ISSN 1028-334X, Doklady Earth Sciences, 2007, Vol. 414, No. 4, pp. 578–581. © Pleiades Publishing, Ltd., 2007.
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GEOPHYSICS

Possible Nature of the Seismic Boundary at a Depth of 70 km

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Received November 24, 2006

DOI: 10.1134/S1028334X07040204

Classical works on seismology and the physics of the Earth distinguish a boundary at a depth of 70 km, which divides shallow-focus (shallow) and intermediate earthquakes that occupy the depth range from 70 to 300 km. It should be noted that shallow (<70 km) earthquakes comprise approximately 85% of the total number of recorded events. The nature of this boundary remains debatable so far [1].

According to the concepts of geologists [1, 2], fractures can penetrate the lithosphere to a depth of 100 km. Block divisibility of continents is also traced to the same depths. The upper boundary of the asthenosphere (weakened and slightly melted layer of rocks) occurs beneath the oceans at a depth of ~60 km. Recent seismic investigations in the Urals, Eastern Europe, and the North Sea revealed elongated seismic boundaries at depths of 65–80 km in the continental upper mantle [1]. Seismic topographic charts presented by Japanese geophysicists show characteristic levels at depths of 80–150 km [2].

In the present work, we attempt to substantiate the seismic interface of earthquakes by depth based on new results of statistical analysis of modern world catalogs and physical concepts about the role of free water in the seismic process.

The data from World ISC Catalogue [3] (from 1964 to 2004) and NEIC Catalogue [4] (from 1973 to 2005) were used for statistical analysis. The total set of events studied here was divided into several subgroups by their energy level (magnitude ranges, MR) for the analysis of spatiotemporal regularities in the distribution of earthquakes: $4 \le M_b < 4.5$, $4.5 \le M_b < 5$, $5 \le M_b < 5.5$, $5.5 \le M_b < 6.0$, $6 \le M_b < 6.5$, and $M_b \ge 6.5$. Aftershocks were omitted from the list of events.

The equatorial plane is a natural symmetry plane for many geophysical processes on the Earth. Recently, the authors of [5] demonstrated that both random and statistically reliable nonrandom (according to nonparametric series criteria) components exist in the time distribution of earthquakes between the northern and southern parts of the Pacific region. This is true for the majority of magnitude ranges. Manifestation of a nonrandom component (with periods from one to a few years) in the distribution of earthquakes in such a vast region as the Pacific can be caused by external periodical perturbations, which influence the entire lithosphere of the Earth. The existence of a nonrandom component is confirmed in our work by numerical experiments with a numerical model of the composite process, which consists of the superposition of random processes and a periodical one.

It is also shown that a statistically reliable nonrandom component caused by periodical perturbations is only manifested in relation to shallow earthquakes (with $H \le H_{por}$), while deep earthquakes (with $H > H_{por}$) are randomly distributed in time (without statistically reliable periodical components) between the northern and southern parts of the Pacific region. The H_{por} value is located in the depth interval 60–80 km.

The analysis of intrannual distribution of earthquakes based on the same material [6] showed that shallow events (with epicenter depth smaller than H_{por}) are nonuniformly located on the discrete time scale during the year and the noted nonuniformity is statistically significant. We present an analysis for 31 Pacific subregions over five magnitude ranges (MR) for each subregion and three depth ranges (a total of 80 000 events were analyzed). The estimates of probability P that the statistical sampling belongs to a nonuniform distribution were within 0.95–0.999 (in 75% of samplings, $P \ge 0.99$). The Pearson criterion was used to estimate the significance of P for samplings with good representation (not less than 10 events in each discrete interval), and the Monte Carlo method was used for samplings with weak representation.

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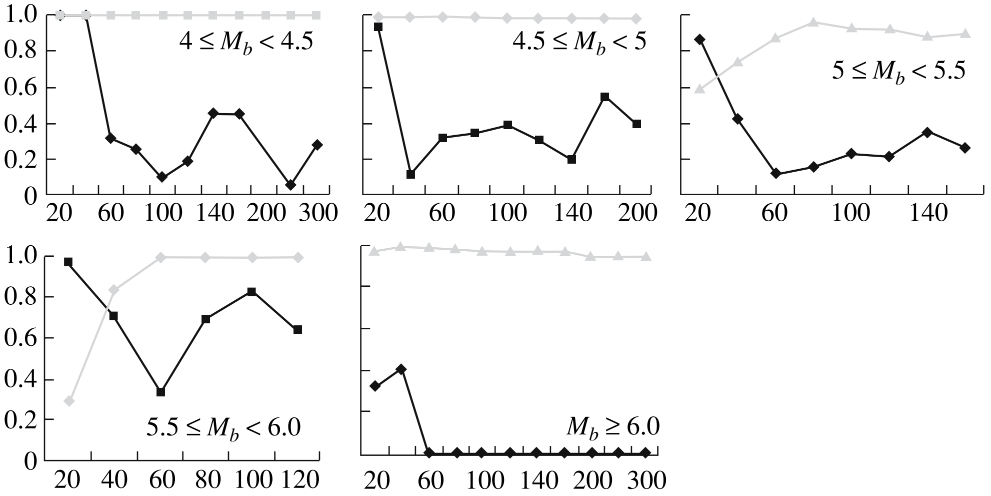

Fig. 1. Probabilities P_{Dp} and P_{Sh} vs. the threshold depth relationship for five magnitude ranges. Black and gray lines denote deep (P_{Dp}) and shallow (P_{Sh}) events, respectively. The threshold depth (H_{por}) is shown in all abscissa axes for all fragments. Ordinate axes show the value of probability that the given sequence of events does not obey the uniform law of distribution. The curves were calculated using a discrete scale with a monthly step for the Kamchatka region.

The results show that the sources of shallow earthquakes respond to additional periodical forcing, while deep earthquakes are uniformly distributed over the year so that external periodical forcing does not influence these events. The distribution of deep earthquakes was considered only for the regions with representative samplings.

The next step to determine H_{por} using the method developed in [6] was sequential examination of the threshold values by depth. We used the following H_{por} values (km): 20, 40, 60, 80, 100, 120, 140, 160, 200, 250, and 300. The procedure of testing the samplings for each threshold value was repeated to determine the boundary at which the events are divided into two subsets: (i) events depending on external periodical factors and (ii) events not depending on these events and uniformly distributed throughout the year. This boundary would pass at a depth where P_{Sh} (probability of the fact that the events in the given sampling are distributed nonuniformly for shallow events) becomes maximal, while P_{Dp} (the corresponding probability for deep events) is minimal. Figure 1 presents the results of such tests in Kamchatka as an example. The analysis of calculations carried out for each subregion shows the existence of such a boundary. It is located in the depth interval 60–100 km (for the majority of regions, at a depth of 70 km).

This depth interval includes a sharp change with depth in the parameters of the focal process, such as the mean value of apparent stresses σ_a, half-duration of the source process $\Delta\tau$, and half-length of the source region by height ΔH. The depth dependence of $\Delta\tau$ and ΔH was determined from the mean difference of the momentum and earthquake depth based on the first arrival data and the solution of the seismic moment [7]. Figure 2 demonstrates the depth dependences of mean values of $\Delta\tau$ and ΔH as examples. The sharpest variations are observed in both graphs in the depth interval 70–100 km.

In the last few years, concepts about the important (or even determining) role of the water fluid in seismicity process are gaining more and more support [1, 7, 8, and others]. Within the framework of these concepts, let us try to correlate the seismic regime boundary mentioned above with the variations in the fluid regime. With this in mind, we shall consider the physical mechanism of transition of water from the bound state to the free state [9].

It is known that the chemical bonds of oxides of the majority of elements induce appreciable changes in their volume (from 10 to 50%) with respect to the initial volume of atoms. Hence, the degree of relative compression of water in the bound state within minerals is $\sigma = \frac{\rho}{\rho_0} = 1.1–1.5$ (on average, approximately 1.2–1.3). On the other hand, analysis of the equation of state of water [10] allows us to determine the characteristic depth level at which the relative variation in compression of water molecules increases to 1.2–1.3. Let us use the equation of state of water in the following form of the Tate equation:

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

where B is a function of entropy and ρ and ρ_0 are the current and standard water density. According to the experimental data of Bridgeman, at temperatures up to 1000°C and pressures up to 50 kbar, we can accept that $B = 3 \cdot 10^8$ Pa and $n \approx 7.15$.

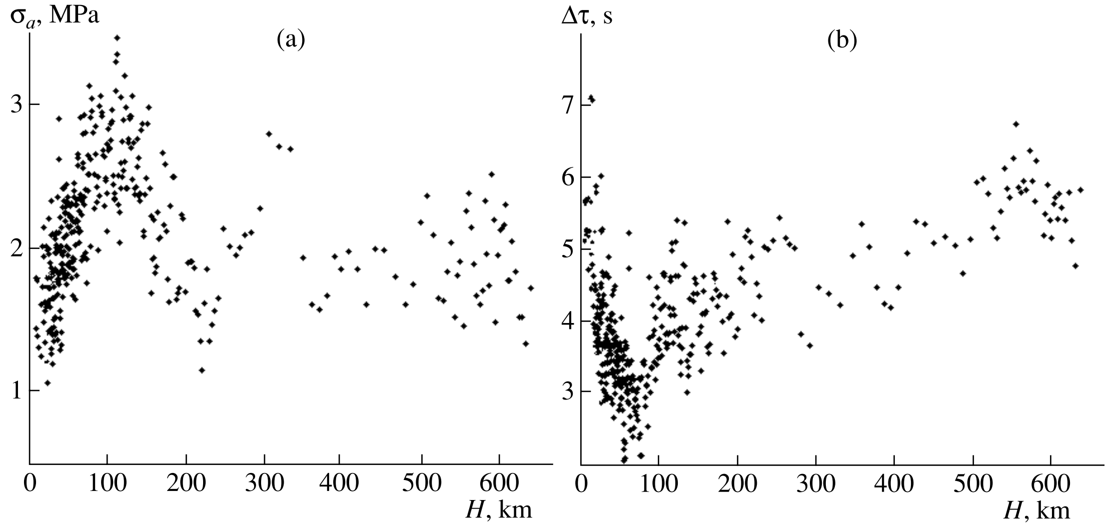

Fig. 2. Mean values of source parameters of earthquakes vs. depth (dots) relationship: (a) values of apparent stresses σ_a; (b) semi-durations of source processes $\Delta\tau$. The data were sorted by increasing earthquake depths. Mean values are shown for sequential groups of earthquakes consisting of 51 events according to [7].

Then, the depth dependence of the degree of relative water compression can be presented as a graph (Fig. 3). According to (1), we get that the degree of relative water compression at a depth of ~70 km increases to 1.3 and becomes equal to the values of its compression in the crystal lattice. The depth of such a boundary would naturally depend on the temperature, the mineralogical–chemical composition of the rock, and its individual components. Water will tend to remain in the free phase above the 70-km boundary and to incorporate into the crystallites of the rocks beneath this boundary.

The response of the free water-containing rocks to periodical (even weak) tidal forcing should principally differ from the response of the water-free rocks. Water-saturated rocks of the Earth's crust are media with a nonlinear response to periodical forcing. Variations in the pressure and corresponding changes in the density of the medium lead to the formation of a system of cracks filled with free water, development of ruptures, accumulation of defects, and preparation of the main fracture in the future earthquake source. In the rocks without free water, weak tidal effects are not accumulated and the nonlinear mechanism of strain accumulation is not realized.

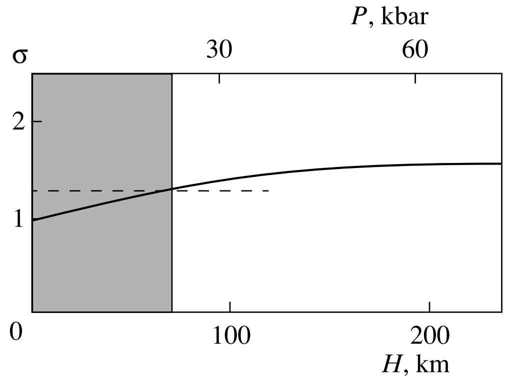

Fig. 3. Variation of relative water compression $\sigma = \frac{\rho}{\rho_0}$ vs. depth H relationship. Pressure variation versus depth is shown in the upper axis. Dashed area denotes existence of free water (H < 70 km).

Thus, the shallow (60–80 km) seismic boundary, which divides different types of earthquakes, is simultaneously the boundary between events that can (or cannot) respond to external forcing. It is likely that the distinguished boundary should also be considered a possible boundary surface representing the lower boundary of the hydrosphere. Further research mainly in the field of physical and geochemical experiments could refine the concept presented here.

ACKNOWLEDGMENTS

The authors are grateful to V.V. Adushkin, Yu.M. Pushcharovsky, D.Yu. Pushcharovsky, and Yu.I. Zetser for useful discussions and advice.

This work was supported in part by the Russian Foundation for Basic Research (projects no. 04-05-64274, 06-05-96026, and 06-05-64334) and the Foundation of the President of the Russian Federation for the Support of Leading Scientific Schools (project nos. NSh-8043.2006.5 and NSh-5009.2006.5).

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