Deep-seated tectonics and its relationship to dynamic processes caused by ore mining (according to xenolith study)

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Abstract. The paper examines a possible relationship of the occurrence of catastrophic situations (earthquakes, rock bursts, etc.) in unordinary conditions and manifestations of tectonic processes in the bowels of the Earth at the “lower crust-upper mantle” level. It is shown that such tectonics is observed in basite-ultrabasite xenoliths bearing clear features of deep-seated deformation (olivine twinning, curved crystals, drag grains of spinel, preferred orientation of optical indicatrices of minerals, etc.). The mentioned relationship is studied from the viewpoint of relaxation reaction of rock masses, rocks and their element components on mass displacements in the Earth’s depths.

1. Introduction
In mining practice, disastrous events (earthquakes, rock bursts, displacements of rock blocks, etc.) that occur time and again worldwide, are sometimes found inexplicable due to their conditions seemingly showing no prerequisites for their occurrence. Most often, such situations are explained by a combination of random circumstances, the absence of systematic observations or proper subsurface forecasting, and by the human factor. However, should the recent tendencies be taken into account, first, for the coal mining technologies to move from open pit to underground mining, and, secondly, for increasing human impact on the subsurface state to the extent that it leads to the concentration of stresses in rock masses to critical values, one can postulate a certain relationship between these hazards and geodynamic phenomena in the earth's crust. In this case, there arises a need for collecting the information about the mechanism and characteristics of deep subsurface tectonics and a relationship between effects of its manifestations at great depths and man-made objects and structures in the upper earth’s crust. This issue has been currently accepted for consideration in the Chita Division of the Chinakal Institute of Mining, Siberian Branch of the Russian Academy of Sciences (SB RAS).

2. Impact of ore mining on dynamic processes
Many researchers incidentally recognize that near-surface geodynamic processes are largely associated with tectonic motions that have been occurring even at the level of lower crust (the uppermost mantle). Presently, it needs to be recognized that major direct evidence of tectonic processes in deep subsurface are represented by indications of deformations and accordingly structural and textural features in basite-hyperbasite xenoliths transported by magmatic melts onto the earth’s surface. As such, the intrusions, despite a fairly drastic change in their thermodynamic and mechanical conditions liable for disintegration, submelting, and recrystallization, have retained traces of the extant medium and
processes that transpire at depths designated as \( n-n10 \) km. In reality, deep-seated xenoliths are attributed for the most part to the basite-hyperbasite series, whose internal structure includes such features as: striation, flatness, veins and veinlets, milonitization (as zones and bands), crushed and pulled apart grains (often in one direction), fractured and whole spinel grains, signs of deformation-induced curvature of crystals, etc. Moreover, against the background of, for example, recrystallization structures, cumulative textures, the deep-seated xenoliths are characterized by the deformation signatures similar to those inherent in the peridotites from alpinotype massifs of the ophiolite complexes: platy granoblastic texture, porphyroelastic structure, pronounced preferred orientation (alignment) of minerals, their optical indicatrices, etc. The fact that the phenomena of relaxation occur in any system (even those exposed to the action of external factors) will inevitably cause changes in deep occurring rocks under the action of certain dynamic processes, which are recorded in xenoliths (detached masses of these rocks), primarily as the above listed features.

The reality of such phenomena in xenoliths was proved by numerous the experimental works back in the 70s of the last century. Thus, it was found that deformation structures and preferred orientations emerge under high temperature (from 800 to 1300°C) and pressure (from 5 to 20 kbar or more) conditions due to intracrystalline translation (plane shifts, slides) \[1–3\]. Results of the experiments on synthetic dunites \[4\] allowed an inference that the axes of shortening of the rock coincided with the direction of axis [010], while the flattening planes were parallel [100] and [001]. The experiments on the olivine twins synthesis under high \( P–T \) conditions confirmed that such characteristics can actually serve as an indicator of the rocks' great occurrence depth and the presence of “stress-generating” geodynamic processes in the deep subsurface \[5, 6\]. At this, microstructural analysis of the rock specimens showed that the axes of the ellipsoids of olivine crystals are oriented in the direction of the applied load. The study of xenoliths from a number of Kamchatka volcanoes \[7\] confirmed that rotation of the \( N_p \) axes of optical indicatrix of minerals when unidirected with the acting forces eventually leads to a reduction of their effects.

The said preferred orientation of minerals and their optical axes (as well as stress ellipsoids) was probably the most remarkable footprint of deep tectonics. This is typical of xenoliths collected from volcanites from different regions worldwide. Under the action of deep non-hydrostatic stresses, such orientation results in a manifest anisotropy of elastic properties of rock minerals, in particular, olivines \[8–13\]. At this, a direct relationship is reliably established between the packing density of stacked directions in the olivine crystal lattice and \( P \)-waves velocity, which is preserved under pressures of the order of 1 GPa \[14\].

When affected by the external (cosmic, associated with the earth’s orbital motion and rotation, tides in its crust, etc.) and internal forcings (e.g., the motion and rotation of the core), the structured states with different gradient of stresses concentrated dominantly near its defects tend to form within the framework of the deep subsurface system. Similar phenomena typify the areas of mine takes, specifically, in underground mining, where the system of mine workings is interpreted as a major defect. This state is accompanied by relaxation of the accumulated stresses down to the most “advantageous” (from the standpoint of the process energy) values. It stands to reason that these opposite-sign processes are accompanied by the affiliated geodynamic phenomena, whose development depends on the defectiveness of the considered system. At this, the implications of deep geodynamics activity must inevitably be “superimposed” on the stress concentration zones in the vicinity of underground mining operations. In this case, we can assume either a drastic increase in the dynamic phenomena, or, conversely, their leveling off.

The defectiveness of real systems or geological bodies entails much more that variations of their strength and other characteristics: the more heterogeneous and hence more defective the system, be it a massive ore, dry dispersion or pulp, the more non-linear are the processes representing its responses to external effects. Importantly, the stress waves are concentrated near the defects, initiating thereby manifestation of various processes characterized by gradient fields, including electrical (electrochemical) ones—those arising from some differences between the element components of the system \[15, 16\]. Such fields emerge at least because these components are capable of acting as an
electrode relative to each other, while currents between them flow due to the presence of a difference in physical, chemical, electrical, electrochemical and other potentials. The difference in electrical potentials in the earth's interior probably reaches the values at which the relaxation discharge pulses take the form of underground lightning (is this not one of the causes of earthquakes?).

Transformation and analysis of the known stress–strain relation [17] shows that, it contains the relaxation parameter, which is, on the one hand is inherent in the material, on the other hand, a property that depends on the parameters of external factors. Hence, a change in the time and magnitude of loading cause a change in the material’s relaxation responses to this impact. Since the high-load activation triggers certain changes in the system, the final stage of concentration of stresses is accompanied by residual stresses. In this case, the two contrasting variants can possibly develop: when the intervals between the adjacent activations of the system characterized by the summation of the times of stress growth $t_g$ and relaxation $t_r$, turn out to be greater or lower, than $t_g + t_r$. It is clear that from the standpoint of energy physics, the second option is more effective as compared to a single powerful impact the system exposed to, inasmuch as it utilizes the principle of buildup of residual stresses. Taking into account a relationship between periodicity of the external influence and the relaxation characteristics of the system under loading, it turns out that, given the repeated loading, the non-equilibrium state of the the system’s substance can be possibly maintained. Such loads are typical both of the earth’s depths (e.g. due to tidal phenomena), and for mining operations during minerals mining (e.g. ore breakage technologies). Firstly, it is essential that manifestation of critical situations are not necessarily triggered by huge force impacts (which is absolutely optional, as mentioned above), inasmuch as it is sufficient if they are small in energy, but alternating with a period fitting in with the second variant’s criteria. Secondly, a possibility of the interference overlapping of deep and near-surface deformation waves is not ruled out, in which the total stress can either be extinguished or reach a critical value. At this, the system can be changed either quantitatively or qualitatively. To some extent, considering the relaxation phenomena and the frequency of intracrustal stresses generation, this overlap also cause the transition in the rock mass response, accordingly, from dynamic phenomena to pendulum-type waves in the stressed geo-media [18].

3. Conclusions
It is likely that, specifically the interference-driven cause is liable for the accident at Alrosa’s Mir mine due to an unexpected disturbance of rock mass continuity between the quarry and underground mine workings. This was preceded by abnormally high elastic wave velocities which were recorded in the lower part of the geological section while conducting the interwell acoustic logging [19]. Given that characteristics of acoustic emission depend on the dynamics and characteristics of the jointing formation process whose “portrait” is determined by the external influence dynamics, the stress state of rock massif, and a number of other factors, the existence of this reason is justified. This is also confirmed by a series of accidents at coal mines, assigned to the periods of maximum impact of moon's gravitational pull on the Earth [20], when the processes of redistribution of deep masses, generation of various fields, etc., reach the earth’s surface.

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