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Seismotectonics and Earth Tides

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Abstract—The results of the processing and analysis of the global earthquake distribution (more than 250000 events based on the ISC catalog) and the study of moonquakes distribution (about 900 events based on the published materials) are presented. It was found that the number of events and the energy for both cases show a bimodal distribution with maximums in the middle latitudes, zero values at the polarcaps, and a local minimum in the vicinity of the equator. The probable influence of tectonic processes on the revealed character of the seismic event distribution is analyzed, and the role of Earth tides in the activation of the seismicity in the symmetric zones on both sides of the equator is shown.

Key words: *earthquakes, moonquakes, latitude distributions, tectonics, tides, Earth's rotation.*

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INTRODUCTION

According to the modern concepts, tectonics is a section of geology that studies the structure, motion, and deformation of the Earth's crust. This science also considers the regularities in the Earth's crust structure and evolution. Seismotectonics is a section of geophysics that studies the tectonic conditions of earthquake generation. This work was aimed at analyzing the recently discovered regularities in the latitudinal distribution of earthquakes and demonstrating the relationship of these regularities with the tectonic parameters and global geophysical processes.

In the last 160 years, three paradigms have changed in geology [1]: the theory of geosynclines, the theory based on the leading role of lithospheric plates (plate tectonics), and the concept of mantle plume tectonics. The predominant paradigms during their evolution were based on the careful analysis of geological observations that were indisputable and perfect in their time; however, the accumulation of new data highlighted insoluble contradictions that required the revision of the basic paradigm [14, 15].

The situation that emerged stimulated geophysicists to perform a comprehensive analysis of the data on the earthquake parameters accumulated in the world seismic catalogs and to reveal the tendencies of their distribution.

THE METHOD AND PROCESSING RESULTS

The Earth's seismic events were analyzed using data from the International Seismological Catalog (ISC) [18] for the period from 1964 until 2008. The preliminary processing of the data extracted from the catalog involved omitting the incomplete records, the standardization of the magnitude, and the ejection of aftershocks. In the framework of this work, we analyzed more than 250000 earthquakes with $Mb \geq 4.0$. Such a large data set was analyzed using specialized software packages that were developed based on the MATLAB system.

The Pacific Region, which contains more than 80% of all the world's earthquakes, was chosen as the object of study. We determined the Pacific Region (hereinafter, the PR) as the oceanic area with island arcs, marginal seas, and land areas above the subduction zones. The Pacific Belt contains not only the main seismoactive provinces but also the boundaries of the main lithospheric plates, to which the most part of the earthquakes are confined; additionally, the dynamics of these plates have been well studied using satellite geodetic measurements [14, 21].

The simultaneous analysis of the latitudinal distribution of the number of earthquakes and the estimation of the total length of the lithospheric plate boundaries in a given latitudinal belt have allowed us to reveal the peculiarities of the seismic activity in different portions of the tectonic provinces. We considered the normalized latitudinal distributions of the numbers of earthquakes, the amount of released energy, the distribution of the hypocentral depths in the latitudinal zones, and the two-dimensional distributions of the events (by latitudes and depths). Since the latitudinal distributions of events of various energy levels can be different, we considered the distributions for six magnitude ranges independently: $4.0 \leq Mb < 4.5$, $4.5 \leq Mb < 5.0$, $5.0 \leq Mb < 5.5$, $5.5 \leq Mb < 6.0$, $6.0 \leq Mb < 6.5$, and $Mb \leq 6.5$.

The entire PR was subdivided into 18 latitudinal zones 10° in size. In the first stage of the study, we considered the distributions of the numbers of earthquakes in latitudinal zones as normalized to the area of a latitudinal zone. Such an approach appeared to be inefficient and physically unjustified for the PR because the earthquake epicenters are very unevenly distributed over a latitudinal zone, being largely confined to the boundaries of lithospheric plates. Such a peculiarity of the seismic provinces was noted as early as the 1940s by Gutenberg and Richter [2].

Hence, our further study was based on the number of events and the released energy normalized to the total length of the lithospheric plates boundaries within a given latitudinal zone. As a result, we derived the density characteristics of the seismic events and released energy (the number of events and energy per 100 km of length of the lithospheric plate boundaries) for each latitudinal zone as a reflection of the activity (or power) of the tectonic processes.

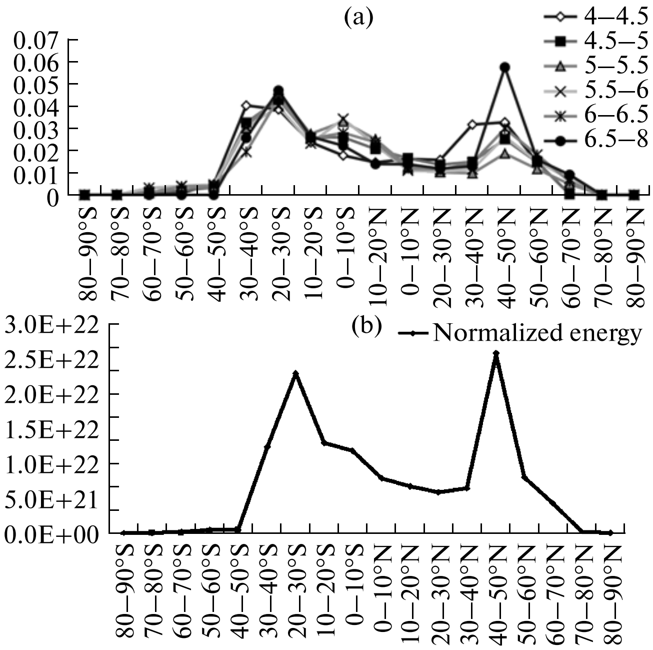

Fig. 1. Latitudinal distribution (a) of the relative density of the seismic events (along the x-axis); the distribution of the energy density (along the y-axis) by the latitudinal zones (b).

The latitudinal interval is denoted on the x-axis. The inset contains the magnitude ranges.

THE RESULTS OF THE STUDY

The analysis of the latitudinal distributions for event density has allowed us to reveal a surprising regularity [6]: seismic activity is nearly absent at the poles and the near-polar zones of the planet, it sharply grows in the middle latitudes reaching maximums at about 40–50° N and 20–30° S, and it forms a steady local minimum near the equator (Fig. 1a). The latitudinal distribution of the released seismic energy demonstrates an analogous pattern (Fig. 1b). The verification of the found peculiarities of the latitudinal distributions has indicated that the bimodal distribution pattern is preserved in each ten-year interval, even if the size of latitudinal zone will be changed to 5° and 2°. A comprehensive analysis of the latitudinal distributions of the events has shown that the peaks of the seismic activity for the shallow-focus earthquakes ($H \leq 80$ km) are located at a greater distance (±35–40°, Fig. 2a) than those typical of deep-focus events (±25–30°, Fig. 2b).

It is pertinent to mention that a similar bimodal distribution of the event energy with close parameters was found by W. Sun during the analysis of the catalog of strong earthquakes (1165 events). The difference between the positions of the activity peaks for the shallow- and deep-focus earthquakes was the same (Figs. 2c and 2d).

Next, we analyzed the latitudinal distribution of the hypocentral depths. For each latitudinal zone, the distribution of the relative number of earthquakes was plotted versus the depths, which allowed us to determine what part of the events in a given latitudinal zone falls within a set depth interval. The analysis was performed separately for the West and East PR (Figs. Ç and 4).

The derived results indicate that the sources of nearly all the earthquakes (up to 90%) are restricted to depths $H \leq 20$ km. While approaching the middle latitudes, the number of events whose hypocenters are located at the depths of $20 < H \leq 60$ km gradually increases. In the near-equator latitudinal zones (30° S–30° N), a substantial part of the earthquake hypocenters is located at the depths of $100 < H \leq 240$ km, submerging to depths of $H \leq 500$ km at certain latitudes. The maximal number of events with $H \leq 500$ km both in the West and East PR falls within the latitudinal zone of 30–20° S.

In terms of the depth distributions of the released energy, the events can be divided into three particular groups (clusters) with sufficiently clear boundaries. The first cluster (C1) unites the shallow events with the depths from 0 to 70 km, the second cluster (C2) contains the intermediate events from the depth range of 120–240 km, and the third cluster (C3) is distinguished at the depths from 500 to 700 km. In high latitudes, only C1 events are present.

Figure 5 demonstrates the two-dimensional distributions of the seismic event density over the latitudes and depths for the three magnitude ranges. The gray scale of the intensity level sets the density of the seismic events in the PR averaged over a 10 year period. Such a representation of the data verifies the clear

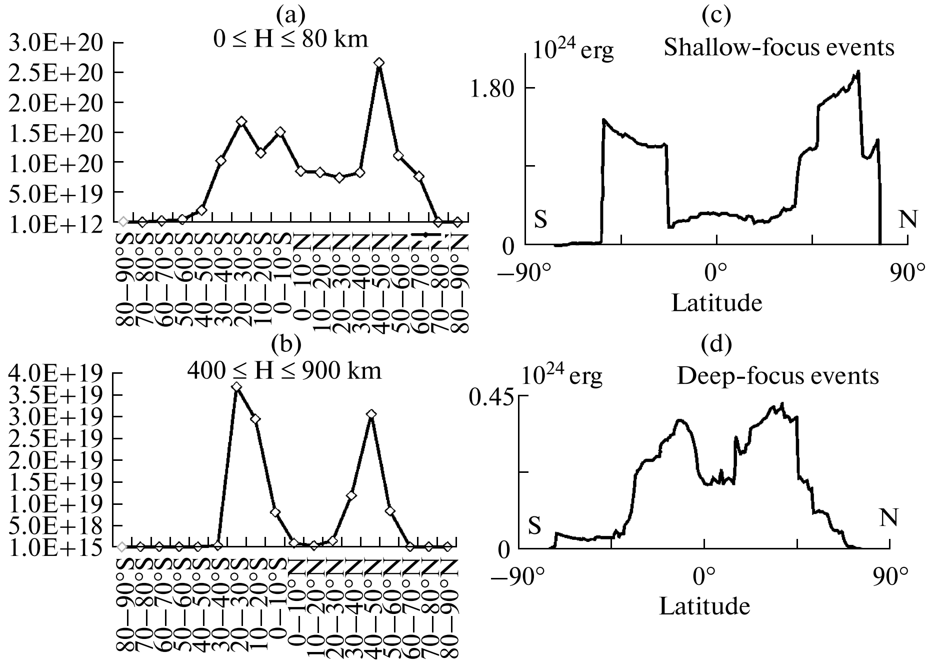

Fig. 2. The distribution of the energy density over the latitudinal zones for shallow- (a) and deep-focus (b) earthquakes with $M \geq 4$ based on the author's data. The distribution of the energy released by shallow- (c) and deep-focus (d) events with $M \geq 7$ over the latitudes (after [3]). The latitudes are denoted on the x-axis, while the density of the energy (erg/km), on the y-axis.

clustering of the seismic events both by the latitudes and depths. In terms of depth, the events are divided into three clusters, and the shallow events are additionally divided into two separate clusters ($H \leq 30$ km and $30 < H \leq 70$ km).

The comparison of the terrestrial and lunar seismicity using data from [3, 17] showed that the bimodal pattern of the latitudinal distribution of the number of seismic events is preserved in both cases (Fig. 6). The polar areas of the Moon, as the polar caps of the Earth, appeared almost aseismic, whereas its middle latitudes record enhanced seismic activity [8]. The positions of the peak values of the moonquakes for the deep (Fig. 6a) and shallow (Fig. 6b) events resembled those for the PR. The maximums of the lunar seismicity for the deep events were noted in the latitudinal zones (±20°), whereas the shallow-focus events are concentrated in the vicinity of the zones (±40°).

On the Moon, seismic events are also divisible into clusters according to the depth. We emphasize that the lunar clusters are isolated and are not overlapped in space. Tectonic (shallow) moonquakes are grouped within depth intervals from 150 to 400 km km, whereas so called tidal or deep moonquakes do not leave the depth interval from 700 to 1200 km. Note that deep moonquakes and intermediate earthquakes occur in the zones where rocks of the Moon and the Earth suffer nearly equal pressures of about 4 GPa. Thus, despite certain differences, the global character of the latitudinal depth distributions is similar for both the studied celestial bodies, while differing only in the number of clusters by the depth.

DISCUSSION

The role of tidal processes and their probable influence on earthquake generation has been repeatedly discussed in scientific publications since Immanuel Kant (1755). In recent years, much attention [12, 16, 19] was given to the consideration of the energetic and time aspects of tidal effects on the rocks of the Earth's crust with estimates indicating the possible role of tides as earthquake "triggers." The analogous viewpoint was stated by W. Sun [23]. He noted that the energy of long-period tides reached its maximum in the area of the middle latitudes (±45°), i.e., approximately coinciding with the maximums of the seismic activity. It was shown in [4] that the variations in the density of the free energy transferable by the tides to the crust and upper mantle reaches its maximum in the middle latitudes, providing a power three times higher than the energy released during earthquakes. The tidal periodicity and related alternating-sign loads caused in the crustal rocks can lead to the accumulation of damages in the structural heterogeneities of rocks and to the development of microcracking, which finally leads to the formation of a main earthquake rupture. The same work showed that tidal forces cannot only trigger an earthquake but also serve as the main source of energy providing an earthquake's generation.

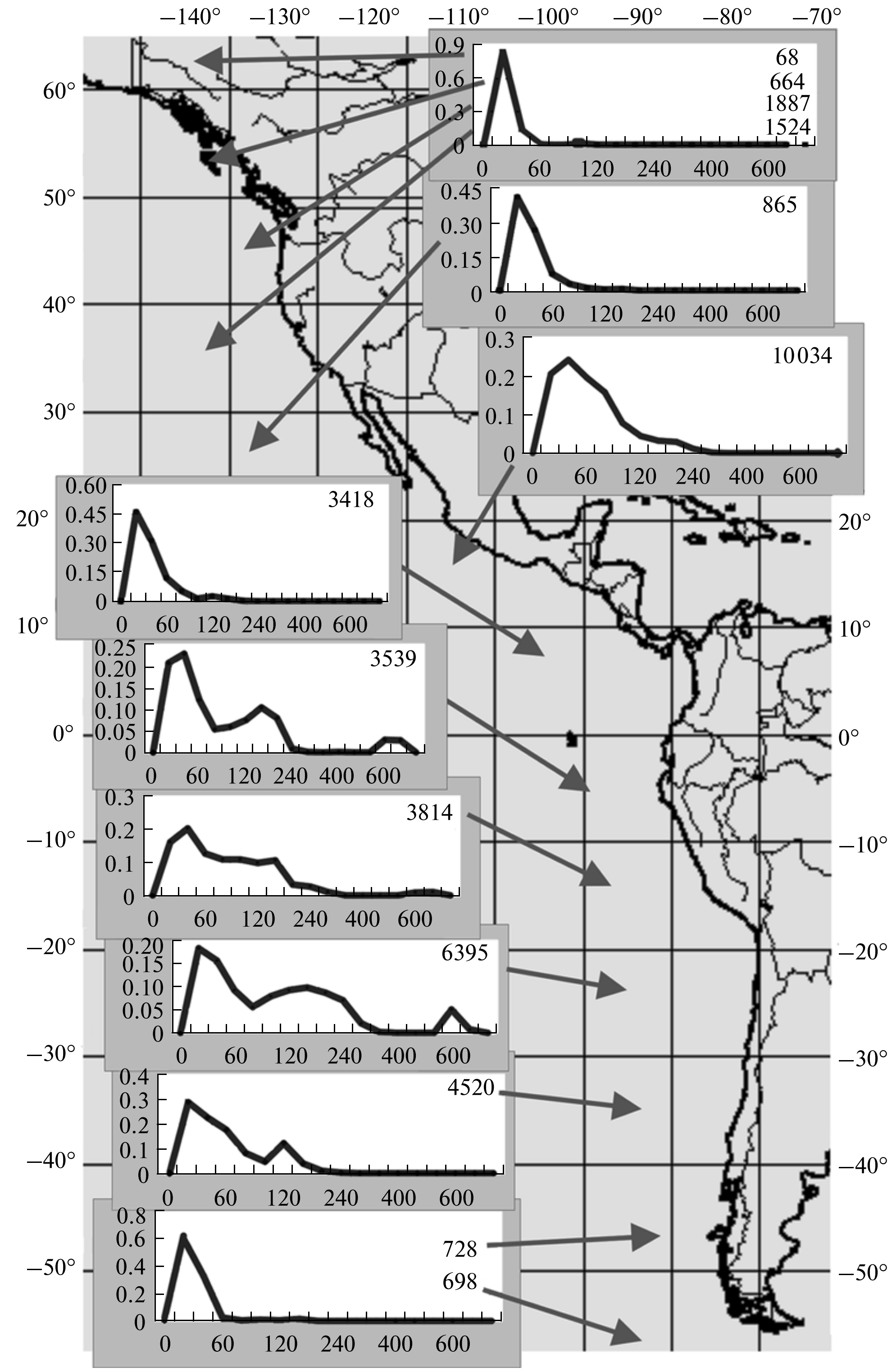

Fig. 3. The depth distribution of the relative number of earthquakes in the eastern part of the PR in the latitudinal range from 70° N to 60° S.

The black line draws the continents. The nine inset panels sequentially arranged vertically demonstrate the depth distributions of the earthquakes for every latitudinal zone; the depths of the earthquake focuses (km) and the relative number of earthquakes (normalized to the total number of earthquakes in a given latitudinal zone) are plotted on the x- and y-axes, respectively. The numerals in the right upper corner of every panel indicate the total number of earthquakes in the given latitudinal zone.

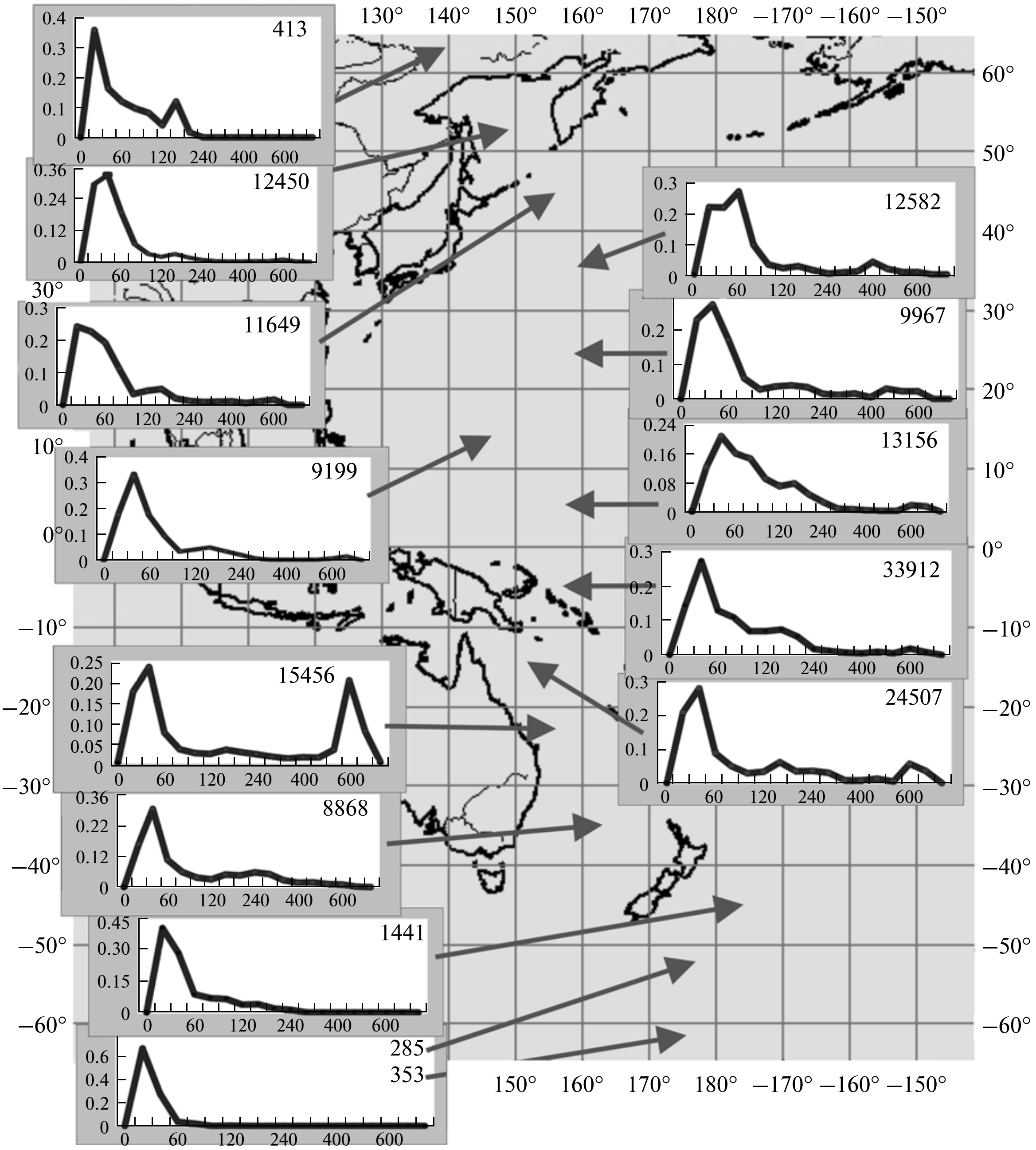

Fig. 4. The depth distribution of the relative number of earthquakes in the western part of the PR in the latitudinal range from 70° N to 70° S.

The black line outlines the continents. The panels showing the earthquake distributions are designed in the same way as in Fig. 3.

Recently, the issue about the effect of tidal forces on earthquake preparation received an absolutely fresh impetus to its development. The gravity forces affect not only the solid matrix of terrestrial rocks but also the fluid filling the crack systems in the crustal rocks. The role played by water and water fluids, as well as fluidization phenomenon, were noted earlier among the factors affecting an earthquake's preparation [5, 20]. In the recent time, high attention is paid to the role of the Rehbinder effect (the absorption drop in rocks rigidity) during earthquake preparation [7, 11]. The presence of an aqueous fluid with high absorption properties, in combination with cracks, intergrain boundaries, dislocations, elevated temperature, and a complex field of variably scaled tidal-induced stresses in the crustal rocks, promotes favorable conditions for the appearance of the Rehbinder effect. This effect causes an increase in the fragility of a soild body; a decrease in its lifetime; the weakening of atomic bonding; and, as a result, a drastic (by an order of magni-

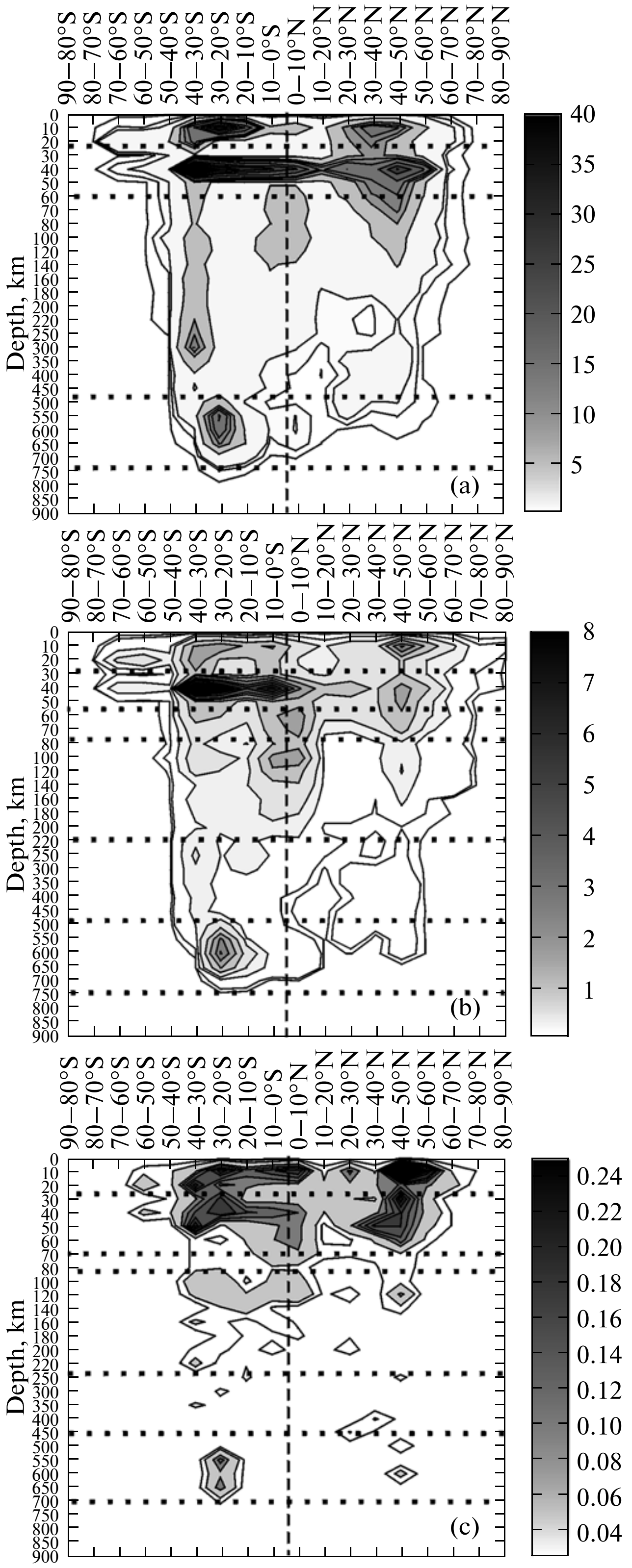

Fig. 5. Two-dimensional distributions of the density of the seismic events for the following magnitude ranges: (a) $4.0 \le Mb < 5.0$; (b) $5.0 \le Mb < 6.0$; (c) $Mb \le 6.0$. The vertical axes denote the depth in km, while the horizontal axes, the latitudinal zones. The gray scale of the density of the seismic events is shown right of every fragment.

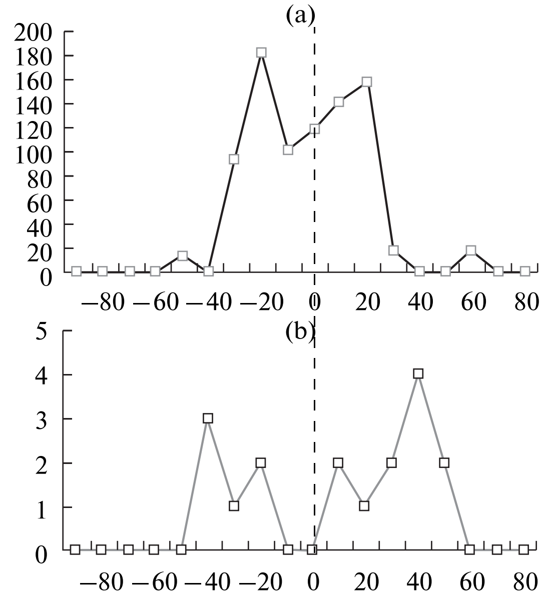

Fig. 6. Latitudinal distributions of the seismic events on the moon: deep (a) and shallow (b) moonquakes. The latitudes (the negative latitudes are for the Southern Hemisphere) are shown on the horizontal axes. The numbers of seismic events are shown on the vertical axes.

tude) decrease of the rock's strength in the area of the earthquake source preparation and the rapid formation of a main rupture. Note that an increase in the variation of the free tidal energy density in the middle latitudes should lead to an increase in the degree of the rock fluidization precisely in these latitudes and, therefore, to the corresponding growth of the seismic activation as well (this is verified by observations).

Tidal effects of the Moon and the Sun on the Earth lead to changes of the angular velocity of the Earth's rotation [10]. Variations in the Earth's rotation velocity, in turn, cause changes of the Earth's shape. An increase in the angular velocity leads to an increase in the Earth's ellipticity, while a decrease, to a decrease of the ellipticity. Simple estimates indicate that the variations in the kinetic energy of the planet's rotation owing to the changes in its rotation velocity can be about 10^{21} J per year. This value is 2–3 orders of magnitude higher than the total energy annually released by earthquakes. The changes in the ellipticity of the planet in response to variations in the rotation velocity must be manifested in the zones of spatial resonances or in the zones of critical latitudes (near ±35°). In these zones, compression stresses typical of polar caps are replaced by extension stresses, which are peculiar to the equatorial zone.

The well-known phenomenon of the differential rotation of the Sun (every 25 days in its equatorial zone and 29 days in the polar areas) gives the following dependence of the angular velocity (ω) on the latitude (θ) [9]:

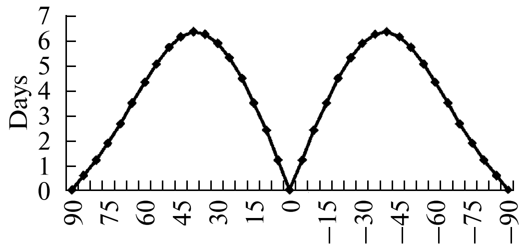

Fig. 7. The distribution of the latitudinal gradient of the solar surface rotation period over the heliocentric latitudes.

$$\omega(\theta) = (2.78 + 0.35\cos^2\theta + 0.44\cos^4\theta)\ 10^{-6}\ s^{-1}.$$

The analysis of this empirical dependence revealed the existence of two maximums at about ±35° in the latitudinal gradient of the angular velocity of the Sun (Fig. 7). The latitudinal distribution of the number of hot spots on the Earth [22] also reveals a bimodal pattern with characteristic maximums in the area of the middle latitudes.

CONCLUSIONS

The similarity of the latitudinal distributions of the earthquakes, the Earth's hot spots, moonquakes, and the zones of the Sun's differential rotation with distinguishing the middle latitudes as domains of spatial resonance leads us to the idea about the existence of a general physical mechanism affecting a rotating body. This mechanism can manifest itself against the background of the general tectonic processes, additionally distinguishing the characteristic latitudinal zones with elevated activity of geodynamical processes. Such areas are referred to as lineaments in the ±40° latitudes in the geological literature and have attracted the attention of geophysicists for a long time.

The investigation of the hydrodynamic instability in celestial bodies and structures actively developed in the recent time [13] indicates the probability of the formation of instabilities and critical latitudinal zones within rotating celestial bodies. As is indicated by the observation results and the theoretical estimates, the areas of instabilities and sharp changes in the rotation parameters usually occur in the middle latitudes of planets. These fundamental physical phenomena can be responsible for the formation of anomalous latitudinal zones of high seismic activity, which were found in this work. The further investigation of the revealed regularities will promote insight into the physical mechanism operating in the latitude zones on both sides of the equator. Such symmetric domains could play the role of spatial resonances in geophysics or serve as generators of zones of hydrodynamic instability.

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