ISSN 1069-3513, Izvestiya, Physics of the Solid Earth, 2010, Vol. 46, No. 5, pp. 452–460. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © B.V. Levin, M.B. Rodkin, E.V. Sasorova, 2010, published in Fizika Zemli, 2010, No. 5, pp. 88–96.

Specific Features of the Seismic Regime in the Lithosphere: Manifestations of the Deep Aqueous Fluid Action

B. V. Levin[a], M. B. Rodkin[b], and E. V. Sasorova[c]

[a] *Institute of Marine Geology and Geophysics, Far East Division, Russian Academy of Sciences, ul. Nauki 2. Yuzhno-Sakhalinsk, 693002 Russia*
e-mail: levinbw@mail.ru
[b] *Geophysical Center, Russian Academy of Sciences, Moscow, Russia*
e-mail: rodkin@wdcv.ru
[c] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia*
e-mail: sasor@orc.ru

Abstract—We considered the seismic regime in the upper 70–100 km of the lithosphere and identified the layers (at depths of about 10, 20–30, and 60–80 km) characterized by relatively reduced effective strength and increased seismicity. The existence of such layers is related to changes in the regime of fluid–rock interaction, namely, to the characteristic depths of a jump-like decrease in the effective permeability of rocks and an increase in the spatial homogeneity of a fluid–rock system.

DOI: 10.1134/S1069351310050113

INTRODUCTION

Recently, geophysicists, seismologists, and specialists in tectonophysics with increasing frequency have directed their attention to the problem associated with the role of water in processes of preparation and realization of earthquakes. It is believed that the presence of aqueous (or some other) fluid in the region of a seismic movement can explain the considerable discrepancies between the experimental data on breaking stresses in geomaterials and the estimates of stresses acting in the Earth's interior [Fyfe et al., 1981; Kasahara, 1985; Kalinin et al., 1989; and others]. It is supposed that aqueous fluid not only decreases high lithostatic pressures by the value of the pore pressure of this fluid but also behaves as a surfactant. The action of fluid as a surfactant is called the Rebinder effect [Goryunov et al., 1966; Traskin and Skvortsova, 2006; and others]. In the case of a spatial configuration of the fluid phase that is connected with the surface, the fluid pressure is close to hydrostatic, whereas for isolated fluid volumes, this pressure can approach and even exceed the values of the lithostatic pressure. As distinct from the role of pressure of the fluid pore, methods for the quantitative estimation of the Rebinder effect in conditions of the Earth's interior have not been developed as yet.

Evidently, the existence of an active fluid phase in the lithosphere of the Earth is necessary for the explanation not only of seismicity but also of a number of other geological phenomena, in particular, for the explanation of processes of ore and oil geneses [*Large and Extra Large É,* 2006; Sokolov, 2001; and others].

The presence of aqueous fluid seems also necessary for the explanation of data on the seismic structure and electric conductivity of the Earth's crust. Evidently, only the existence of fluid-saturated zones can explain the complex of data on the predominant coincidence of layers with increased conductivity and lower propagation velocities of seismic waves and on the confinement of such zones to regions of increased seismic activity and to faulted disturbances [Hyndman and Shearer, 1989; and others].

The conclusion about the presence of aqueous fluid in the crust and mantle raises the problem of investigating the character of the interaction of the fluid with the substance of the lithosphere. Substantial changes in the character of such interaction will be associated with zones of transition of rocks from the brittle to cataclastic and then to the plastic character of rheology. Indeed, different types of rock voids will cause distinctions in the spatial configurations of the fluid phase and in the fluid pressure values. It would also be expected that with increasing pressure, the solid and fluid phases will not exist separately but fluid will become more and more completely and homogeneously incorporated into the rock structure.

We will describe the main features of depth changes in the character of fluid–rock interaction as they are interpreted by different authors. The works [Ivanov, 1990, 1998; and others], emphasize the important role of the layer ("separator," according to S.N. Ivanov), which closes the paths of the free redistribution of fluid and, accordingly, corresponds to the boundary between the predominantly subhydrostatic (above) and sublithostatic (below) values of the fluid pressure. It has been substantiated that such a transition corresponds to depths of 8–15 km; however, this transition can be closer to the surface in very high-temperature regions of the crust and in zones of present-day volcanism. Abrupt changes in seismotectonic and rheological properties of the Earth's interior correspond to the layer-separator. It is supposed that formation processes of some types of ore deposits are associated with this layer, and that the maximum of seismic activity can be confined to it.

Fairly similar conclusions were made in [Nikolaevskii, 1979, 1982; and others]. These works put forward the idea that the main changes in the structures and properties of rocks correspond to changes in the character of the fracture of geomaterials with depth (with an increase in pressure). It is supposed that the K boundary often identified in the middle crust corresponds to the transition between the brittle and cataclastic (pseudoplastic) characters of the fracture. The M boundary in this model corresponds to the transition of rocks into the true plastic state; that is why the region below the M boundary is believed to be virtually impermeable for fluids. Thus, two horizons of abrupt changes in the character of fluid–rock interaction are identified in the Nikolaevskii model. The first of these horizons is close in depth to the Ivanov layer-separator and corresponds to the transition from the fractured to microfractured character of the fluid distribution. Such a change in the empty space sharply decreases the permeability of rocks and can correspond to the transition from subhydrostatic to higher fluid pressures, up to their sublithostatic values. Thus, as applied to the region of the K boundary in the middle crust, the conclusions from the Nikolaevskii and Ivanov models are rather similar. The second transition layer confined, according to the Nikolaevskii model, to the M boundary corresponds to the transition from the location of fluid in microfractures to its accommodation in disturbances of the crystalline structure of a rock, which involves a further sharp decrease in the effective permeability of this rock.

The next depth change in the character of fluid–rock interaction is associated with the incorporation of aqueous fluid into the crystalline lattice of a rock. The characteristic depth of this transition can be estimated from the results presented in [Adushkin and Rodionov, 2005], who state that the energy of the chemical bond of water with quartz oxides and other minerals corresponds to the relative compression of the water molecule by a factor of 1.3. At this and greater degrees of compression, the bound state of aqueous fluid in the structure of the crystalline lattice of a rock is thermodynamically preferable (on average) than its separate existence. Preliminary estimates have shown that the threshold pressure, at which such changes take place, is about 22 kbar and corresponds to depths of about 70 km [Levin et al., 2007].

The models discussed above disregard a number of important factors. Thus, it is easy to see that the Nikolaevskii model corresponds to the case of stable mineral associations and high, nearly breaking tectonic stresses (when the rock structure is largely controlled by the character of the fracture process). Speaking generally, both these suggestions do not correspond to the conditions of the Earth's interior, where the characteristic values of acting stresses are rather small [Fyfe et al., 1981; Rodkin, 1996; and others] and, where numerous solid-state transformations of rocks are realized in a wide range of P, T conditions of the lithosphere. As is well-known [Kalinin et al., 1989; Rodkin, 1993; and others], such transformations are accompanied by abrupt changes in the strength and rheological properties of the substance; consequently, the development of some or other solid-state transformation can strongly distort the general tendency of changes in the character of fluid–rock interaction with depth.

However, one can presume that during the averaging over large volumes of rocks with different compositions and temperatures, these general tendencies will manifest themselves in the average character of the changes in the strength and rheological properties of rocks with depth. Indeed, the sequence of changes discussed above in the configuration of the space occupied by fluid from fractured to microfractured, to the fluid location in crystalline lattice disturbances, and then to the fluidÕs incorporation into the crystalline 1
lattice corresponds to a progressive increase in the homogenization of the geophysical medium. Such a process is quite expected and natural, if temperature and pressure increase with depth.

The universal character of the hydrostatic pressure decrease in the fluid pressure and the Rebinder effect also testify in favor of the probability of the manifestation of the general tendencies described above. Indeed, the effect of a decrease in adsorption on the strength of solids (the Rebinder effect) is realized in a very wide range of conditions on the contact of a solid, which is located in the field of tensile stresses, with a fluid (liquid or gaseous) in an adsorption-active phase. The Rebinder effect was observed in ionic, covalent, and molecular mono- and polycrystalline substances, as well as in glasses and polymers. This effect manifests itself as an abrupt drop in strength, an increase in the brittleness of the solid, and a decrease in its longevity. In a complicated way, the Rebinder effect depends on the interatomic interactions of the solid and fluid phases, the value and type of the stress state, and the temperature. The real structure of the solid phase, i.e., the concentration of dislocations, microfractures, and foreign inclusions, plays a substantial role. Thermodynamically, the Rebinder effect is caused by a decrease in the work spent on the formation of a new surface as a result of a decrease in the free surface energy of a solid in the presence of fluid. The conditions existing in the Earth's interior, i.e., the presence of adsorption-active aqueous fluid, fractures, intergranular boundaries, dislocations, a complex field of variable-scale stresses, and increased temperature, ensure favorable conditions for the development of the Rebinder effect. The distribution of fluid becomes more and more disperse with depth, and this can enhance the Rebinder effect in the middle and lower parts of the crust.

The hypothetical effect of the incorporation of water into a crystalline lattice at high pressures is fairly universal. For estimating the predominant depth of this process, we will use the Theta equation of state for water:

$$P = B(S)\left\{\left(\frac{\rho(T,p)}{\rho_0(T,0)}\right)^n - 1\right\}, \quad (1)$$

where $B(S)$ is the function of entropy, n is the exponent of the isentropy, and ρ and ρ_0 are the water densities at the pressure P and at normal pressure. According to Bridgman, at pressures up to 70 kbar, it is possible to use the following values: $B = 3047$ kg/cm^2 and $n = 7.15$.

In this case, the degree of the relative compression of water will be determined from the expression:

$$\sigma = \frac{\rho}{\rho_0} = \left(\frac{P}{B} + 1\right)^{1/n}. \quad (2)$$

Assuming now [Adushkin and Rodionov, 2005] that the region, where water is incorporated into the crystalline lattice, corresponds to a ratio of water compression equal to 1.3, we estimate (see also [Levin et al., 2007]) the mean depth of the transition of aqueous fluid into the bound state at about 70 km. Note that previously, such a characteristic depth was repeatedly used in seismology. Traditionally, at a depth of 70 km separates the regions of surface and deep seismicity ([Pisarenko and Rodkin, 2007] and references therein).

The goal of this paper is to reveal and describe some effects of the variability of the seismic regime with depth, which can take place owing to the expected changes in the character of fluid–rock interaction noted above.

CHANGES IN THE CHARACTER OF FLUID–ROCK INTERACTION IN THE SEISMIC REGIME

Previously [Levin et al., 2007], it was demonstrated that the fluid regime of the Earth's interior changes at the 70-km boundary due to the transition from the free state of aqueous fluid to its incorporation into the crystalline lattice of a rock. It was shown that in the depth interval 60–100 km corresponding to a diffuse boundary of 70 km, the seismic regime and mean values of some source parameters of earthquakes appreciably change.

It has been shown that the annual cycle of the number of earthquakes with different magnitudes is reliably identified for earthquakes with source depths smaller than 70 km, whereas such a cycle cannot be identified for earthquakes with deeper sources. This distinction is explained by the fact that the microfractured fluid-bearing medium located above the 70-km boundary is sensitive to weak changes in the stress state caused by cosmic and, possibly, seasonal actions associated with the annual cycle, whereas the more homogeneous medium located below the 70-km boundary is not sensitive to such actions.

It was also shown in [Levin et al., 2007] that in the same depth interval (60–100 km), the behavior of the mean values of some characteristics of earthquake sources qualitatively changes with depth. Thus, if, up to a depth of about 100 km, the mean values of apparent stresses σ_a tend to increase with depth, at larger depths, this parameter first drops to values close to those typical of near-surface sources, whereupon it remains approximately constant.

In a similar way, it has been demonstrated that at a depth of about 70 km, the mean duration of the source process qualitatively changes. The half-duration of the source process σ_a was estimated as the difference between the time in the source, obtained from the first preludes and the time of the event obtained from the calculation of the parameters of the seismic moment. If, at depths smaller than 70 km, the time interval ΔT clearly tends to decrease with depth, at greater depths, the tendency is qualitatively different: the mean values of ΔT increase with depth, first rapidly and then more slowly.

Now, we will briefly describe the method of the calculation, which was previously used in [Levin et al., 2007] and will be used below in this paper. The values of $\sigma_{à}$ were estimated in the standard way from the data of the Harvard catalog by using the seismic moment M and the seismic energy $E\sigma_{à} = \mu Es/M$,s:

$$\sigma_a = \mu Es/M, \quad (3)$$

where μ is the shear modulus, and E_s is the seismic energy calculated in the standard way from the magnitude m_b [Sobolev, 1993]. The value of the shear modulus μ was assumed to depend on depth in accordance with the HB_1 model [Bullen, 1978].

Data on individual earthquakes were sorted in order of the increasing depths of events, and the mean values of σ_a (ΔT or some other parameter under investigation) were calculated for groups of events with consecutively close depths.

The results obtained in [Levin et al., 2007] indicate that the seismic regime undergoes a qualitative change at depths of 70–100 km. In this work, we investigate the character of seismicity above the 70-km boundary in order to reveal the possible effects associated with the changes in the character of the fluid–rock interaction suggested above. As previously, we considered all events from the Harvard catalog; however, only earthquakes with magnitudes exceeding 4.8 (without omissions) were taken as the initial data from the USGS/NEIC catalog.

In the Harvard catalog of seismic moments and in the USGS/NEIC world catalog, a large number of events are related to the three typical depths: 10, 15, and 30 km. It can be suggested that these events include not only earthquakes that actually occurred at such depth but also earthquakes, whose depths were determined inaccurately. Due to the contribution of

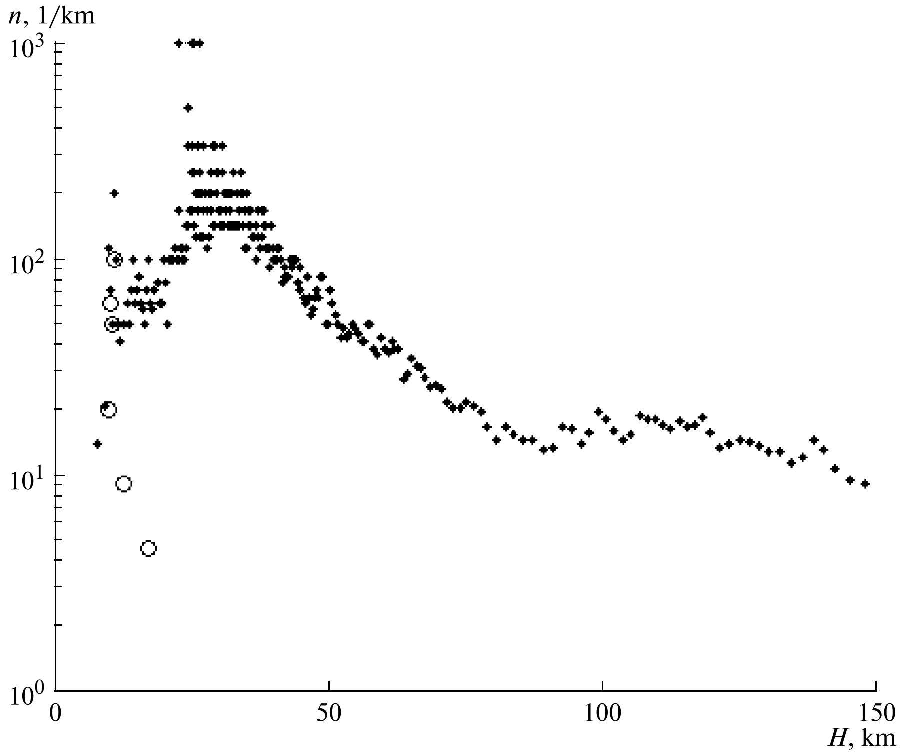

Fig. 1. Dependence of the density of the numbers of events n on the depth H. The circles mark the regions of mid-oceanic ridges and rhombs and the dots mark the remaining earthquakes.

inaccurately determined earthquakes, the variabilities of different source parameters for the earthquakes, which formally occurred at the specified three depths, are anomalously large. Against the background of such anomalously large scatters, the tendencies of parameter changes depending on the source depth are poorly traceable. In order to decrease the contribution of inaccurately determined events, we rejected the earthquakes, whose depths, according to the data of both catalogs (Harvard and USGS/NEIC), correspond to one of the specified depths, which is evidently typical of poorly determined earthquakes. As a result of such a rejection, 16 416 of 22 547 earthquakes of the Harvard catalog remained, which allowed us to perform the required statistical analysis. If the selection is stronger, and the events, for which at least one depth value (from both the Harvard and USGS/NEIC catalogs) is 10, 15, or 33 km, are rejected, the number of remaining earthquakes will be insufficient for statistical analysis.

We investigated depth changes of mean source parameters for groups of earthquakes with similar depths (here and below, the source depth means the mean value between the determined hypocenter depth and the solution of the seismic moment). We considered such parameters as the density of the numbers of events in depth n, the values of the apparent stresses σ_a, the ratios of magnitudes m_b/m_w, and distinctions in depth ΔH and time ΔT between the first arrival parameters (hypocenter) and the solution of the seismic moment. In addition, we analyzed the slopes of the recurrence plot of the seismic moment β.

Figure 1 shows the data of depth changes in the density of the numbers (selected) of earthquakes (for consecutive, in order of increasing depth, groups of earthquakes, 100 events in each group). As seen from this figure, a relative increase in seismicity takes place in depth intervals of 10 and 20–30 km. Note that without rejecting events with poorly determined depths, the first maximum would sharply increase, owing to events with depths of 10 and 15 km, and the second maximum, owing to events with a depth of 33 km. The data presented in Fig. 1 indicate that the seismicity maximums, often recognizable in the middle part and near the base of the continental crust, are evidently not a consequence of the inclusion of poorly determined events with fixed depths of 10, 15, and 33 km, but actually exist.

In the depth range 70–80 km, the changes in the density of the numbers of earthquakes with depth acquire a different character. While a monotonic decrease in the density of the numbers of earthquakes is observed in the depth interval from 30 to 70–80 km, in the depth interval from 80 to 150 km, this parameter changes relatively slightly and is characterized by weak maximums and minimums. On the whole, we noted that the theoretically expected depth intervals, where substantial changes in the character of fluid–rock interactions (8–15 km and near 30 and 70 km) take place, are distinguished by specific features, which

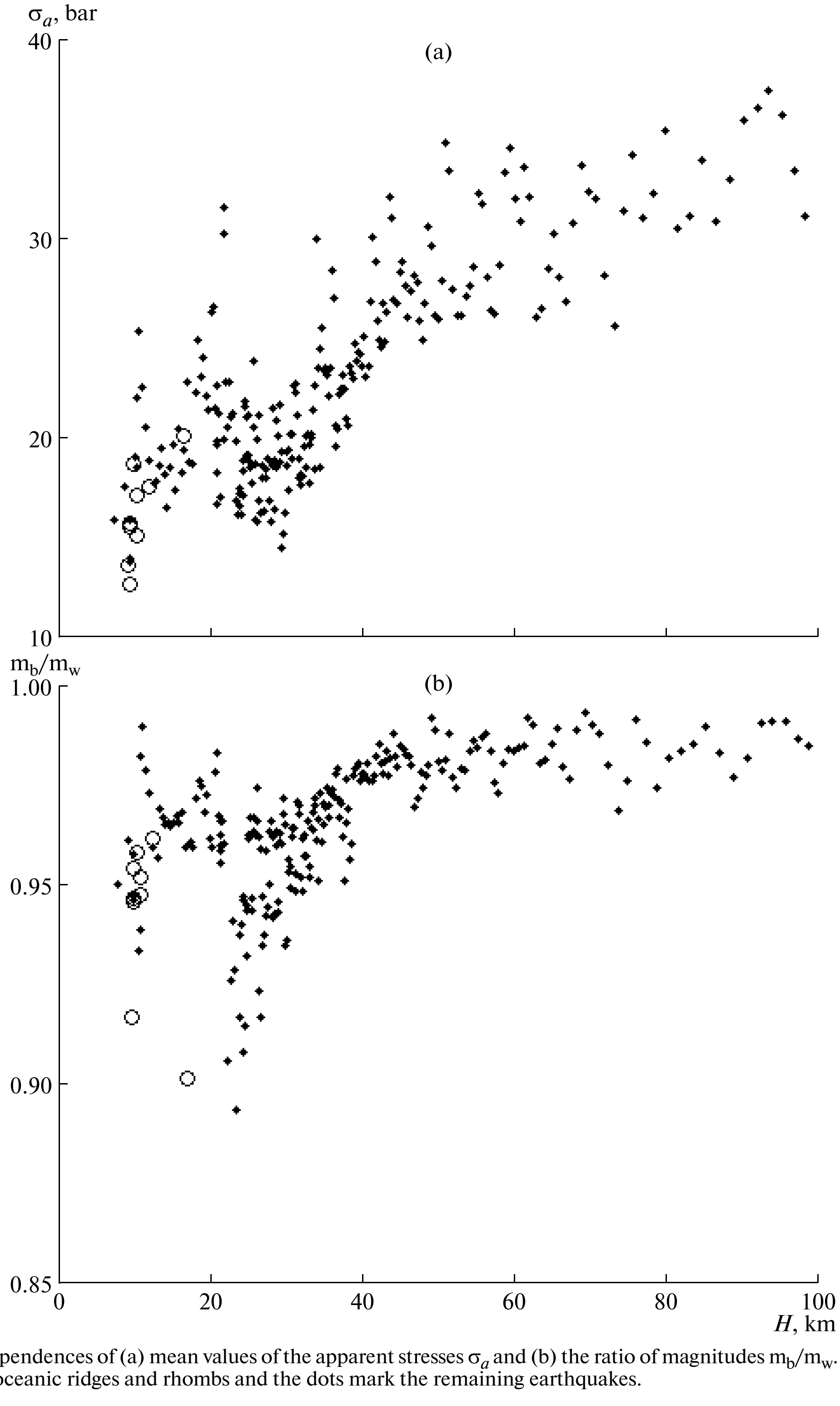

Fig. 2. Depth dependences of (a) mean values of the apparent stresses σ_a and (b) the ratio of magnitudes m_b/m_w. The circles mark regions of mid-oceanic ridges and rhombs and the dots mark the remaining earthquakes.

characterize changes in the density of the numbers of earthquakes with depth. Below, we will consider depth changes in other parameters of the seismic regime.

The mean values of the apparent stresses σ_a and the ratios of the magnitudes m_b/m_w are presented in Figs. 2a and 2b, respectively. The regions of relatively decreased σ_a values confined to depth intervals of about 10 and 20–30 km, as well as the less clearly pronounced region of relatively decreased σ_a values at depths of about 50–70 km, are seen in Fig. 2a. The qualitatively analogous but differently pronounced features are observed for the mean values of the ratio

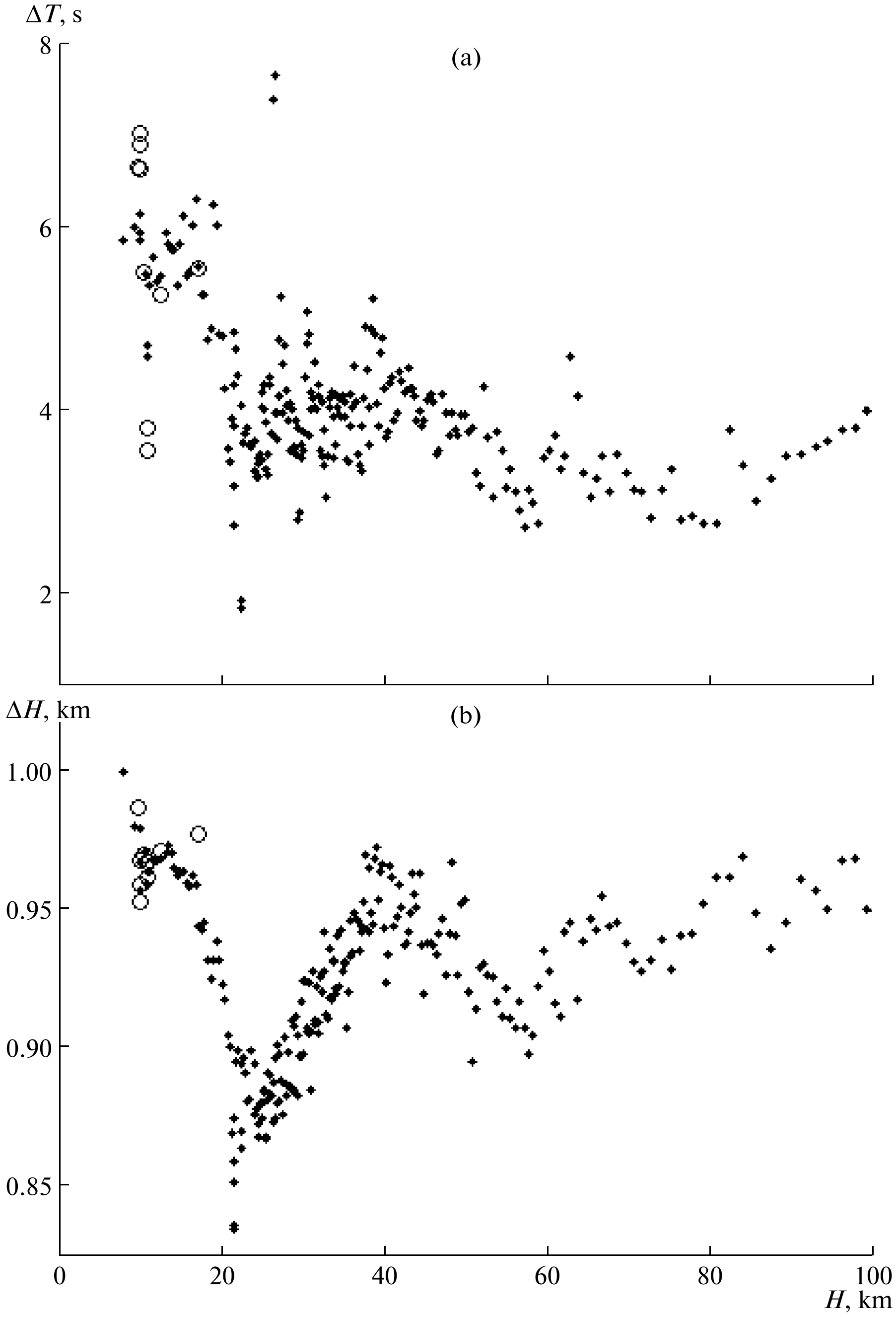

Fig. 3. Depth dependences of mean values of the differences for (a) the time moment of the event ΔT(a) and (b) the source depth ΔH, determined from the solution of the seismic moment and from the first preludes. The circles mark the regions of mid-oceanic ridges and rhombs and the dots mark the remaining earthquakes.

m_b/m_w (Fig. 2b). The nearly identical changes in σ_a and m_b/m_w with depth are quite predictable, based on the formula for calculating the apparent stress (3), in which the numerator and denominator are increasing functions of m_b and m_w, respectively. Note, however, that the ratio m_b/m_w characterizes the contributions of the high- and low-frequency seismic radiations, because the magnitude m_b is determined from predominantly high-frequency seismic oscillations, and m_w, from the low-frequency component of the seismic radiation. This leads to the fact that events that occur at depths of about 10, 20–35, and, less definitely, 60–80 km, have reduced apparent stresses σ_a and are characterized by a lower-frequency seismic radiation.

The changes in the mean half-duration of the source process ΔT(a) and the displacement of the source process along the vertical $\Delta H$are presented in Figs. 3a and 3b, respectively. From the results of the determination of the seismic moment, the negative ΔH values correspond to the shallower depth of the

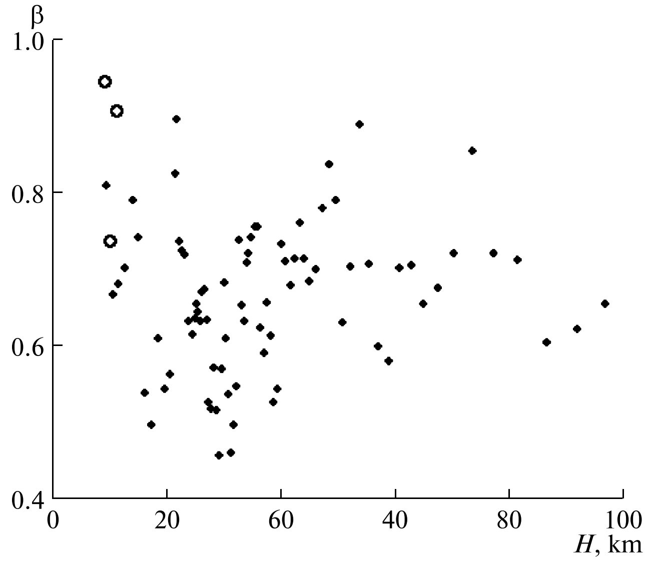

Fig. 4. Depth dependence of mean values (for groups of earthquakes arranged in increasing order of depths) of the slope of the recurrence plot of the seismic moment *M*. The circles mark the regions of mid-oceanic ridges and rhombs and the dots mark the remaining earthquakes.

source. Both figures display rather clearly pronounced maximums in depth intervals of 10, 20–30, and 50–80 km. The duration of the radiation process of seismic waves in these depth intervals is relatively reduced, whereas the process of opening in the source develops predominantly toward the surface. Such features of the source can be related to the more active role of a low-density fluid, which favors the fastest development of the fracture process and the fracture propagation into a region of low pressures (which can be explained by the fact that a low-density fluid tends to break through in this direction).

The variability with depth of the recurrence plot slope β for the seismic moment values is presented in Fig. 4. The recurrence plot slope β was estimated for groups of earthquakes by the maximum likelihood method with the use of the Hill formula [Pisarenko and Rodkin, 2007]:

$$\beta = \{1/m\sum \ln(M_i/\mathrm{A})\}^{-1}, \quad (4)$$

where m is the number of ranked maximum values of the seismic moment ($M_1 \geq M_2 \geq M_3 \geq \ldots \geq M_m$). In our case, taking into account the incomplete representativeness of the catalog in the region of weaker events, the quantity A was assumed as $\mathrm{A} = M_{50}$. Accordingly, in formula (4), $m = 50$. Recall that the mean value of β for the crustal seismicity is close to 0.66, and the β value typical of zones of mid-oceanic ridges are somewhat larger and approach unity [Pisarenko and Rodkin, 2007]. The data presented in Fig. 4 correspond to this general regularity: the minimum values of β are grouped near a depth of 30 km, and a less pronounced anomaly is outlined at depths of 15–20 km.

The decreased values of β at depths of about 30 km indirectly indicate that the anomalies shown in Figs. 1–3, which are inherent in these depths, are not caused by poorly determined (predominantly weaker) earthquakes related to this depth interval. Indeed, the prevalence of weak events could cause an increase in the recurrence plot slope (as is the case for regions of mid-oceanic ridges) rather than a decrease. The confinement of decreased β values to depths of about 30 km indicates that a relatively large fraction of relatively stronger earthquakes occur here.

It was previously noted [Levin et al., 2007] that the annual cycle of seismic activity is characteristic of shallow earthquakes, whereas no such cycle is identified for deeper sources. The degree of uniformity of the monthly mean distributions of the numbers of earthquakes and the characteristic depths of regime changes were statistically estimated for each of 31 subregions located along the perimeter of the Pacific Ocean in five magnitude ranges for each subregion. In all, about 80000 events were used. We estimate the value of P, i.e., the probability that the statistical sample belongs to a nonuniform distribution. The hypothesis of the uniformity of the distribution was rejected for samples with shallow events, for which the values of P lie within the range from 0.87 to 0.999 (for 75% of samples, P 0.99).

For determining the threshold depth, we carried out a selection process from the following depth levels: 20, 40, 60, 80, 100, 120, 140, 160, 200, 250, and 300 . The procedure of testing was consecutively repeated for each threshold value in order to determine the boundary, which divides the entire set of events into two subsets: shallow events distributed nonuniformly during the year and deeper events, whose distribution can be regarded as uniform. As an example, Fig. 5 illustrates the results of such testing for Kamchatka over five magnitude ranges. The analysis performed for the set of subregions showed that the threshold boundary Hth exists and is located in the depth interval 60–100 km (for the majority of subregions, at a depth of 60–70 km).

DISCUSSION

As seen from the above analysis, a number of common features have been revealed in the variabilities of the depth of the mean density of the numbers of earthquakes n, the slope β of the recurrence plot, the apparent stresses σ_a, the ratio of magnitudes m_b/m_w, as well as the mean values of the half-duration of seismic radiation ΔT and the half-length of the source zone along the vertical ΔH. Changes in these parameters are confined to a depth of about 10 km and to the depth intervals 20–30 and (less clearly) 60–80 km. The relatively increased density of the numbers of earthquakes n (excluding the 70-km boundary) and decreased values of the apparent stresses σ_a, the magnitude ratio m_b/m_w, and the slope β of the recurrence plot are char-

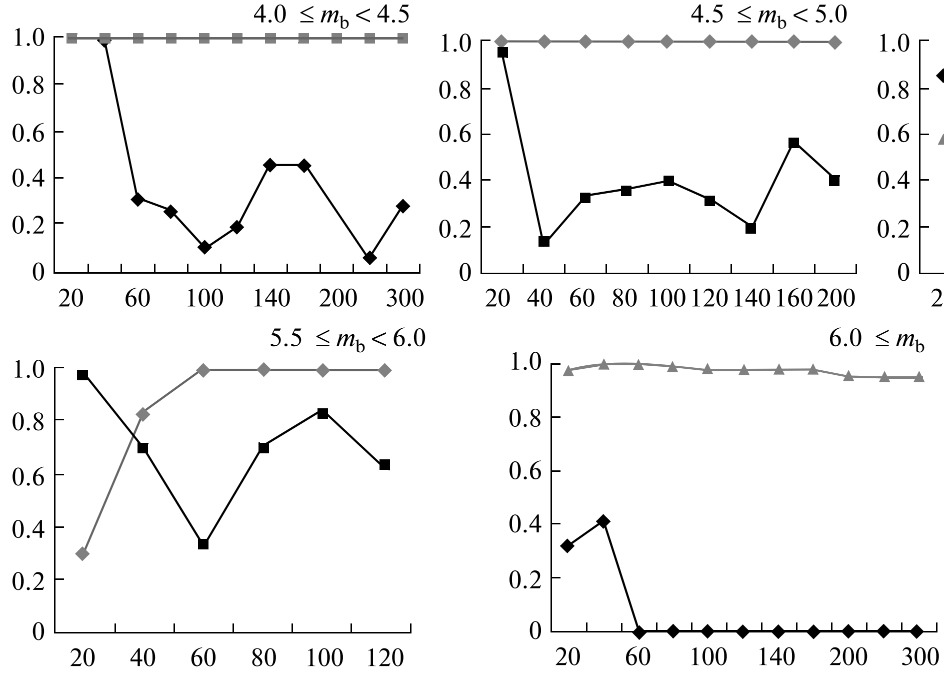

Fig. 5. Plots showing the dependence of the probability on the threshold depth value for five magnitude ranges: the black and gray lines are for shallow and deep events, respectively. In all fragments, the threshold depth values *H*th are plotted on the abscissa axis, and the values of the probability that the given sequence of events does not obey the uniform distribution law are plotted on the ordinate axis. For the Kamchatka subregion, the curves are calculated from the discrete monthly scale.

acteristic of these depth intervals, as well as the faster process of opening and a more clearly expressed tendency toward the development of the process of opening in the direction of the Earth's surface. The set of such changes can be interpreted in the sense that the geophysical medium in these depth intervals has a reduced strength, because the deep fluid regime is more active there, whereas the predominant development of earthquake sources toward the surface can be explained by the fact that a low-density fluid tends to break through into the region of lower pressures.

The revealed depth intervals with specific seismic regimes correspond fairly well to the depths, at which substantial changes in the character of fluid–rock interaction were supposed to occur from model considerations [Nikolaevskii, 1979; Ivanov, 1990; Levin et al., 2007; and others]. All these changes take place, when the effective permeability of the underlying sequences of the lithosphere decreases in a jump-like manner. Accordingly, in these sequences, the fluid will be at higher pressures, and its occasional breakthroughs could cause the specific features of the seismic regime described above.

A certain discrepancy between the expected depths, and the depths revealed by us, of the anomalous layers is observed for the region located at the base of the continental crust. According to the Nikolaevskii [1979] model, the anomalous layer corresponds to the M boundary. According to our results (Figs. 1–3), this layer is located somewhat higher, in the depth interval 20–30 km. Therefore, it seems more justified to relate this layer not to the M boundary but to the transition from rocks of the flooded amphibolite facies to the anhydrous (according to petrological notions) rocks of the granulite and eclogite facies.

The division of lithospheric sequences into depth intervals, where aqueous fluid can be in the free state, and where it will be (predominantly) incorporated into the crystalline lattice, is supported by the results of the analysis of the degree of the manifestation of the activation of the annual cycle in the seismic regime. This cycle is reliably recognizable for earthquakes with source depths of at least 70–80 km and is not recognizable for deeper earthquakes. This distinction can be explained by the fact that the microfractured medium above the characteristic 70-km boundary is more sensitive to weak external actions and responds to external disturbances having an annual cycle of actions. On the contrary, more homogeneous sequences, where fluid is incorporated into the crystalline lattice, are more stable and insensitive to weak annual variations in external (in particular, cosmic) actions.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research (project no. 06-05-64971) and by the program "Leading Scientific Schools" (project no. NSh-1270.2003.5).

REFERENCES

1. V. V. Adushkin and V. N. Rodionov, "On the Nature of Mechanical Motion in the Earth's Interior," Fiz. Zemli, No. 2, 88–91 (2005) [Izvestiya, Phys. Solid Earth **41** (2005)].
2. K. E. Bullen, *Density of the Earth* (Mir, Moscow, 1978).
3. Yu. V. Goryunov, N. V. Pertsev, and B. D. Summ, *Rebinder's Effect* (Nauka, Moscow, 1966) [in Russian].
4. W. S. Fyfe, N. J. Price, and A. B. Thompson, *Fluids in the Earth's Crust* (Elsevier, Amsterdam, 1978; Mir, Moscow, 1981).
5. R. D. Hyndman and P. M. Shearer, "Water in the Lower Continental Crust: Modeling Magnetotelluric and Seismic Reflection Results," Geophys. J. Int. **93,** 343–365 (1989).
6. S. N. Ivanov, "Separator (on the Nature and Meaning of the Geophysical Boundary K_1)," Dokl. Akad. Nauk SSSR **311**(2), 428–431 (1990).
7. S. N. Ivanov, *On Rheological Modelsof the Earth's Crust; Critical Consideration* (Ed. UrO RAN, Ekaterinburg, 1998) [in Russian].
8. V. A. Kalinin M. V. Rodkin, and I. S. Tomashevskaya, *The Geodynamic Effects of Physical-Chemical Transformations in the Solid Medium* (Nauka, Moscow, 1989) [in Russian].
9. K. Kasahara, *Earthquake Mechanics* (Cambridge Univ. Press, New York, 1981; Mir, Moscow, 1985).
10. *Large and Superlarge Deposits of Ore Minerals* in 3 Vols., Chief Editors N. P. Laverov, D. V. Rundquist (IGEM RAN, Moscow, 2006) [in Russian].
11. B. V. Levin, M. B. Rodkin, and E. V. Sasorova, "On a Possible Nature of the Seismic Boundary at the Depth 70 km," Dokl. Akad. Nauk **414**(1), 101–104 (2007).
12. V. N. Nikolaevskii, "The Mohorovi@ci@c Boundary as the Limiting Depth of the Brittle–Dilatancy State of Rocks," Dokl. Akad. Nauk SSSR **249**(4), 817–824 (1979).
13. V. N. Nikolaevskii, *Review: the Earth's Crust, Dilatancy, and Earthquakes. Mechanics of the Earthquake Source* (Mir, Moscow, 1982), pp. 133–215 [in Russian].
14. V. F. Pisarenko and M. V. Rodkin, "Distributions with Heavy Tails: Supplements to Analysis of Catastrophes," in *Vychislitel'naya Seismoligiya*, Issue 38 (GEOS, Moscow, 2007) [in Russian].
15. M. V. Rodkin, *The Role of Deep Fluid Conditions in Geodynamics and Seismotectonics* (National Geophysical Committee, Moscow, 1993) [in Russian].
16. M. V. Rodkin, "Contradictions in the Recent Seismogenetical Notions," Phys. Chem. Earth **21**(4), 257–260 (1996).
17. G. A. Sobolev, *Principles of Earthquake Prediction* (Nauka, Moscow, 1993) [in Russian].
18. B. A. Sokolov, *New Ideas in the Oil and Gas Geology* (MGU Press, Moscow, 2001) [in Russian].
19. V. Yu. Traskin and Z. N. Skvortsova, "The Rebinder Effect in Geodynamic Processes," in *Fluids and Geodynamics* (Nauka, Moscow, 2006), pp. 147–164 [in Russian].

SPELL: 1. fluidÕs