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GEOPHYSICS

General Regularities in the Distribution of Seismic Events on the Earth and on the Moon

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Abstract—In this work, characteristic features of seismic event distribution by latitudes and depth are compared for the Earth and the Moon. It is shown that earthquakes and moonquakes are distributed similarly by latitudinal belts.

The problem of earthquake epicenter distribution by latitudinal belts of the Earth was stated in the 1960s. Firstly, only the distribution of strong earthquakes ($M > 7$) was studied. In the early works [5, 8], heterogeneity in events distribution by latitudes was noted. A substantial progress was achieved in [9]. On the basis of a Chinese catalogue of strong earthquakes in 1897–1980 (1165 events), it was noted that the energy released after seismic events is almost zero for high latitudes and the two main peaks of seismic activity are located in moderate latitudes and are divided by a zone of less activity near the equator.

The papers of the authors of the present communication contain the results of the analysis of earthquake latitudinal and depth distributions [2, 3]; however, comparative analysis of earthquake and moonquake distributions taking into account latitude, depth, and energy of events has not yet been undertaken. The aim of the present work is to present the results of such analysis and to comment on the possible relationship of the seismic process with exogenous effects on both the Earth and the Moon.

Analysis of a wide spectrum of seismic events was carried out on the material of the ISC catalogue [6] (more than 200 000 events with $M \geq 4$) on the basis of the approached elaborated in [2]. It was stated that seismic activity of the planet is almost absent in the poles and in polar caps of the Earth and reveals clearly expressed maximums in moderate latitudes of the Northern and Southern Hemispheres and the stable local minimus near the equator. These distributions by latitudinal belts of the Earth are characteristic for a number of seismic events and for released energy as well. Because of the fact that most earthquakes are concentrated in the boundaries of lithospheric plates, in [2] normalizing of earthquake number and released energy by length of the lithospheric plate boundaries in every single latitudinal belt was used. Such a normalizing gives us a power of this area of a plate boundary (average number of earthquakes generated per every 100 km of plate boundary). Using of this characteristic, the physical sense of which is clear, allows us to compare seismic activity of latitudinal belts in various parts of the world. The total number of studied events was subdivided into several subgroups by values of magnitude ranges (MRs: $4.0 \leq M_b < 4.5$; $4.5 \leq M_b < 5.0$; $5.0 \leq M_b < 5.5$; $5.5 \leq M_b < 6.0$; $6.0 \leq M_b$).

Global regularities in seismic event distribution for various latitudinal belts of the Earth and varied energy levels were presented in [3]. For every single latitudinal belt, distributions in the number of events by depth and distribution of the released energy for all the MR were considered. It was shown that, for high latitudes, the sources of almost all earthquakes (up to 90%) are concentrated at depths of $H \leq 20$ km. In going to moderate latitudes, the share of events with depth of $20 < H \leq 60$ km increases gradually. For latitudinal belts close to the equator (30°S–30°N), a substantial share of earthquake sources is located at depths of $100 < H \leq 240$ km and $H \geq 500$ km. Concerning distributions of released energy by depth, it was found that there is a tendency to subdivide events into three particular groups (clusters) with sufficiently clear boundaries. The clusters unite events with certain depths: C1 (from 0 to 80 km), C2 (from 120 to 240 km), and C3 (from 500 to 700 km). At high latitudes only events from the C1 are present.

Analysis of lunar seismicity was base on observations related to positioning of seismic stations within the framework of the "Apollo" Project (1971–1974). In [7], the obtained observation data was systematized, the table of recorded moonquakes was made up, and the temporal periodicities for lunar seismic events were analyzed. Seismic events on the Moon

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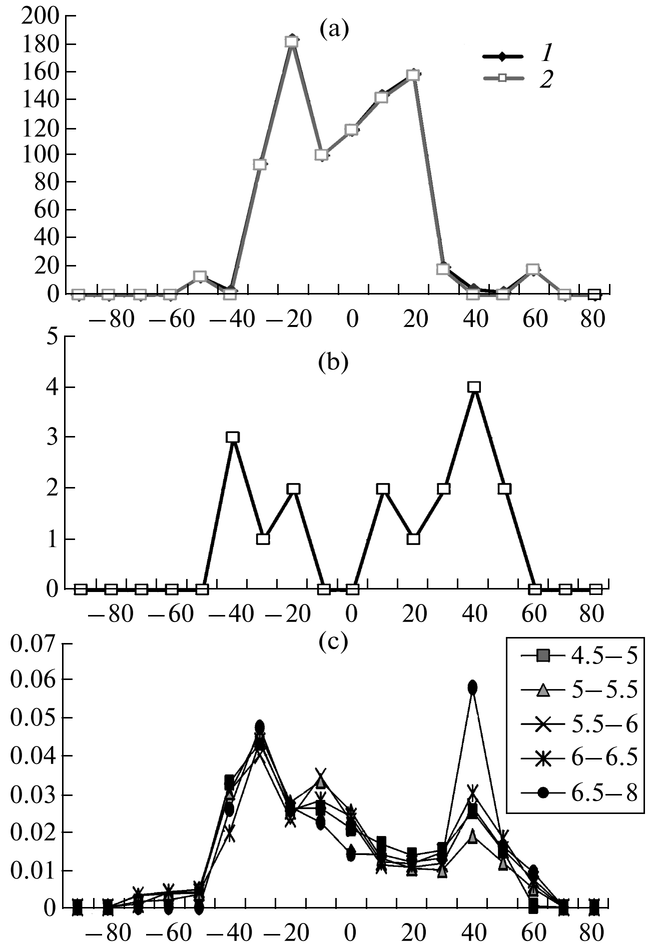

Fig. 1. Latitudinal distributions for seismic events for the Moon (a, b) and the Earth (c): (*1*) by all the events; (*2*) by deep events; the fragment (b) is for shallow lunar events; the fragment (c) is for five varied magnitude ranges on the Earth. Horizontal axes in all the fragments are latitudes (negative latitudes are for the Southern Hemisphere). Vertical axes are number of seismic events for the fragments (a) and (b); and the doubly normalized number of seismic events for the fragment (c).

were subdivided into deep ($800 \leq H < 1100$ km) and shallow ones ($100 \leq H < 300$km).

We processed the data on moonquakes, taken from [7], and obtained latitudinal distributions of moonquakes (Figs. 1a, 1b). The size of the latitudinal belt for these distributions was chosen to be the same as for the Earth (10°). Latitudinal distributions for all the moonquakes (861 events, black curve) and for deep events (844 events with $800 \leq H < 1100$ km, gray curve in Fig. 1a) were considered. Because of the fact that the number of recorded shallow events was substantially less than number of deep ones, these curves almost coincide. In Fig. 1b, latitudinal distributions for shallow events (17 events with $100 \leq H < 300$km) are given.

Thus, seismic activity on the Moon is almost absent at high latitudes, reveals clearly expressed maximums at middle latitudes of both hemispheres, and has a stable local minimum near the lunar equator. Such pattern of distribution is characteristic for both deep and shallow events. The difference is that expressive maximums of distributions for shallow events are formed at latitudes 30°–40° in both hemispheres, while those for deep events are in latitudinal belts of 10°–30°.

In Fig. 1c, latitudinal distributions for the double-normalized number of terrestrial seismic events (by summarized number of events of a considered magnitude range and by length of lithospheric plates in a given latitudinal belt) are given. Five distributions are presented for five MRs with no differentiation of events by depth. Latitudinal distributions for terrestrial events are asymmetric, and the near-equatorial minimum is shifted northwards.

Despite some differences, the global character of latitudinal distributions remains identical for both the Earth and the Moon. We carried out the analysis for stability of the obtained terrestrial distributions in space and time. For this purpose, all the calculations for the events in all the MRs were doubled for latitudinal belts of 5° and 2° and for four 10-year periods. All the noted peculiarities in distributions have remained.

To analyze two-dimensional distributions of earthquakes (by latitudes and depths), we considered the doubly normalized number of events (by length of lithospheric plates in every latitudinal belt and by temporal period of ten years). To built distributions, we used a nonuniform depth scale (0, 10, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900), and width of the latitudinal belt of 10°.

In Fig. 2, the two-dimensional distributions for three MRs ($4 \leq M < 5$, $5 \leq M < 6$, $M \leq 6$) are presented. In all three fragments, a clear spatial clustering of events is traced by both latitudes and depths. Event concentrations are distinguished at latitudes of 30°–40° S and 40°–50° N and at depths of 0–60, 100–250, and 500–700 km. A sharp decrease in the number of events near the equator (10°–20° N) and almost complete absence of them in polar latitudes are found. The most clearly expressed concentrations are saved in all the fragments of Fig. 2. Clusters with the maximal number of events for deep earthquakes ($500 \leq H < 750$ km) are located closer to the equator than clusters of crustal earthquakes. An analogous pattern is seen for lunar seismicity.

In [4], clearly expressed clustering was noted for moonquakes by two depth levels of $100 \leq H < 300$ and $800 \leq H < 1100$ km. It had been also shown that lunar pressure values at depths of $800 \leq H < 1200$ km correspond to terrestrial pressure values for deep layers of 120–240 km (cluster C2, by the classification given in [3]).

Deep clusters of lunar seismic events are isolated and do not cross themselves in space. One can observe

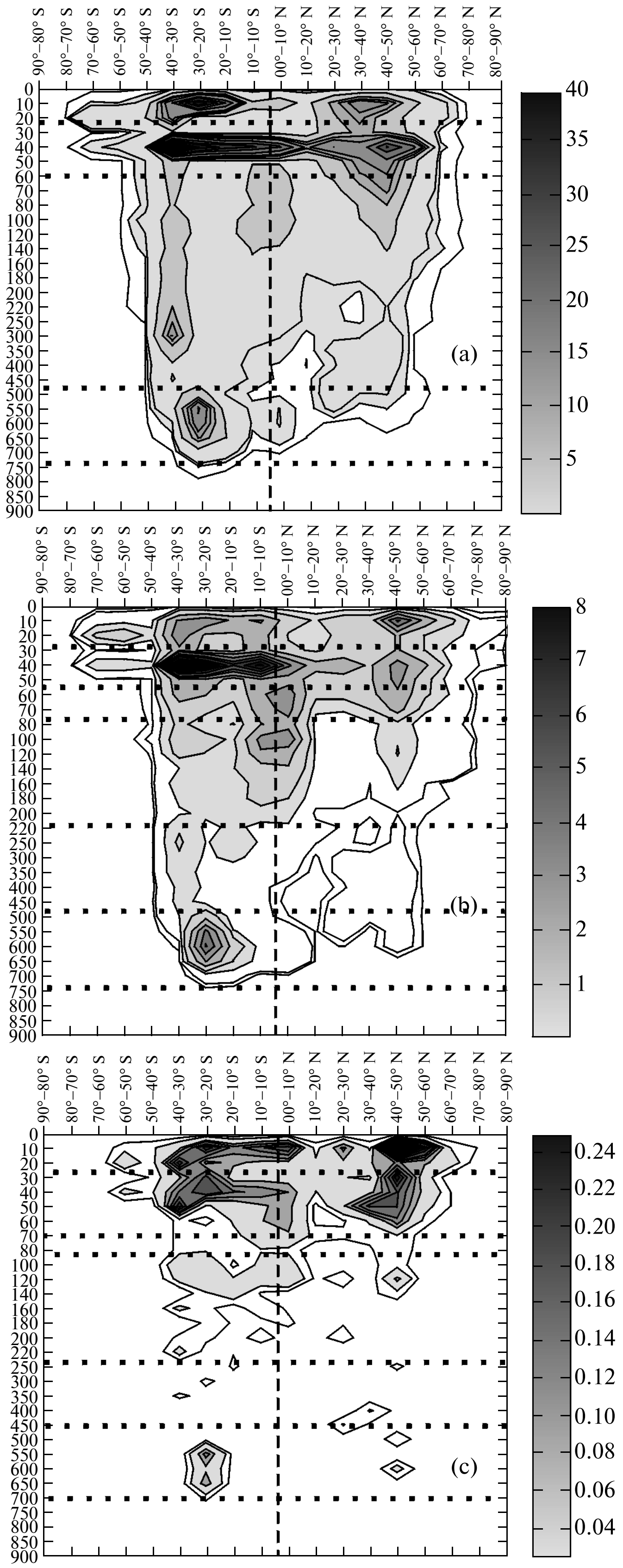

Fig. 2. The two-dimensional distributions of the normalized number of seismic events on the Earth; vertical axes are depth in km and horizontal ones are latitudinal belts. Magnitude ranges are (a) $4.0 \le M < 5.0$; (b) $5 \le M < 6$; (c) $M \le 6.0$. The half-tone scale for the normalized number of events is to the right of every fragment.

approximately the same pattern for earthquake clustering, but there are three groups of clusters on the Earth. Deep events on the Moon correspond to intermediate earthquakes, while deep earthquakes have no analogue in the Moon's seismicity. Thus, despite some certain differences, the global character of latitudinal distributions by depths is also similar for both the Earth and the Moon (difference in number of clusters by depth).

Analysis of results for latitudinal distributions in the number of seismic events on the Earth and the Moon has shown almost absolute identity in the pattern of both distributions. Such a similarity in the distribution of seismic activity for such different celestial bodies may evidence a fundamental relationship of seismic process with certain physical events, which are revealed in the same way for both the Earth and the Moon. As is known (see, for instance, [1]), the Earth and the Moon are revolving around a general mass center (baricenter), which is revolving around the Sun in an elliptical plane. At insufficient ariations in the Earth–Moon's orbit inclination (±5°), both celestial bodies suffer from solar gravitation in the elliptical plane.

Thus, long-period tidal effects from the Sun have their influence on both the Earth and the Moon. In accordance with modern ideas, it is these components of tidal forces that influence seismic processes effectively [1, 9].

Today, it is obvious that the way in which tidal forces have their influence on the Earth's lithosphere is quite complicated and there is no direct reaction of tidal effects on process of seismic event generation. But the long-term repeated summarized impact of tidal forces with varied periods can lead to very sufficient nonlinear effects. Long-period tides cause slow alternating deformations in rocks, promote fluid motion from depths to the surface, help the development of microcracks in rocks under the impact of the Rehbinder effect, and lead to rupture accumulation and creation of conditions for seismic fault generation.

Localization of seismic activity sources at certain depths can also evidence for similarity in ways of seismic event preparation. Elastic properties and equations of the rock state, the determined P–T conditions in event clustering zones, and the growth in density variations of free energy from tidal forces as depth increases can create similar conditions for implementation of seismic process.

The common idea on the predominant influence of geothermal flux energy and convective motion of masses in the Earth's depths on seismic process generation has become weak in light of the presented observations of nature. For instance, the maximal difference in speed of plate motion in subduction zones for the Pacific coast of South America (from 5°N to 45°S) does not exceed 7–8%, but the number of events for the same latitudinal belts differs 20–30 times, and the difference in released energy is more than 100 times.

The presented peculiarities in global distributions for the Earth cannot be explained from the viewpoint of the theory of plate tectonics alone. A more difficult thing is to substantiate the found similarity in global distributions of seismic events for two different celestial bodies by interaction of inner forces of the Earth and the Moon only. It is obvious that outer forces, which have influence on both terrestrial and lunar media and have a similar influence on seismic processes of both celestial bodies, do exist.

The found general regularities are based on a quite poor body of statistics of moonquakes and require additional critical analysis. However, the presented results direct us to the necessity to state the problem about the initial causes of seismic process. The existing common opinion that the main cause of moonquakes is tidal forces, while earthquakes are generated by mainly tectonic processes, should, probably, be revised in the very near future.

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