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Article *in* Geologiya i Geofizika · January 2001

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Institute of the Earth's Crust
56 PUBLICATIONS **232** CITATIONS

ISSN 1068-7971

RUSSIAN GEOLOGY AND GEOPHYSICS

ГЕОЛОГИЯ И ГЕОФИЗИКА

2

Vol. 42, 2001

Allerton Press, Inc. / New York

Russian Geology
and Geophysics
Vol. 42, No. 2, pp. 297-306, 2001

Geologiya
i Geofizika
UDC 551.243+551.312.4

FRACTURES IN THE BAIKAL BOTTOM SEDIMENTS
(*studies of BDP-98 core*)

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Structural studies of BDP-98 cores recovered during deep drilling on the submerged Akademichesky Ridge as part of the Baikal Drilling Project have shown that the Baikal bottom sediments are cut by extension and shear joints of various scales, locally clustered into zones of fracturing. The conditions of rifting and diagenesis are responsible for the latent character of joints, effect of fluid pressure on the formation of extensional joints, prevalently normal slip on shear joints, and the structure of the fracture zones favorable for horizontal extension. The results provide an insight into the regularities of active extensional jointing, as in Baikal it is not overprinted with earlier deformation.

Fractures, sediments, Baikal basin, joints, zones of jointing, rifting, Baikal Drilling Project

INTRODUCTION

Lake Baikal fills the deepest intracontinental rift basin in the center of Asia (Fig. 1, *a*) [1–3]. Lithospheric extension that has acted in the region for the past 25–30 Ma favored accumulation of up to 8 km of basin fill [4–7] composed of unconsolidated diatom-bearing silty clays and sands with nearly horizontal bedding away from the basin sides.

Single-channel seismic profiling [8–11] revealed four major units in the strongly fractured Baikal basin fill, and recent multichannel seismic profiling provided more details of the fracture pattern [12–16]. Reflection profiles along and across the basin strike in the lake center (region of the submerged Akademichesky Ridge) showed that the basin fill responds to the ongoing extension by tectonic fracturing. The largest fractures continue active basement faults, and smaller ones are restricted to sedimentary layers (Fig. 1). Faults are mostly of normal geometry and northeastern or northwestern strike and dip at 50° on the average. Transverse faults, including NS and WE fractures [14], bear strike-slip components of various magnitudes [12].

The same structural pattern has been obtained from mass measurements of fractures on Ol'khon Island and in the Ol'khon region (the land that continues northeastward into the submerged Akademichesky Ridge) [17]. Moreover, the same strike directions are known from land surveys to be the principal components of the general fault pattern of the Baikal Rift [18].

The Baikal Drilling Project [4–6] offered an opportunity to investigate fractures in the Baikal bottom fill from visual examination of drill cores. The 600 m long BDP-98 core [7] differs from the previous 100 and 200 m cores (BDP-93 and BDP-96, Fig. 1, *a*) as it contains structural elements (Fig. 2) that can be classified as fractures (joints) unlike commonly encountered features of layering, erosional surfaces, cross lamination, bioturbation, diagenetic layering, sliding and flow structures, etc.).

Fractures in the BDP-98 cores are numerous, and their origin is not related to coring. Therefore, special structural studies were needed to analyze their character and distribution to make a basis for geophysical and paleoclimatic implications and to gain an insight into the general regularities of extensional fracturing. The specific objectives of this study were (1) to typify the fractures in the core on the basis of their geometry; (2) to analyze relationships among fractures of different types and their downcore distribution; (3) to identify the origin and hierarchy of fractures; and (4) to assess the degree of fracturing in the core and related quality of paleoclimatic information.

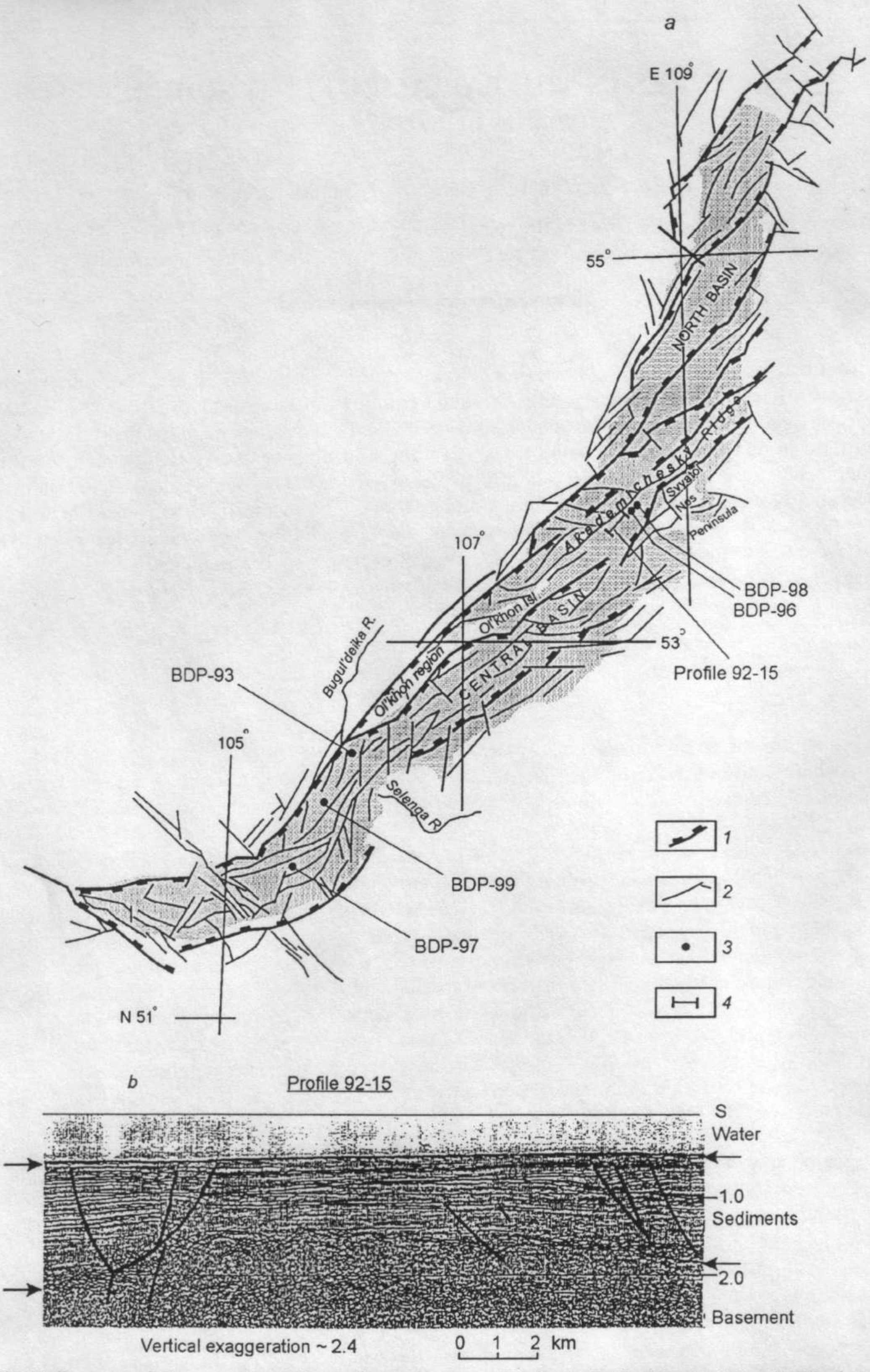

Fig. 1. Structural framework of the study region. ***a*** **— Faults in Baikal basin (after [15]);** ***b*** **— multichannel seismic profile 92-15 (after [16]) located <1 km away from BDP-98 borehole.** ***1*** **— major faults (teeth show dip direction);** ***2*** **— smaller-scale faults;** ***3*** **— location of BDP boreholes;** ***4*** **— location of multichannel seismic profile 92-15.**

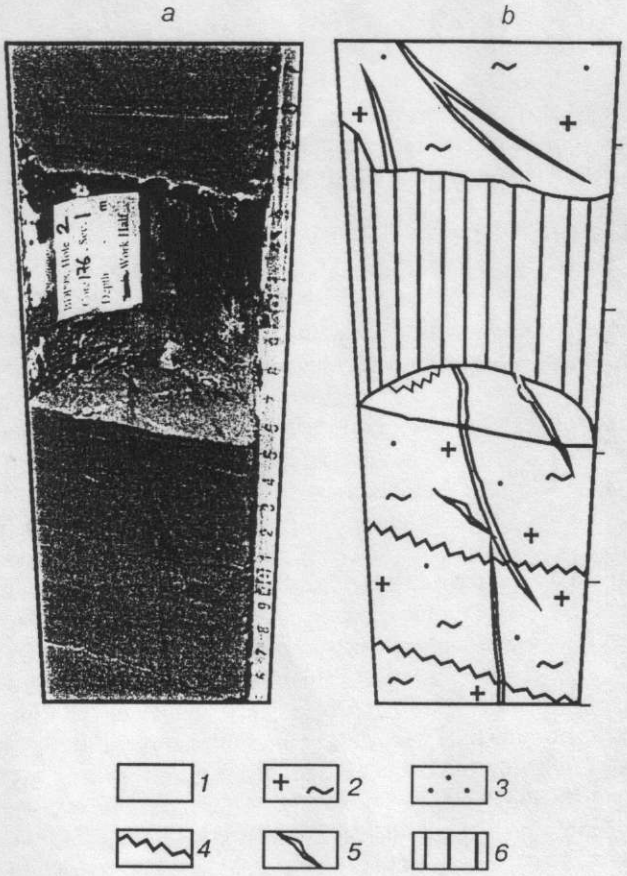

Fig. 2. ***a*** **— Photograph (courtesy Ko-Ichi Nakamura, Geological Surveys of Japan, Tsukuba) and** ***b*** **— documentary sketch of core section 176 (core depth 320 m) in which fractures are clearly evident. Scale bar (on the right core edge,** ***a*****) is 5 cm.** ***1*** **— representative part of core sample;** ***2*** **— pelitic diatom ooze;** ***3*** **— sand;** ***4*** **— core breakage;** ***5*** **— fractures;** ***6*** **— back wall of plastic liner.**

MATERIALS AND METHODS

For details of drilling and coring techniques see the previous BDP publications [4–6]; we confine ourselves to what is relevant to the state of the core. The BDP-98 borehole was drilled under 333.4 m of water on the eastern slope of the submerged Akademichesky Ridge (53°44′48′′ N, 108°24′31′′ E, Fig. 1, *a*). The ridge is an asymmetric fault-bounded horst that crosses obliquely the Baikal basin and divides it into the northern and central subbasins (Fig. 1, *a*). The horst rises from 500 m above the lake bottom in the northwest to above 1000 m in the southeast, and its top is 300–500 m below the water surface.

The borehole is less than 1 km away from the CMP multichannel seismic reflection profile 92-15. The departure from the vertical during drilling never exceeded 3–4°, i.e., no correction is needed to measure slopes of planar structural elements in the core. Drilling stripped 674 m of sediments (of the total 1000 m section at the site) and provided continuous unoriented coring, with a unit core 220 cm long and 75 mm in diameter in the most strongly deformed depth interval. The upper 270 m of sediments were sampled by piston coring, with an output of about 95% of undisturbed core; the lower 270 to 600 m were sampled by rotary coring, with a lower output (90%), and the cores were retrieved in plastic liners.

The core sections in the plastic liners were cut with a special high-speed saw, and all their structural and textural features were carefully sketched and documented, the structure of sediments was analyzed microscopically, and their physical properties were measured.

The cored sediments are composed of finely laminated silty clays with thin interlayers of fine sand, the alternation frequency increasing downcore. The sediments contain from 5 to 80% diatom frustules. The density and water content of sediments vary at different depths from 1.27 to 1.87 g/cm^3 and 17.1 to 73.9%, respectively.

The section deposited under the subaqueous conditions of a deep lake. The basal age of the core is 10.3 Ma (at 600 m).

Deformation was studied in more than 600 m of the BDP-98 cores, focusing mostly on the geometry of fractures (for this their surfaces were cleaned and carefully documented), as well as their length, gape, slip, dip, and frequency. The data collection was large enough (about 2800 small fractures examined) to allow statistical processing.

RESULTS AND DISCUSSION

Second order fractures (joints). Visual examination of the BDP-98 core showed that most of the largest-scale fractures are latent *in situ*, because the sediments subject to diagenesis are in the plastic state. The evident fractures that break the core and are also encountered in bedrock exposures have appeared during core retrieval and were not taken into consideration. They can be easily discriminated as they are always oriented across the core, filled with drilling mud, and have rugged surfaces and crumbling edges, etc. Other fractures, frequent in the core below ~50 m, are of two main types.

Fractures of the first type (Fig. 3, *a*) are curved, with tortuous edges and zero longitudinal displacement, 5 to 10 cm long, occasionally 40–50 cm. Their fairly large gape indicates origin under extension. That is why the fractures in the uppermost section occur mainly near local heterogeneities, such as intense layering, contacts between sediments of different structural and mechanical properties, or erosional features.

These fractures are well distinguishable from traces of bioturbation (left by worms, amphipods, or fish), as worm channels are round, short (3–5 cm), and narrow (3 to 10 mm), while fractures are, as a rule, long, wide, and straight (in transversal profiles) and have a planar geometry well defined in differently oriented core sections (Fig. 2). Note that worm channels were taken for joints at the first stage of the core studies.

All fractures are healed with material that resembles a finer-grained and darker variety of the host sediment. Voids, up to 2 mm in diameter, in the broader central parts of some fractures indicate that the filling may have formed by dilution of the ambient sediments with fluids released during consolidation in a subaquaeous environment. Activity of these fluids in the region of the Akademichesky Ridge may have been favored by heating of the upper crust, which is marked by relatively high temperatures in the BDP-98 borehole (31.35 to 31.75 °C) [7] and elevated surface heat flow (70–80 mW/m^2) [19].

Therefore, the fractures of the first type can be classified as extension joints (parting fractures [20]) or even "veins" [21] as their opening can be visually evaluated. Nielson et al. [22, 23] used this term for healed fractures encountered together with open ones in the lithified sedimentary cores in the Philippines and New Mexico (USA).

The joints we revealed differ from those often encountered in natural and excavated exposures as they formed in unconsolidated sediments. Fracturing in unconsolidated sediments is not unique to Baikal. Cook and Johnson [24] described sandstone-filled joints (larger than those we studied), which formed, among other factors, under the effect of tectonic forces at the early stage of deposition and preserved in rock after its burial. Larchenkov et al. [25] report that geophysical exploration and drilling in the Dnieper-Donetsk basin revealed a specific type of joint which is filled with salt or terrigenous material (inversion joints) and was produced during broadening and subsidence of the sedimentation basin. In all these regions, sedimentation occurred under the conditions of tectonic activity.

The complex geometry of extension joints and their sensitivity to active stress make them difficult to systematize according to the position in the core. However, although the distribution of fractures is somewhat chaotic, the statistically predominant orientation is vertical, while horizontal or oblique orientations are scarcer (Fig. 3, *a*). Therefore, in addition to the effect of pore fluids, which reduces the stiffness of sediments, the latter may have formed under the effect of tectonic movements, as the territory has lately evolved under horizontal extension. The origin mechanism and the size of the joints indicate that fracturing alone has not caused considerable deformation, and perfect cementation is evidence against ongoing activity.

Fractures of the second type are absolutely different (Fig. 3, *b*), being latent and not filled, but are easily distinguishable by a number of specific features. Some fractures become visible on core retrieval because of stress relaxation. Others are evident from offset bedding, contrasting coloration of different parts of sediment layers, or displacement of other fractures that show normal or reverse geometry of fault planes. Most fractures of this type occur in gray sediment and are marked by black rims of hydrotroilite (iron monosulfate). In these cases, stress not only produces fractures but also causes concentration of a diagenetic mineral on their surface, which is contained in pore fluids and was relatively uniformly distributed through the ambient sediment prior to diagenesis.

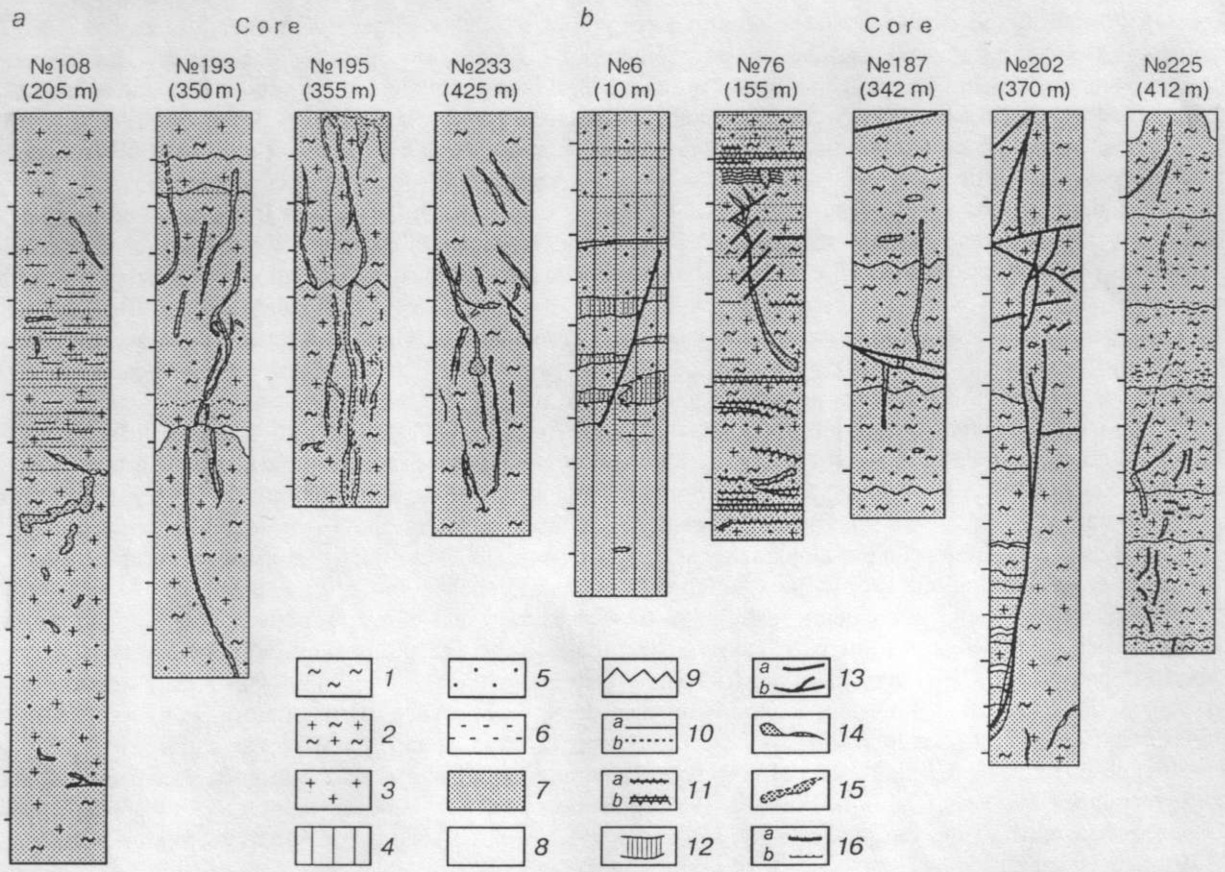

Fig. 3. Extension (a) and shear (b) joints in BDP-98 core (after drill core description by Karabanov, Prokopenko, Gvozdkov, Nakamura, and Hase). Scale bar is 5 cm. 1 – silty pelitic mud; 2 – pelitic diatom ooze; 3 – diatomaceous mud; 4 – glacial clay; 5 – sand; 6 – silt or sand lenses; 7 – representative part of core; 8 – missing parts of core; 9 – core breakage; 10 – well-defined (a) and weak (b) lamination; 11 – small (a) and larger (b) elements of layering marked by green-color material; 12 – bedding elements colored with hydrotroilite; 13 – small (a) and medium (b) shear joints; 14 – extensional joints; 15 – extensional joints with poorly pronounced contacts; 16 – shear joints (a) and elements of bedding (b) lined with hydrotroilite.

The probability of this phenomenon is implicitly proved by migration of ore from rocks into fractures during compression of samples under high pressure and temperature [26]. Quartzite containing subparallel hematite flakes (5%) was compressed perpendicular to layering (100,000 kg/cm^2) at 250 °C and the ambient pressure of 3000–6000 kg/cm^2. As a result, the samples were split into blocks by oblique joints. Hematite flakes from nearby rock were squeezed into the joints but retained their original orientation in the central parts of the blocks. Some joints are fully healed with hematite and became microveins.

In spite of different pressure and temperature conditions, this process may be similar to redistribution of hydrotroilite in the Baikal sediments, as the structural and mechanical properties of the deformed substrate differ correspondingly in both cases. In general, lining of longitudinal fractures with organic matter (hydrotroilite in Baikal sediments) is quite frequent in nature and is similar to coalification of faults initiated during deformation of poorly lithified coal-bearing sedimentary sequences, as it occurs, for instance, in Jurassic rocks on the southern periphery of the Irkutsk amphitheater [27, 28].

The hydrotroilite-lined fractures (Fig. 3, *b*) are most frequently 20–30 cm long and 0.1–0.2 cm wide and are visible as relatively straight lines in the plane section of core samples; larger fractures (up to 1 m long and 0.4–0.5 cm wide) leave undulated traces, as they consist of conjugate straight segments. In this they are similar to fractures that form in models of wet clay or sand and make the internal structure of shear zones [29–31]. Analogy is observed in the arrangement of fracture sets: One or two sets mostly predominate in the disturbed core fragment, and the most frequent is the set with dips of 60–70°.

On this basis, the fractures of the second type should be rather classified as shear joints [20, 21, 32] contrary to the opinion that all fractures showing longitudinal slip are faults [33]. Shear joints are less frequent than extensional joints but are rather abundant in the BDP-98 core. Though being predominantly latent because of specific conditions of the host rocks, they cause numerous small displacements (up to 20 mm).

The extension and shear joints together make up the majority of fractures in the bottom sediments in the BDP-98 region. Other fracture-like elements are less frequent but require special investigation.

Thus, the high-order fractures in the Baikal sediments are joints. Unlike similar fractures in consolidated rocks, they are latent because of the specific state of the diagenetically altered substrate. The diagenetic pressure of pore fluids and the load of the overlying sediments play a considerable role in fracturing, primarily in extensional jointing. However, the spatial orientation of the latter as well as the character of displacement and the presence of shear joints attest to the effect of tectonic forces, which is normal for an active seismic zone of the crust such as the region of drilling. This hypothesis can be checked by investigation of the relationships between the extension and shear joints and of their downcore distribution.

First-order fractures (zones of jointing). There are three typical patterns of spatial relationships of extension and shear joints in the core. Most often joints of the two types exist independently in the neighboring parts of the core (Fig. 3, *b*, samples 6 and 202). Shear joints may displace extensional ones (Fig. 3, *b*, samples 76 and 187), but we have never observed that extensional joints crosscut the shear joints; occasionally, the extensional and shear joints can be conjugate (Fig. 3, *b*, sample 225). These relationships show formation either in a single or in different stress fields; in the latter case most of shear joints are younger.

The qualitative description being insufficient to discriminate between diagenetic and tectonic origin of fractures, their spatial distribution was analyzed quantitatively by estimating depth-dependent variations in fracture density (Fig. 4). Density of joints (N) was estimated as their visible number in a core section of a certain length, at least 5 m. This simple parameter provides a realistic idea of rock failure, as was checked by similar calculations from the total length of fracture traces (a more precise parameter).

It is seen from Fig. 4, *b* that joints of both types demonstrate polymodal distribution of N, and extensional joints are almost everywhere more numerous than shear joints. At the same time, most of the density peaks of shear joints (and all the ten peaks in the most strongly deformed core interval) are correlated with local peaks of extensional joints. The existence of segments with the highest density of joints of both types cannot be explained by variations in the physicochemical properties of the deformed sediments. Moreover, the ordered pattern of joints is evidence of their common origin. The highly fractured zones of the core, as a rule, show a clear zonation, with extensional joints mostly on the periphery and shear joints in the center, and the joint sets are those as in known zones of shear stress [21, 29–31].

Figure 5 shows interpretation of the structural setting in one of ten zones of jointing (peak 6 in Fig. 4, *b*) in which the major sets are roughly orthogonal to the core plane. The angular relationships and the types of four sets of fractures revealed on the rose diagram correspond to the R-, R'-, t, and $e(n)$-fractures of the second rank that precede the appearance of a fault plane in shear zones. Therefore, the borehole has penetrated a small zone of jointing with nearly vertical extensional joints on its periphery and shear joints in the center. The shear joints are dominated by specimens of two oppositely sloping conjugate sets (R and R') that displace each other on a normal fault plane, according to the model of double gliding [30], which is effectuated there in a setting of horizontal extension.

This zone of jointing is of a higher order than the extensional and shear joints within it. The density peaks of shear joints, spatially coinciding with the peaks of extensional joints, correspond to the sites in which the borehole stripped other zones of jointing of a similar scale. The interpretation of fracture patterns within some of them is difficult because the fracture surfaces are not orthogonal to the core plane. However, the extensional joints are always attributed to the periphery and shear joints to the center of the zones of jointing. Moreover, sediments in the axial parts of both zones experienced carbonatization, possibly, at the cost of substance precipitated from fluids that easily penetrate through these most strongly deformed parts of the section.

The existence of proximal zones of jointing is reflected in peaks in the $N = f(H)$ plots for an interval about an order of magnitude greater. The fracture density first increases insignificantly with depth and becomes well evident from 140 m (for extensional joints) to 180 m (for shear joints). However, below 260 m (for extensional joints) and 300 m (for shear joints) it increases to a maximum at 380 m. Then the density of fractures decreases unevenly to a minimum typical of the deepest section. The distribution of shear joints is more stable, which makes evident the lower and the upper boundaries of the most strongly deformed section (180 to 500 m).

This pattern of downcore distribution of fracturing density, without a lithological control, the existence

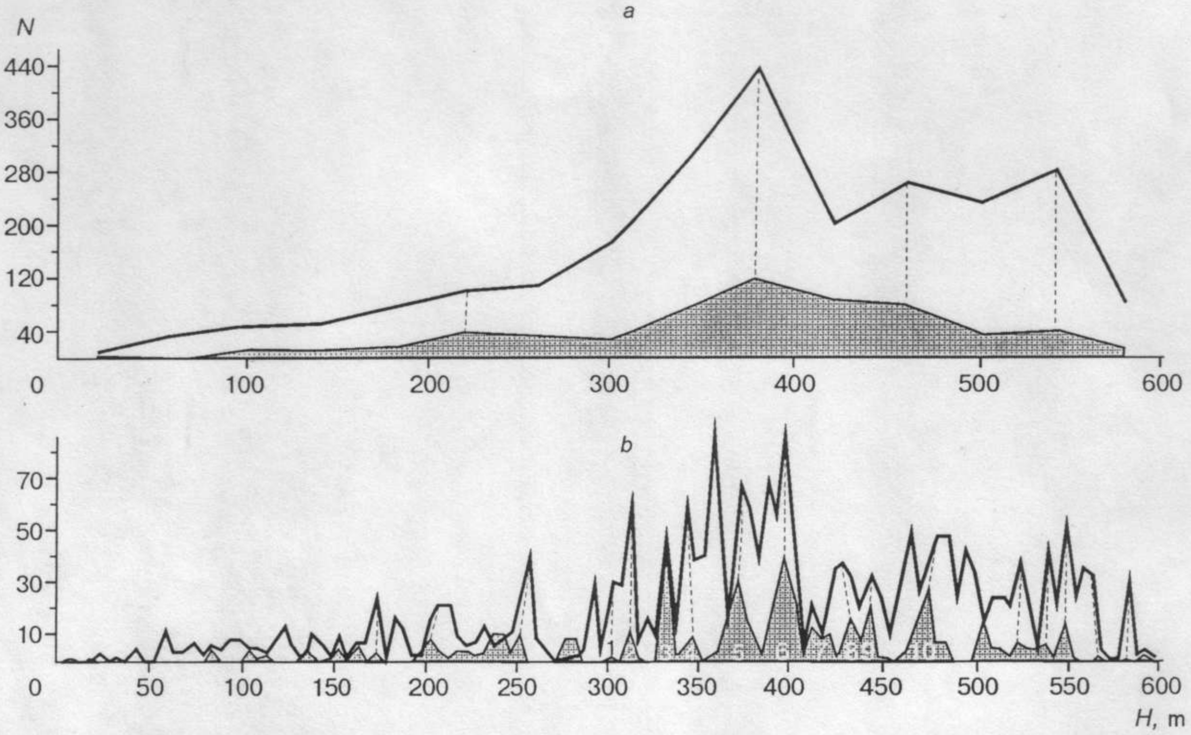

Fig. 4. Depth-dependent variations in density of shear (gray) and extension (white) joints, plotted for different averaging intervals: a — 40 m, b — 5 m (dashed line shows coinciding peaks of the two types of joints. See text for explanation).

of zones of jointing of the above structure, and the close relationship between spatial distributions of shear and extensional joints, along with the previous data, attest to a more complex effect of external forces than it would be solely from the load of the overlying sediments during diagenesis and under the effect of fluid pressure. The structural role of these two sources of stress is apparently minor relative to that of rifting-related tectonic forces.

Taking into account the seismic profiling data on the tectonics of the Baikal basin fill in the region of the Akademichesky Ridge, the most suitable explanation for the existence of a long zone of intense fracturing in the depth interval from 180 to 500 m is that the borehole stripped a larger-scale strongly fractured zone. Judging by weak deformation (almost uniform horizontal bedding and the absence of traction structures), the effect of tectonic forces was not strong and long enough to cause a single, relatively large fault plane. The structure of smaller-scale zones of jointing shows that they formed under the effect of shear stress in nearly horizontal extension.

CONCLUSIONS

Visual examination of the BDP-98 core showed that the poorly lithified sediments in the drilling locality experienced minor horizontal deformation under the effect of tectonic forces, which was accompanied by pressure of pore fluids and consolidation of sediments during diagenesis and produced joints of various scales. The most strongly fractured section (180 to 500 m of core depth) can be interpreted as a tilted zone of jointing, which consists of a number of similar smaller zones. In the latter, extensional joints occur mostly on the periphery, and shear joints are located mostly in the center and are oriented in the same way as joints in the known shear zones. At the same time, this jointing did not cause considerable displacement of sedimentary layers, which allows using the BDP-98 core as a reliable paleoclimatic record.

Fracturing of this type must be quite broadly distributed in the sedimentary fill of the Baikal basin. The existence of joints in the BDP-98 core which are not overprinted with older deformation will make it possible to investigate the earlier inaccessible evidence of fracturing under extension.

Like any deformation under load, fracturing in the Baikal sediments is accompanied by formation of

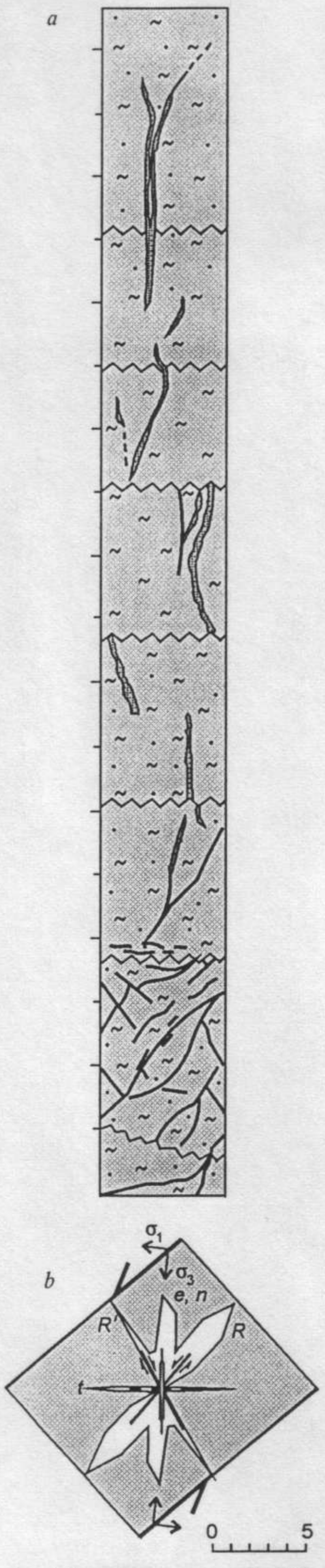

Fig. 5. Interpretation of structural setting of core sample 221. *a* — Structural setting (symbols are the same as in Fig. 3); *b* — setting formed under minimum horizontal (σ_1) and maximum vertical (σ_3) principal stresses: joint sets revealed from rose diagram (white color) correspond to fractures (*R*-, *R'*-, *t*-, and *e*, *n*-types) in shear zone (gray color), of normal-fault geometry (half-arrows show slip direction of hanging and footwall).

hierarchically ordered patterns, but, unlike the surficial fractures, those in the unconsolidated Baikal basin fill are poorly evident: Active fractures are latent, and passive ones disappear in a short time. Therefore, the fractures produced by external strain during diagenesis can hardly be revealed after lithification. Thus, the Baikal Drilling Project has offered a unique opportunity to gain a deeper insight into active fracturing at a stage of sedimentation, which is otherwise inaccessible for direct investigation.

We wish to thank project coordinators D. Williams, T. Kawai, and B. Khakhaev for the opportunity to investigate the BDP-98 core and A. Gvozdkov and Ya. Hasa, members of the preliminary core description group, and, especially, A. Prokopenko and K. Nakamura whose sketches and photographs of core surfaces (samples 108, 193, 202, 221, 225 and 195, 223) were very helpful. Drilling was financially supported by the Russian Ministry of Science and Technology, Siberian Branch of the Russian Academy of Sciences, National Science Foundation of the USA (grant EAR-9614770), Science and Technology Agency of Japan, and International Continental Drilling Project.

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Received 29 June 2000