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Paradoxes of High and Low Velocities in Modern Geodynamics

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Abstract. An analysis of the data on the vertical and horizontal movements of the Earth's crust obtained within recent 40 years has revealed paradoxical deviations of its deformations from the movements inherited from the past geological times. Currently, high local deformation velocities are observed both in the aseismic and seismically active regions. There are no clues to this phenomenon within the conventional concepts of geodynamics and mechanics of deformed solids. It is shown in this work that the paradoxes of high and low velocities could be solved if deformation processes taking place in the Earths' crust would be treated as the evolution of the stress-strain state of the loaded medium as a typical non-linear dynamic system. In this case, fracture develops in two stages—a comparatively slow quasi-stationary stage and a superfast catastrophic one, wherein the spatial localization of parameters is followed by the localization of the deformation process in time. This property is a fundamental characteristic of any non-linear dynamic systems.

SPATIAL-TEMPORAL INHOMOGENEITY OF DEFORMATIONS IN THE EARTH'S CRUST

Investigations of the contemporary vertical and horizontal movements of the Earth's crust have revealed the presence of anomalies in the geodynamic processes typical both for aseismic and seismically active territories. It has been found that these anomalies are not exceptions to the rule but are quite common throughout the Earth's crust. Moreover, they contradict the views formulated of the inherited movements of the past epochs. Until quite recent times, late decades of the XX century, we used to believe that the contemporary movements of aseismic plainland-platform regions were characterized by low velocities of the Earth's crust movement, on the order of 5–10 mm/year, while seismically active zones were characterized by considerably higher velocities, 50 mm/year and higher, which was quite consistent with the concept of inherited movement.

In 1970–1990, a number of detailed studies of the features of vertical and horizontal movements of the Earth's surface both in the aseismic and seismically active regions, which were summarized and analyzed in the works of Yu.O. Kuzmin [1, 2], reported paradoxical deviations of deformations in the fault zones from the inherited deformation behavior. It turned out that in the aseismic regions there are numerous different-scale local zones of anomalous vertical and horizontal movements of the Earth's crust which are related to the faults. These movements have very high amplitudes (50–70 mm/year), short duration periods (0.1–1.0 year), they are localized in space (0.1–1.0 km) and possess pulsating and sign-variable directivity. The average annual deformation velocities were found to be extremely high (5×10^{-5}–10^{-4} mm/year) and were therefore defined as superintensive deformations (SDs) [2]. This anomalous behavior of the geomedium was termed by Kuzmin as the high-velocity paradox. This considerable spatial-temporal inhomogeneity of the deformation processes in the Earth's crust has far-reaching implications, which requires that the conventional approaches to investigating the deformation mechanisms and fracture of the Earth's crust elements have to be revised.

The aforementioned activations of the pulsating deformation processes allow the faults and the adjacent regions to be treated as autowave systems giving rise to deformation-induced response of a medium in the form of slow deformation autowaves [3–5]. Such deformation-induced excitations treated as autowaves can propagate along the

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faults—intra-fault waves, or from one fault to another—interfault waves [4, 6]. The velocities of interfault autowave excitations are estimated to be within 20–30 km/year and higher, while those of intrafault waves—4–10 km/year [4]. It should be noted that a large number of slow deformation disturbances are currently ‘observed’, whose velocities vary in a very wide range [6]. Let us also note that all estimations of the parameters of slow deformation waves rely on indirect data; they are primarily made based on the observations of the migration of the deformation and seismic activity, and from variations in the geophysical fields; it is for this reason that the word ‘observed’ appeared here in the inverted commas. There is sufficient ground to believe that slow deformation autowave disturbances make a considerable contribution into the formation of fracture foci and, by activating the faults, they can act as earthquake triggers [4, 6, 7].

On the other hand, in seismically active regions such anomalies of geodynamic processes are referred to as a low-velocity paradox [1, 2]. It portrays the following situation: according to the GPS data obtained using long-baseline measurements, the average annual rates of deformation of the Earth’s crust are about 10^{-8}–10^{-9} and lower, while according to the geodetic data and deformographic high-accuracy short-baseline observations, they are estimated at the level 10^{-6}–10^{-7} per year and higher. The paradoxes of high and low rates and the phenomena of deformation activity manifested as deformation autowave processes cannot be explained from conventional concepts of inherited movements or from the standpoint of classical mechanics of elastoplastic flows, while they naturally fit the paradigm of the evolution of a medium as a typical non-linear system.

DEFORMATION RESPONSE OF A GEOMEDIUM AS AN EVOLUTION OF A STRESS-STRAIN STATE

The concept of a geomedium as a multi-scale block system has long been an accomplished fact. The debating points are the rules that govern the scaling of the blocks, i.e., how much larger the subsequent block is than the previous one. We believe that it is more adequate to discuss the linear scales of the structures in a geomedium rather than blocks, in particular, the scales of the system of cracks and faults that obey the principle of universal fractal divisibility of solids and media [8]. In accordance with this principle, the minimal scale is the lattice parameter of a loaded medium, and every succeeding scale is the sum of two preceding scales. This principle is valid both for small specimens and extensive geological bodies. None of the parameters has been observed to contradict this principle so far. This viewpoint allows us to treat both rock specimens and geomedia as natural fractals, for which systems of cracks and faults are fractal structures. These structures are peculiar geological bodies dividing the object into a statistically ordered system of structural elements, from the tiny ones, comparable to interatomic spacings, to the largest structural elements comparable to tectonic plates in their dimensions.

The deformation response to loading of such a multi-scale, hierarchically organized natural fractal would be quite inhomogeneous both in time and space. Due to non-linearity of the medium as a typical non-linear dynamic system, all deformation processes would also be non-linear (without any inheritance of movements from the past geological times, at least for small scales). It is non-linearity which gives rise to the localization of spatial distribution of parameters and subsequently to the temporal localization of processes. The availability of positive and negative feedback types and their competition increase the spatial-temporal inhomogeneity of deformation processes. A negative feedback stabilizes the deformation process. The presence of localized inelastic deformations and/or damage results in stress relaxation in these regions, which in turn slows the deformation process down, favoring healing of the damaged regions. A positive feedback accelerates the fracture process in an auto-catalytic mode; the localized damage results in lower strength characteristics, which intensifies localization processes. These deformation processes develop in the entire hierarchy of scales, which results in the formation of fractal structures of cracks and/or faults as lengthy, insecure regions. Spatial localization is succeeded by the deformation localization in time, which develops in a superfast mode as a catastrophe in the respective local region. This general pattern of evolution of the deformation processes accounts for the paradoxes of high and low velocities.

The above fundamental properties (non-linearity—spatial localization of parameter distribution—process localization in time) determine the evolution of any non-linear dynamic systems, which has two stages: a comparatively slow quasi-stationary stage of accumulation of changes, in this case damage accumulation at the microscales, and a superfast mode of its propagation onto the macroscales, which generally develops as a catastrophe. For this reason, in the aseismic region, where the average deformation rates are small, there would be local regions of different scales with high transient deformation velocities, implying the superfast evolution of stress-strain state (SSS) in a geomedium as a typical dynamic system. Within the slow quasi-stationary stage of evolution of an SSS, the damaged medium is healed. This scenario is of quasi-periodic character.

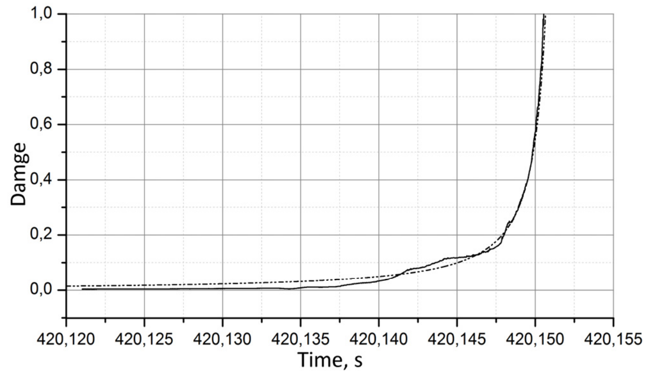

FIGURE 1. Experimental duration of the catastrophic fracture stage (solid line) and the curve calculated via the model of damage accumulation (dash-dot line) [9]

Due to the scale invariance of the deformation processes, including fracture, they are self-similar within the entire scale hierarchy. Such a pulsating character of the deformation processes gives rise to local instabilities resulting in the excitation of the active loaded medium and generation of deformation autowaves in it. It is very likely that the local zones of anomalously high vertical and horizontal movements in the asesmic regions mirror the dynamics of a large number of different-scale deformation processes localized in space (0.1–1.0 km) and time (0.1–1.0 year). These local instabilities of the deformation process ensure the global stability of the asesmic region as a whole. The process is similar to the phenomenon of discontinuous yielding of metal specimens, in the case where within a steady trend of a macroscopically slow process there is a range of failures—local, low-amplitude disturbances developing at high velocities. This is the fundamental property of evolution of any non-linear dynamic system, being in a state of self-organized criticality (SOC), where the global stability of a dynamic system is sustained due to the development of multiple local instabilities.

The duration of the catastrophic stage measured during fracture of small marble specimens, both in compressive and three-point-bending tests, was not higher that 20 ms. Figure 1 presents the measured duration of the stage of catastrophic fracture in comparison with the calculations performed via the damage accumulation model from [9]. The experiments included the measurements of the motion velocity of free surfaces of loaded specimens. In Fig. 1 it is normalized with respect to unity using the maximum velocity value. It was assumed that variations in the motion velocity are controlled by the specimen fracture process, in other words, by a dependence determining the law of damage accumulation. It is clear from Fig. 1 that this proved to be true. The model of damage accumulation has provided a high-accuracy description of both the long quasi-stationary stage of fracture and the superfast catastrophic stage.

The time range near the transition of the fracture process to the catastrophic stage for another specimen is shown on the Fig. 2 in increased scale. For this specimen the fracture time was $t = 60.174$ s.

Nonmonotonicity of the measured curve is accounted for by multiple cracks in the region of formation of the main crack. It is clear that at large scales of fracture of the Earth's crust elements during earthquakes the catastrophic stage duration would be much longer.

CONCLUDING REMARKS

By now a large body of data has been accumulated from detailed studies of deformation processes in the components of the Earth's crust, which cannot be explained either from conventional point of view, relying on the concept of the character of geodynamic processes inherited from the past geologic times, or from the standpoint of conventional mechanics of solids. A number of investigators back in the 1980s had put forward an idea on discrete or pulsating sign-alternating character of motion of the asthenospheric layer. This idea allowed removing the contradictions observed. On the other hand, identification of the so-called superintensive deformations in the asesmic regions, localized in comparatively small spaces, cannot be explained within the framework of dynamics of global asthenospheric processes [2].

A view of the geodynamic processes from the standpoints of the theory of non-linear dynamic systems provides a reliable interpretation of the observed dynamics of deformation processes in the Earth's crust, which sweep the entire hierarchy of scales.

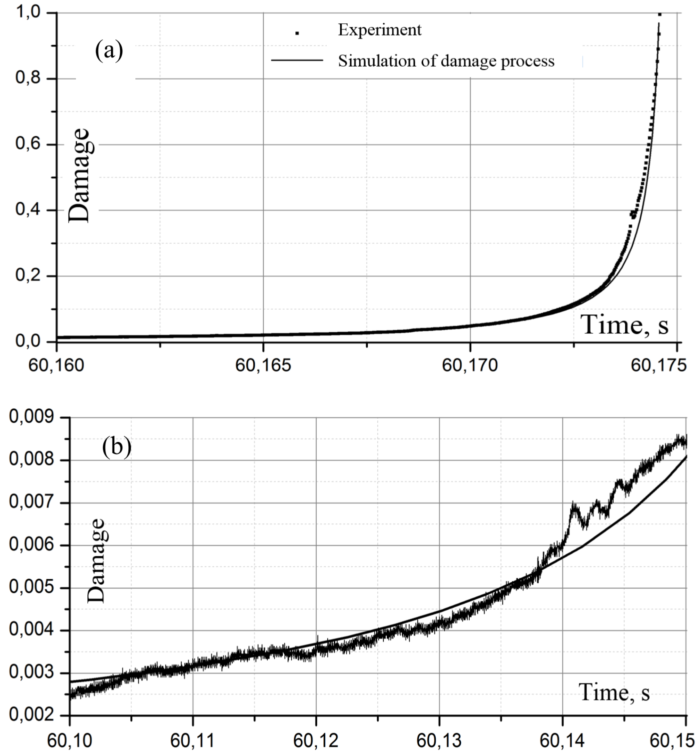

FIGURE 2. The transition of the fracture process to the blow-up regime (a), the evolution of damage near the transition of the fracture process to the catastrophic stage (b)

The fundamental properties of a deformed, fractally-organized geomedium treated as a non-linear dynamic system are the processes of localization of deformation and fracture, which evolve within the entire hierarchy of scales, and their temporal inhomogeneity. At every scale level, the processes of deformation and fracture correspond to a slow evolution phase and a superfast autocatalytic stage, which often develop as a catastrophe of the respective scale level. Thus, the superintensive deformations illustrate the evolution of the deformation process in the final stage under the conditions of a blow-up regime. These processes are of a quasiperiodic character. The recurrent dynamic stages of the SSS evolution cause local instabilities and can give rise to a local response of the medium in the form of slow deformation auto-waves, which is observed in reality.

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