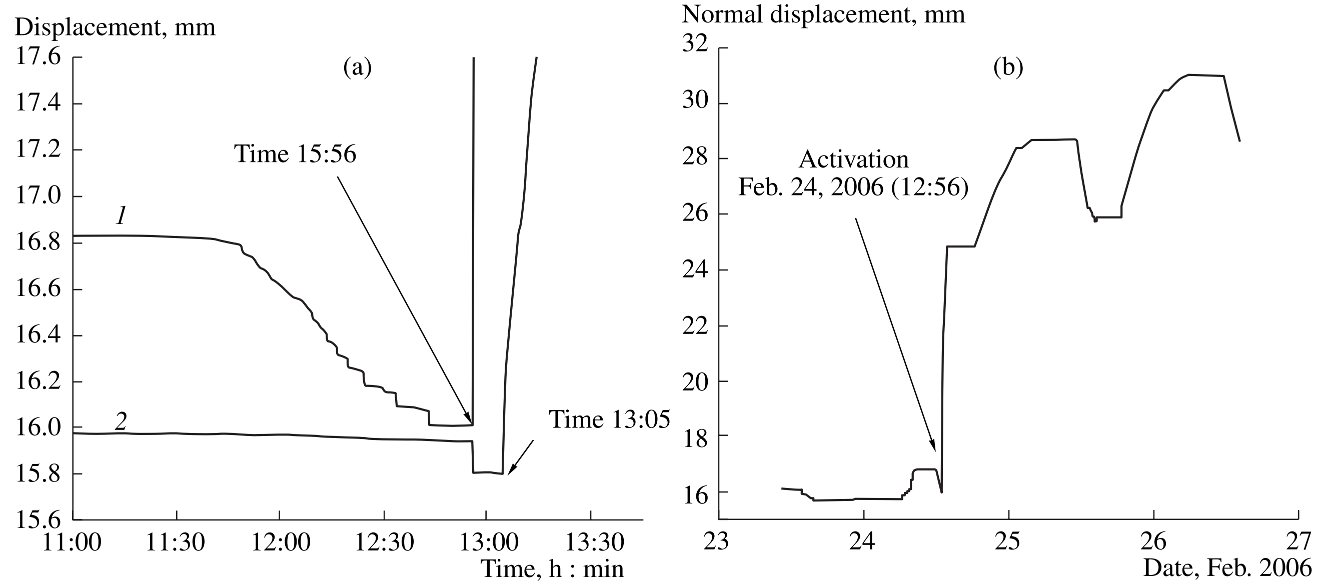

Fig. 4. Diagrams of relative normal displacements of the edges of conjugated fractures A and B during the expedition in 2006. (a) Displacements at fractures A (curve *1*) and B (curve *2*) during the recording of the icequake on February 24 (arrows indicate the moments of activation); (b) displacements at fracture A from February 23 to February 27 (arrow indicates activation at 12:56 accompanied by a strong icequake).

ture. In this case, very strong icequakes can be heard well even at a great distance.

One of the strongest icequakes was recorded during the formation of large ice fracture B1 as a result of local flexure stresses. During the next few days, flexure stresses produced parallel accommodation (weaker) fractures B2 and B3. Similarly to the block geological medium, we can expect with high probability the generation of a series of seismic shocks in areas of strong flexure stresses.

During the expedition in 2006, we managed to establish an unambiguous correlation between several strong icequakes and the beginning of activation phases of the studied interface formed by fracture series A and B. Analysis of the results of displacement records showed that activation of the interface is stepwise; i.e., it spreads from one conjugated fracture to another. Figure 4 shows relative normal displacements of ice blocks along fractures A and B for one of the recorded icequakes. It is seen that drastic widening of fracture A at time moment 12:56 started 9 min before the stage of fracture B activation. The results of instrumental measurements and numerous data of visual observations allow us to suppose that activation of the studied interface, which is a series of fractures, starts far from the coast and then propagates toward the coast. This confirms the conclusion about significant local flexure stresses in this fragment of the ice cover.

Similarly to earthquakes, the icequakes are kinetically related to changes in the stress–strain state of the block system. For example, the response of the medium changed after the icequake recorded on February 24 (Fig. 4a). This can be illustrated by the recorded significant change in the daily evolution of relative normal displacements along fracture A (Fig. 4b). It is likely to be related to an increase of fracture B1 and possible formation of a subblock, which increased the deformation ability of the system as a whole. This confirms the results of measurements obtained by other sensors.

We note that the character of deformations of the fragment of ice cover in Lake Baikal described above is typical for different block media (or their regions) located in complex constrained conditions of stress. In particular, the kinematics of the formation of the major fracture demonstrates a physical similarity to the development of seismogenerating faults in the Earth's crust in the regions of seismic hazard, such as the Obruchev, Dolinoozero (Mongolia), and San Andreas (United States) faults, among others. Judging from the collected data [14], a similar event could take place in the pleistoseist zone of the Altai earthquake in 2003.

The main results of observations and measurements of deformations and destructions of fault-block ice cover in Lake Baikal obtained during the expedition in 2005–2006 are as follows:

(1) Some mechanisms of deformation of the ice cover in Lake Baikal can be correlated with effects known in geodynamics, such as spreading, collision or subduction, pull-apart, and others.

(2) In the studied fragment of the ice cover in Lake Baikal, the concentrator of stresses was formed in the zone of flexure stresses caused by rotational deformation of one of the blocks.

(3) Stresses caused by flexure deformations relaxed owing to the generation of fractures as icequakes

(recorded by acoustic methods and measurement of ice displacements). Hence, earthquakes can also be genetically related to flexure deformations and rotations of blocks in the Earth's crust. This statement corresponds to the concept of structural levels of deformations and destructions in modern strength and elasticity physics [15]. According to one of the corollaries of this science, constrained shear generates rotation. On the contrary, constrained rotation initiates the development of shear deformation.

Thus, the observed processes of deformation and destruction in the block medium of the ice cover in Lake Baikal demonstrated its high potential as a model of a unique medium for investigating mechanisms of tectonic processes in the Earth's crust. In particular, this method opens the possibility for efficient modeling of physical phenomena of earthquake source preparation.

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