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

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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.

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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]. It is 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 presence 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 E, 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 rheologi-
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 fluid's incorporation into the crystalline 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:

\[ P = B\theta \left( \frac{\rho(T,\theta)}{\rho_0(T, 0)^n} - 1 \right), \]

where \( B\theta \) is the function of the isentropy, \( n \) is the exponent of the isentropy, and \( \rho \) and \( \rho_0 \) 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: \( B = 3047 \text{ kg/cm}^2 \) and \( n = 7.15 \).

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

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

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 \( \sigma_a \) 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 \( \sigma_a \) 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 \( \Delta T \) clearly tends to decrease with depth, at greater depths, the tendency is qualitatively different: the mean values of \( \Delta T \) 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 \( \sigma_a \) were estimated in the standard way from the data of the Harvard catalog by using the seismic moment \( M \) and the seismic energy \( E = \mu E_{s}/M/s: \)

\[ \sigma_a = \mu E_{s}/M/s. \]

where \( \mu \) 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 \( \mu \) was assumed to depend on depth in accordance with the HB2 model [Bullen, 1978].

Data on individual earthquakes were sorted in order of the increasing depths of events, and the mean values of \( \sigma_a (\Delta T \text{ or some other parameter under investigation}) \) 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
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 \( \sigma_a \), the ratios of magnitudes \( m_b/m_w \), and distinctions in depth \( \Delta H \) and time \( \Delta T \) 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 \( \beta \).

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 maxima, 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
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 $\sigma_a$ and the ratios of the magnitudes $m_b/m_w$ are presented in Figs. 2a and 2b, respectively. The regions of relatively decreased $\sigma_a$ values confined to depth intervals of about 10 and 20–30 km, as well as the less clearly pronounced region of relatively decreased $\sigma_a$ 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 $m_b/m_w$. The circles mark regions of mid-oceanic ridges and rhombs and the dots mark the remaining earthquakes.

![Fig. 2. Depth dependences of (a) mean values of the apparent stresses $\sigma_a$ 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.](image-url)
m_b/m_w (Fig. 2b). The nearly identical changes in \( \sigma_a \) 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 \( \sigma_a \) and are characterized by a lower-frequency seismic radiation.

The changes in the mean half-duration of the source process \( \Delta T(a) \) 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 \( \Delta H \) values correspond to the shallower depth of the
The decreased values of $\beta$ 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 $\beta$ 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, $P \approx 0.99$).

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 km. 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 $H_{th}$ 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 $\beta$ of the recurrence plot, the apparent stresses $\sigma$, the ratio of magnitudes $m_b/m_s$, as well as the mean values of the half-duration of seismic radiation $\Delta T$ and the half-length of the source zone along the vertical $\Delta H$. 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 $\sigma$, the magnitude ratio $m_b/m_s$, and the slope $\beta$ of the recurrence plot are char-

![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.](image_url)
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 break-throughs could cause the specific features of the seismic regime described above.

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.

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.

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