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GEOLOGY

Denudation and Seismicity of the Earth's Crust

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The distribution $N(h)$ of the number of earthquake sources (N) through the section of the continental crust (h) is similar even in regions with different tectonic styles [1]. Most sources concentrate on a seismoactive layer at a depth of 10–15 km. The number of sources diminishes abruptly upsection toward the Earth's surface and more slowly (almost exponentially) downward along the section.

A similar distribution of sources of seismic pulses, though on a different scale, is recorded in seismicity excited by underground mining. The maximum of the pulse distribution commonly passes ahead the stope over a distance of 1.5–2.0 m. The number of pulses abruptly falls toward the stope and diminishes more slowly from a maximum at the source toward the intact rock massif.

The seismic pulses reflect the process of rock disintegration, which is maximum at the surface of the mine working (crush zone [2]). The next (less destroyed) zone shows a more ordered fracturing. The fractures here are nearly parallel to the contour of the mine working (oriented fracturing zone). In the third (elastic) zone, the newly formed structural features excited by mining are either insignificant or absent. Thus, the maximum of mine seismicity occupies a transitional position between the crush and oriented fracturing zones.

The character of mine seismicity changes with variation of the structural setting. Many relatively weak pulses are typical of the short-range zone of a mine working, and the most important events happen at the weakly active periphery in the long-range zone of the working [3].

Geological–geophysical data and the fine structure of seismic fields indicate that the structural state of the Earth's crust corresponds broadly to the scheme of mine seismicity considered above. Near the day surface, the rocks are crushed intensely, and the degree of disintegration gradually decreases downward along the section. In particular, it has been established that the seismoactive layers coincide with low-velocity zones (waveguides). According to [1], the waveguides are fluid-saturated crush zones. From this standpoint, the maximum at a depth of 10–15 km corresponds to a layer with the maximum disintegration at a given moment. The base of this layer is characterized by the appearance of sporadic but more extended fractures of early generations. The roof is marked by the development of more numerous earthquakes related to the fractures of later generations and mainly represented by relatively weak seismic events (figure). The figure compares two distributions of the $N(h)$ type based on the data on seismicity of Eurasia. The location of 16000 earthquake hypocenters was taken into account. The data array of type 1 distribution comprises the sources of strong earthquakes ($M \geq 5$), while the data array of type 2 distribution characterizes the sources of weak earthquakes. One can see that the distribution of strong earthquakes is shifted statistically downward relative to the distribution of weak earthquakes.

This pattern is inherent to the process of rock failure according to the scenario of fragmentation, when the rocks are consecutively disintegrated along the jointing into smaller fragments [4, 5]. Such structuring, inherent to a substrate with natural energetic potential, is related to unloading of this potential [6].

The natural potential is defined as an energy resource accumulated beforehand by a body. This resource exists in a body irrespective of the system of forces acting upon the body from outside at a given moment even when external forces are equal to zero.

Thus, seismicity in the Earth's crust arises in the process of unloading of its own energetic potential.

What is the cause of unloading that provides the characteristic distribution of an earthquake with depth? What is the nature of the energetic potential of the crustal rocks?

The following reasoning suggests a possible answer to the first question. Since the distribution of earthquake sources is similar in the regions with different

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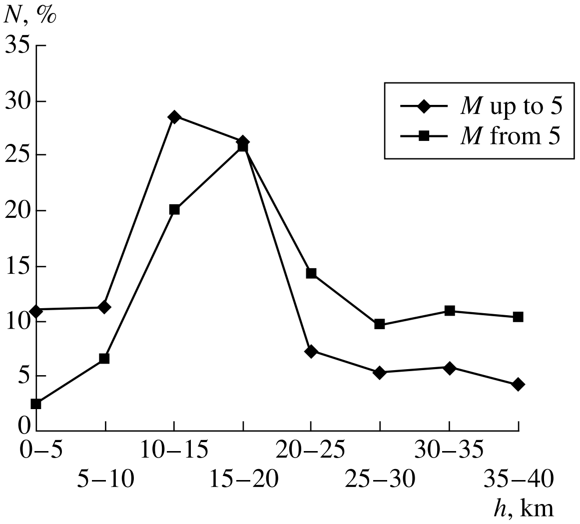

Distribution of strong and weak earthquakes in Eurasia with depth.

tectonic styles, e.g., in Tien Shan and the Baltic Shield, the tectonic style does not exert a direct influence upon the character of source distribution. The recent geological history of both Tien Shan and the Baltic Shield is characterized by their steady uplift with a rate of 8–10 mm/yr. The uplift promoted denudation of positive landforms and removal of a few kilometers of rock sequences. One can suggest that a substantial decrease in lithostatic pressure on the underlying rocks was responsible for the unloading.

If we assume such a possibility, the regions of a stable uplift should be distinguished by elevated crustal seismicity. This phenomenon is actually observed. The process of uplift is differentiated. For example, this process is expressed in Tien Shan in the alternation of basins and uplifts. The correlation of seismicity maps and geological structure of Tien Shan has shown that the seismoactive zones are concentrated in uplifted landforms, whereas the seismicity of basins is sharply lowered. This is evident for the large basins (Fergana, Isyk-Köl, and Chu) and not so distinct for smaller basins. This effect can be veiled by many reasons, including scatter in the determination of coordinates of hypocenters. The relationship is more prominent in areas furnished with more precise data. For example, according to observations at the Garm test site distinguished by a high accuracy, seismicity is virtually absent in relatively narrow basins marked by the Surkhob, Obikhingou, Sorbog, and Komarou river valleys. This phenomenon is concentrated in their mountainous framing [7].

As concerns the nature of the energetic potential of the crustal rocks, we should mention the following points.

Let us discriminate two types of elastic deformation: (i) deformation ε_F relaxes with release of the external loading; (ii) deformation ε_ϕ is fixed by the material of the body. In the general case, $\varepsilon = \varepsilon_F + \varepsilon_\phi$.

The "latent energy" is an energetic function of elastic deformations, whereas the "latent stress" is their force function (potential). In the technical and mining fields, these functions are commonly named "residual stress."

The fixed elastic deformation is a consequence of incompatible changes in sizes of the adjacent structural elements as a result of not only change in the system of external forces acting upon the given body, but also variation of any thermodynamic parameters (pressure, temperature, chemical potential, and others) that characterize the body as a thermodynamic system. In other words, the fixed elastic deformation may arise due to diverse physical, chemical, and mechanical transformations of a substrate. Various mechanisms of fixation of elastic deformations in solids, as applied to problems of the technology of materials and engineering works, are considered in many publications [8, 9, and others].

The decrease in lithostatic pressure results in the comprehensive change of the thermodynamic state of the geologic medium and excitation of numerous interrelated processes. This is eventually expressed in the appearance and growth of the natural energetic potential. If this potential grows to the critical level, the system becomes energy-saturated, i.e., extremely nonequilibrium, and this state predetermines brittle failure.

It is suggested that the temperature is ~500–600°C at a depth of 13–17 km corresponding to the maximum seismic activity. Is brittle failure possible at such a high temperature? As is known from the science of materials, precisely this temperature range fosters phase transformations in metals that give rise to high latent stresses and thus impart elevated brittleness to metals [10, 11].

It has been established that brittle failure with the formation of tensile cracks is possible at high temperatures, when the material is still sufficiently plastic. The initiating fractures appear at faces of crystals, the orientation of which is closest to that of planes normal to the tensile stress [12]. Further displacement along these fractures (tectonic flow) can provoke the foliation of material, and the fracture zones can serve as conduits for fluid transport.

In conclusion, let us note the following points. The unloading of crustal rocks due to denudation of positive landforms is a rather universal, but not the sole, factor that promotes the appearance of natural energetic potential sufficient for exciting seismicity. The disturbance of confining pressure during the differential vertical displacement of rock blocks [13] or the tectonic extension in zones of continental rifting is another factor responsible for the unloading of crustal rocks.

However, the examples presented above are only particular cases. The unloading of the energetic potential of a medium and its subsequent destruction according to the scheme considered above will occur in all cases of the development of fixed elastic deformations and possibility of their release for one reason or another. It is worth noting that the same stereotype is traceable in the structure of large fault zones across their strike: the disintegration of the medium is maximal in the axial zone; the number of fractures decreases exponentially toward the walls of faults; their orientation becomes more ordered; and the fractures become longer [14]. In this case, the release of the fixed elastic deformations (similar in a physical sense to the unloading of the energetic potential of the medium) is provided by the displacement of fault walls.

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