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# Magnetoplasticity and the physics of earthquakes. Can a catastrophe be prevented?

A L Buchachenko

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## Contents



**Abstract.** **The reasons for elastic energy accumulation in a lithospheric macroreactor — a seismic focus — are discussed. The nonlinear kinetics of the phenomena of an earthquake, a chain chemical explosion, and a nuclear explosion are analyzed. The transition from a stationary regime to an explosion in these three processes occurs as a critical phenomenon with critical parameters representing the concentrations of dislocations, active chemical centers, and neutrons, respectively. It is proposed to stimulate the slow relaxation of the elastic energy of the deformation stress of the seismic focus by low-frequency microwaves, which provide the accelerated motion of dislocations, reduce the yield limit, and increase plasticity. This phenomenon, known as magnetoplasticity in solid-state physics, can be used to keep the seismic focus far from a critical catastrophic regime by artificially stimulating its slow relaxation. The observed features of the influence of magnetic storms on earthquake dynamics are, in principle, consistent with the concept of the stimulated magnetoplasticity of the seismic focus as a means to avoid a catastrophe.**

## 1. Introduction. The sense of the problem: to predict or to prevent?

An earthquake is a phenomenon of pulsed relaxation, an active dump of the elastic energy stored in the region of Earth's crust, called a seismic focus. The seismic focus constitutes a giant physicochemical and mechanochemical reactor, whose 'life' and events are governed by two competing processes: energy accumulation due to deforming forces (strain energy pumping), and the relaxation of this energy via catastrophic shear, where one region of Earth's crust slips with respect to others. It is this shear that brings countless disasters. Both these processes are inevitable and natural for a living, dynamical system such as Earth. Intriguing, however, is the incommensurability of the temporal and spatial scales of these two processes. Tectonic velocities providing the energy pumping of the seismic focus are on the order of a few centimeters or even millimeters per year, whereas the energy dump occurs during the motion of Earth's regions at velocities reaching one meter per second, the difference in these velocities exceeding ten orders of magnitude. This circumstance is also manifested in the periodicity of earthquakes generated by the same focus: the energy accumulation time — the preparation or 'silent' period — of the focus usually lasts for years, and sometimes for decades or even hundreds of years, whereas the energy is released in a few seconds (or a maximum of minutes).

The earthquake problem is a global one, common to all humankind. There are two points of view about this problem. The first one assumes that it is impossible to act on an earthquake, because it is a monumental phenomenon, and therefore it is necessary to search for signs of its approach — earthquake precursors — and to predict the time of occurrence of this catastrophe in order to take safety measures. This point of view dominated for many decades. The other, careful, point of view assumes that the seismic focus is a sensitive system, which can be vulnerable to external actions, and therefore we can affect and even search for ways of stimulating the energy dump by small doses, thereby preventing the development of a catastrophe in the focus.

The aim of this paper consists in comparing and estimating these two positions based on the concept that the earthquake problem is one of putting bridges between mechanical stress and its consequence, strain, being a part of the general problem of solid-state physics and mechanics. We will not discuss here the origin and sources of elastic energy

**A L Buchachenko** Semenov Institute of Chemical Physics, Russian Academy of Sciences,
ul. Kosygina 4, 119991 Moscow, Russian Federation
Tel. +7 (495) 939 13 16, +7 (495) 939 71 28
E-mail: abuchach@chph.ras.ru

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accumulation in a seismic focus. This problem belongs to the dynamics of the geosphere and tectonic plates [1–3].

## 2. Is it possible to predict an earthquake?

A seismic focus, just like a mechanochemical macroreactor, has room for all aspects of mechanochemistry. It begins from the dissociation of the chemical bonds, covalent or ionic, followed by the creation and motion of dislocations, the generation and multiplication of cracks, and shear microdisplacements. Microcrack opening can generate electric discharges between the edges of a crack, like across the capacitor plates. Direct Rogowski-coil measurements showed that a growing microcrack also transfers charges, from $10^{-7}$ to $10^{-5}$ C per crack, and the moving crack generates an electromagnetic field of power of $10^{-20}$–$10^{-17}$ W [4]. Microdisplacements generate acoustic emission. A system of microcracks changes the diffusion of gas components and the permeability of rocks, and therefore the seismic focus is a source of chemical emission along with acoustic and electromagnetic radiations in a broad spectral range, from infrasound to radio frequencies and up to X-rays. It is clear that all the events in the seismic focus, the 'creative power' of this lithospheric macroreactor can be directly or indirectly detected. Moreover, the behavior of the lithospheric reactor produces an echo in another giant reactor, the ionosphere. The relation between these two macroreactors is now clearly understood, and this has given new impetus to the search for the signs and precursors of earthquakes maturing in the seismic focus [5, 6].

Large-scale observations of seismic foci and studies of their functioning performed for many years have revealed a number of the key features most dynamically related to the focus, which can be determined with a very high metrological quality (accuracy and sensitivity):

(i) the motion of crust regions, relative (mutual) displacements, and absolute displacements (with respect to the sea level);

(ii) the propagation velocity of longitudinal and transverse seismic waves, and their velocity ratio;

(iii) electrical conductivity, electric fields, and their gradients;

(iv) geomagnetism and the gravity force (the Earth's gravitational acceleration $g$);

(v) water levels in wells and boreholes;

(vi) chemical signs: the content of radon and other gases (He, Kr, Ar, $H_2$, $N_2$, $CH_4$) in water; the content of ions ($HSO_4^-$, $HCO_3^-$, etc.) and microelements (Si, Ge, Hg, Fe); and isotopic ratios ($^{13}C/^{12}C$, $^{36}Ar/^{40}Ar$, etc.) [7]

In this field, excellent scientific schools, like those of Sadovskii, Keilis-Borok, and Strakhov, have been established [8–10]. The great importance of this work for the general monitoring of Earth and, in particular, the diagnostics of seismic foci is evident. Moreover, the successes in the focus diagnostics have given rise to the feeling that the location and time of earthquakes can be predicted based on its precursors [11–18]. Unfortunately and disappointingly, these hopes have proved to be illusive.

Numerous earthquake predictions over the last 100 years have proved to be unsuccessful and erroneous. Charles F Richter, whose name was assigned to the earthquake scale, said way back that "he did not take a pathological interest in predictions." However, the matter here is not of taste, the cost of the problem being too high, because an erroneous prediction may be more dangerous than the earthquake itself. All the history of earthquake observations has seen only one prediction that took place with an accuracy of a few hours, but the waiting cost in this case also proved to be higher than the cost of the earthquake itself [3].

The International Association on Earth's Seismology and Physics, involving physicists from many countries around the world, has performed a fundamental analysis of all the signs, called precursors, and of all predictions. The result is that none of the signs have been satisfactory in their reliability; they are often mutually contradictory; and none of them can be efficiently used [19, 20]. Statements about breakthroughs in this line of inquiry are beneath criticism and are often simply honest delusions. The level of the parameters of the signs themselves is very low and lies below that of climatic and technogenic disturbances [21]. 'Successful' predictions are found only in retrospect, after the catastrophe has occurred. These have even been called *retrodictions*, unlike *predictions* [22]. It was concluded that reliable precursors not only cannot be identified, but do not exist at all [20]. There is even a point of view that earthquake seismology is not a science in the strict sense, because science begins where it can predict (note, by the way, that it also ends there).

Such conclusions are based on physical grounds. A seismic focus constitutes an open dynamical system, where the boundary between quasistationary and nonstationary (explosive) regimes is determined by critical conditions, which are unpredictable and uncontrollable. Because the system is strongly nonlinear, it cannot be controlled along the 'action–response' coordinate, and infinitely small instabilities can stimulate the development of large instabilities. It is impossible to take all the accidental perturbations into account, as it is 'impossible to live in detail' (Lev Tolstoy).

The seismic focus is not the only system of this kind. The moment of breaking of a glass plate with fixed ends loaded in the middle is unpredictable; it is also impossible to predict the moment of explosion of a flask filled with a detonating $H_2 + O_2$ mixture, although all the reactions and their rates in this system are known with a good accuracy; the passage from a laminar to turbulent flow is uncontrollable, as well is a social explosion (revolution), etc.

Notice here that numerous models of this phenomenon have been developed [23–28], including the 'quantum' model [29]. However, none of them are reliable, perfect, and consistent [26]. The reason lies, of course, in the complexity of the phenomenon and an extremely limited knowledge about the seismic focus. Moreover, even if a 'good' model were built, it is unlikely that it would help to solve the main problem of predicting the moment of a catastrophe. For comparison, the model of the chemical explosion of hydrogen and oxygen mixture is reliable and unambiguous because everything is known in it; however, it is absolutely useless for predicting the moment of explosion.

## 3. Why is elastic energy accumulated?

Certainly, during the deformation of a solid, different energies are stored, but for an earthquake as an event, the elastic part of the stored energy is most important: it is this energy that initiates macroscopic displacements and the 'shaking up' of regions of Earth's crust in the vicinity of the seismic focus. A key question containing all the intrigue of an earthquake is why, in the presence of a huge number of relaxation mechanisms and channels of energy delivered by strain (through the generation of defects and vacancies, dislocations, micro- and macroscopic cracks, etc.), the strain energy pumping nevertheless exceeds the energy leakage or dump.

We will first try to answer a naive question: could an earthquake occur if Earth's crust were an ideally plastic body? The negative answer is absolutely obvious: the total strain pump energy would escape to a plastic flow to overcome atomic displacement barriers, to cause the motion of atomic groups, to overcome the interatomic and intermolecular potentials, to break chemical (covalent and ionic) bonds, etc.

Now, we will ask another, even more naive, question: could an earthquake occur if Earth's crust were an ideally elastic body (for example, diamond)? The answer is also negative, though not so obvious: in this case, the total elastic energy would be spent on producing microcracks and breaking of chemical or intermolecular bonds. Microcracks originate on structural defects and grow until the elastic energy is transferred to the cracking energy. A crack in an ideal elastic body makes up a structural element of the elastic energy gain. The crack generation, propagation, and multiplication dynamics are the energy relaxation dynamics. This is the well-known and very efficient Griffith energy relaxation mechanism in elastic bodies. The Griffith science about cracking is so well developed and reliable that we will not consider it here [30].

Thus, no delay exists in absolutely plastic and absolutely elastic bodies between the strain energy pumping and the energy relaxation, release or conversion. Earth's crust constitutes neither an absolutely elastic nor an absolutely plastic body, elastic energy is accumulated in it, and the time delay between strain energy pumping and catastrophic energy dump (an earthquake) can reach a few years and sometimes a few hundred years. Why do Earth's crust and the deformable rocks contained in it accumulate elastic energy? Why do they keep it so long — all the period of earthquake preparation? Moreover, there is a distinct relation: the longer the preparation period (the focus 'silence') the greater the elastic energy storage and the stronger the catastrophe (on the Richter scale) [31–33]. The answer can be found in the physical mechanics of solids, the physical nature of crystal plasticity and strength, and the functional relationships between stress and strain [34, 35].

The plastic deformation of crystals (and, of course, rocks contained in a seismic focus) is caused by the motion of dislocations, while the strain rate is determined by the density and the velocity of propagation of dislocations. In turn, both the density of moving dislocations and their propagation velocity (friction) are controlled by a totality of processes, such as the generation of dislocations, their multiplication on obstacles and 'forest' dislocations (according to the Franck–Reed mechanism), and their immobilization and transformation into immobile, 'captured' dislocations ('pairing' into edge dipoles, capturing by edge dipoles, impurities, and the elastic fields of other dislocations). It is the interactions of dislocations with impurities and (or) structural defects and other dislocations that are assumed to be the main factors governing the mechanics of crystals and the stress–strain functional dependence [35, 36].

The main contribution to the strengthening comes from the contact interaction of dislocations. The kinetics (time evolution) of dislocation ensembles resemble the behavior kinetics of active centers (atoms and radicals) in branched chain chemical reactions (the hydrogen–oxygen ignition type). The main stages in the evolution of dislocations and active centers have almost identical kinetics: generation events exist in both cases; there are dislocation multiplication processes which are equivalent to the branching of kinetic chains and the multiplication of active centers; there are the quadratic annihilation of dislocations and the equivalent quadratic recombination of active centers, i.e., the quadratic break of kinetic chains, and, finally, there are the linear break of dislocations (the capture and trapping of mobile dislocations by impurity centers, edge dipoles, and the elastic fields of other dislocations, which 'switch them off' from the participation in plastic deformation) and the linear break — the destruction of active centers (on the walls of a vessel or on inhibitor additions), which remove active centers from the reaction. The linear break of dislocations reduces the plasticity and causes deformation strengthening. The linear break of active centers in a chain reaction is accompanied by an equivalent fall in its rate and a decrease in the yield of reaction products.

The plastic deformation rate is kinetically identical to the chemical reaction rate, while plastic deformation itself is identical to the product yield in the chemical reaction. The kinetics of dislocations (considered in detail in excellent review [35]) are described by the same equations as those of chain reactions. Moreover, both the evolution of dislocations during the slow deformation (it is this regime that is important in a seismic focus at its preparation stage) and the kinetics of active centers in slow chain reactions (at the stage preceding the explosion) are described by quasistationary equations, when the rates of change in the concentration of mobile dislocations and active centers are infinitely small and can be set equal to zero. Of course, this condition is drastically violated at the moment of a catastrophe (an earthquake or a chain explosion), when the densities of dislocations and concentrations of active centers are strongly nonstationary and catastrophically change.

An analysis of the dislocation kinetics gives the expression for the deformation strengthening coefficient $\theta = \mathrm{d}\sigma/\mathrm{d}\varepsilon$:

$$\theta = \theta_{\mathrm{m}}(Q_0\sigma^{-3} - Q\sigma^{-1} + 1 - \sigma)\,. \qquad (1)$$

Here, $\sigma$ is the dimensionless stress normalized to $\sigma_\infty$, and $\theta_{\mathrm{m}}$ is the parameter including the shear modulus. The parameters $Q_0$ and $Q$ play an important role in the strengthening. The first of them is determined by the ratio between the rates of dislocation generation and quadratic annihilation, while the second one includes the competition and balance of dislocation multiplication and immobilization rates (linear break, trapping by defects, edge dipoles, and other dislocations). It follows from formula (1) that strengthening occurs in several stages [35]. However, these details are not too important for the global earthquake 'maturing' process. Notice only that it is possible to obtain from formula (1) the value of $\sigma$:

$$\sigma = \left(\frac{Q}{2}\right)^{1/2}\left[1 + (1-g)^{1/2}\right]^{1/2}, \qquad (2)$$

for which the strengthening coefficient $\theta$ has the maximum value [35]. Here, the notation was introduced

$$Q = \frac{k_{\mathrm{im}} - k_{\mathrm{m}}}{k_{\mathrm{a}}\rho_\infty}\,,$$

where $k_{\mathrm{im}}$ and $k_{\mathrm{m}}$ are the rate constants of dislocation immobilization and multiplication, respectively, and $\rho_\infty$ is the limiting dislocation density:

$$g = \frac{12nk_{\mathrm{a}}}{b(k_{\mathrm{im}} - k_{\mathrm{m}})^2}\,, \tag{3}$$

where $n$ is the dislocation origination rate, $k_{\mathrm{a}}$ is the constant of dislocation annihilation rate, and $b$ is the Burgers vector modulus.

Clearly, the maximum values of $\sigma$ and $\theta$ are determined by the balance between dislocation immobilization (capturing) and multiplication rates, like the dependence of the chain reaction rate on the difference between the multiplication and breaking rates of the kinetic chains. If the immobilization rate is high enough (when $g \geqslant 1$), the dependence $\sigma(\varepsilon)$ assumes the form

$$\sigma = 1 - \exp\left(-\frac{k_{\mathrm{a}}}{2}\,\varepsilon\right). \tag{4}$$

If, however, the dislocation multiplication and accumulation rates dominate (for example, for polycrystalline and highly granular solids), the dependence $\sigma(\varepsilon)$ is described by the expression

$$\sigma = \left[1 - \exp\left(-k_{\mathrm{a}}\varepsilon\right)\right]^{1/2}. \tag{5}$$

It also follows from Eqns (1)–(5) that the deformation strengthening strongly depends not only on the balance between the rates of dislocation immobilization and multiplication but also on the absolute rate $k_{\mathrm{a}}$ of their quadratic annihilation.

Thus, the two pairs of competing processes — generation and annihilation, immobilization and multiplication — determine the destiny and kinetics of dislocations and their transformation channels. The deformation strengthening represents a direct result of the influence of the immobilization channel. No doubt, all these processes coexist in the seismic focus, and we can reliably assume that they are responsible for the accumulation and storage of the elastic strain energy in the focus.

A dislocation-strengthened material makes up already a new, and different, material, which is chemically identical to the initial material, but its strength can be a few orders of magnitude higher, its breaking strength exceeding the theoretical ultimate strength of the initial material. It is also clear that the deformation–dislocation strengthening cannot be infinite; further, a cellular structure is formed from the aggregate of immobilized dislocations, while new slipping lines and bands, deformation mesostructures, and other perturbations appear in a solid [37–39]. The structural regularity of interatomic contacts is violated in places of dislocation condensation; cracks nucleate and grow in an already dislocation-strengthened material, multiple cracking occurs, and a leader crack and a geomorphologic break appear as the final result of the catastrophe. In other words, the strengthening reserve is exhausted; when the critical threshold is reached, even small additional loads induce a catastrophic strain — an earthquake. The high energy capacity of deeply lying rocks is evidenced by the data obtained during the drilling of the Kola Superdeep Borehole: the self-explosion of kerns drilled from the rock mass and released from compression produced by the mountain pressure, and the self-expansion of the hole shaft appearing after the self-destruction of the hole walls after the passage of the turbodrill [40].

The instantaneous switching of the slow-deformation regime to the catastrophic regime is similar to the change from the slow reaction regime to the explosion regime in chain processes; it occurs even for an infinitely small change in the concentration of active centers. The regime in a nuclear reactor changes for the same reasons from a slow reaction to a nuclear explosion when the balance between neutron capture and multiplication is violated. In this sense, all three nonlinear processes — earthquakes, chain chemical explosions, and nuclear explosions — have common kinetic regularities; the change of regimes occurs as a critical phenomenon, in which the concentration of dislocations, active chemical centers, and neutrons serves as a critical parameter. It is because of the strong nonlinearity of these phenomena that the reliable prediction of the moment of a regime change becomes impossible, even when the kinetics and mechanisms of the processes are reliably known with a high accuracy (as, for example, in reactions of hydrogen with oxygen or nuclear reactions, where the rate constants of elementary chemical reactions, neutron-capture cross sections, etc. are known).

The control of a chemical or nuclear explosion means no more than the maintenance of these processes in a stationary regime, which is sufficiently removed from the critical boundary (by introducing inhibiting flegmatizers in chemical processes or neutron absorbers in nuclear reactions). Is it possible to do something kinetically similar to keep the seismic focus far from the critical boundary beyond which a catastrophe is inevitable? Is it possible to force it to function in the stationary regime?

## 4. Is it possible to avoid a catastrophe?

Plastic deformation is provided by moving dislocations. When they are 'frozen' by the elastic fields of defects or other dislocations, and themselves create elastic local fields, they become a source of the dislocation strengthening of the seismic focus. Another source of strengthening concerns the stopping of microcracks. In an ideally elastic body, a Griffith crack grows without obstacles until the elastic energy store is exhausted. In real solids and rocks in the seismic focus, cracks are stopped long before the elastic energy store is exhausted, because plastic deformation produces dislocations and dislocation strengthening in the crack mouths, whose radius is on the order of the interatomic distance, and these dislocations stop, or close, the cracks.

The high densities of trapped dislocations and microcracks, which are energetically 'frozen' into elastic traps, set up a barrier on the way to releasing the stored elastic energy through plastic deformation. When trapped, 'slumbering' dislocations revive and become mobile, then a catastrophe occurs — the pulsed plastic deformation of the seismic focus, or the pulsed relaxation of the elastic energy.

To avoid a catastrophe means avoiding the immobilization of moving dislocations and dislocation strengthening, stimulating the motion of dislocations and deformation plasticity, and reducing the barriers closing the elastic energy of the seismic focus. Of course, it is impossible to do this completely; however, we can bring down the density of slumbering dislocations and cracks, suppress at least partially the dislocation strengthening, and decrease the amount of stored elastic energy. In this case, we can expect that the strength of the catastrophe will be reduced. Of course, the scale of the elastic energy generated by tectonic processes cannot be changed, but it would be desirable to control the release and relaxation of this energy, namely, to stimulate the energy liberation by small portions, thereby 'exchanging' a severe catastrophe for light, less dangerous catastrophes. In other words, it is necessary to artificially stimulate light earthquakes, not waiting for the ripening of a severe earthquake.

Is it possible to affect the giant energy reservoir representing the seismic focus? Can we force it to release its energy in small portions? The vast experience accumulated during observations and studies of earthquakes suggests a positive, although very careful, answer.

First, it has long been found that the construction of large reservoirs in seismically dangerous zones lowers the level (frequency and power) of severe earthquakes. Light earthquakes, however, are preserved [41]. It is assumed (not without grounds) that the high saturation of seismically dangerous rocks with moisture increases their plasticity, thereby reducing the amount of elastic energy stored in them. One of the most realistic mechanisms of this phenomenon is the activation of stopped, trapped cracks. Water penetrating into them reacts with stressed, strongly deformed chemical bonds in the crack mouths (via redox or hydrolytic reactions). As a result, the dislocation strengthening is 'unloaded', dislocations begin to move, and cracks become mobile and accept the elastic energy, thus reducing its amount in the seismic focus.

Another realistic mechanism consists in wedging pressure on crack edges (according to Rebinder) produced by water. This additional pressure stimulates the growth of cracks and accelerates the elastic energy dump. (Marble can be made deformable with the help of a moist sponge, which is well known to brick layers and sculptors.)

It would be naive, however, based on these observations, to propose recommendations for building dams in seismically dangerous zones (which is risky in itself). These observations only suggest that processes in the seismic focus can be affected at the atomic, molecular, and dislocation levels, i.e., at the micromechanics level.

Second, remarkable results were obtained during the deep electromagnetic monitoring of seismically dangerous zones with the help of high-power discharges generated by a magnetohydrodynamic (MHD) generator [42, 43]. For voltages of about a kilovolt and currents of about 3 kA ($\sim 3$ MW power), the MHD generator energy supplied to an electric dipole (with a base of 3–4 km and duration of 1–10 s) was on the order of $10^7$ J [42].

Statistics on the long-term analysis of earthquakes in the test regions of this pulsed electromagnetic technology have revealed the influence of electromagnetic MHD pulses on seismicity regimes. The ratio of the number of earthquakes observed after MHD probing to the number of earthquakes observed before such probing within the same span of time increased. Earthquakes are redistributed in space and on the energy scale: large-scale events are replaced by a series of smaller, less destructive earthquakes. The released energy of earthquakes stimulated by MHD pulses exceeds the pulse energy by a few orders of magnitude [44]. All this reliably demonstrates the interaction of MHD pulses with the seismic focus.

The physical nature of these interactions is not quite clear or certain. We can assume that a strong pulsed electric field $E$ acts on captured charged dislocations with the force $F = EQ$, where $Q$ is the dislocation charge. If this force exceeds the elastic force holding the dislocation in the immobilized state, it 'drives away' the dislocation, thus making it mobile and stimulating plasticity. The same concerns stopped cracks: direct measurements of a charge transferred to the top of a crack give a value of $Q$ on the order of $10^{-7} - 10^{-5}$ C and a dipole moment of order $10^{-14}$ C m [4].

It is unlikely that the efficiency of this mechanism can be reliably estimated, because the seismic-focus parameters are very uncertain. It is not improbable that the effects observed can also be assigned to a shock wave accompanying a high-power MHD pulse and propagating in the focus.

Third, intensive bombardments conducted in Yugoslavia and Afghanistan (especially using depth bombs in Afghanistan) stimulated, as seismologists observed, a number of 'out of order', 'unexpected' earthquakes (although all earthquakes are unexpected). This circumstance demonstrates the vulnerability of an energy-saturated focus even to weak perturbations, which stimulate a critical transition from the quasistationary state of the focus to the nonstationary, catastrophic regime. Shock waves accompanying explosions and propagating through the seismic focus can 'revive' slumbering dislocations, partially remove the dislocation strengthening, and release elastic energy. By the way, apparently a direct relationship between seismic actively and nuclear explosion tests is observed for the same reasons [42, 45].

Fourth, the strategy of the physical control of a seismic focus can be proposed by systematically 'shaking it up' by shock waves. A system of points can be constructed in the focus vicinity (for example, a set of shallow holes or wells) to produce 'microexplosions' at these points. Then, the shock waves outgoing from these explosions will create compression–dilatation dynamical zones, releasing, or 'reviving', trapped dislocations and microcracks, and stimulating the plastic deformation and relaxation of the elastic energy. Of course, such an action can provoke a catastrophe if the seismic focus has 'ripened' and contains huge elastic energy. But if such shock 'microshaking' is performed continuously, systematically, and in a controllable way, then it becomes possible to remove by doses the elastic energy accumulated in the focus. Of course, the building of such a system requires certain expenses. However, they are incomparably lower than those we spend on the development and maintenance of the system of global earthquake monitoring. Such a system is absolutely useless for a rescue from catastrophes. And, of course, the creation of such a 'rescue service' concerns not only scientists, but governments as well.

Finally, the plasticity of the seismic focus can be stimulated by microwaves.

## 5. Magnetoplasticity of diamagnetic crystals

It is known that the hardness, yield stress, plasticity, and other related mechanical properties of diamagnetic crystals (NaCl, PbS, LiF, Si, etc.) decrease in a magnetic field. This remarkable phenomenon is called magnetoplasticity [46–52]. Its nature is determined by the behavior of dislocations: the fraction of free dislocations increases in a magnetic field and their range increases. The interaction energy of a diamagnetic crystal with a magnetic field is negligibly small and, therefore, it cannot affect the high-energy processes of the displacement of dislocations responsible for plasticity. Clearly, we are dealing here not with energy, but with electron angular momentum — electron spin, which is controlled by the magnetic field.

Magnetoplasticity physics is based on the following concept. When a dislocation meets a stopper (for example, an impurity ion or other dislocation), it comes to rest. To escape from the stopper and move further (this process is called depinning), it is necessary to wait for the energy or energy-barrier fluctuation in the stopper–trapped dislocation system. However, there exists a different chemical low-energy depinning mechanism — electron transfer from the dislocation trapped by the stopper to the stopper [53, 54]. This creates a spin-selective and therefore magnetosensitive nanoreactor — a pair of unpaired electrons: one 'sitting' on the dislocation, and the other on the stopper [53, 55]. The Coulomb potential holding the trapped dislocation on the stopper is switched off in the nanoreactor, which is accompanied by the detachment (liberation) of the dislocation.

All these simple processes can be easily schematically represented by the example of the simplest diamagnetic NaCl crystal with $Mg^{2+}$ ions serving as stoppers:

$$(\mathrm{Cl_d^-}\ \mathrm{Mg^{2+}}) \overset{e^-}{\rightleftharpoons} (\underset{\substack{\downarrow\\ \mathrm{F}}}{\dot{\mathrm{Cl}}_\mathrm{d}}\ \dot{\mathrm{M}}\mathrm{g^+})^{\mathrm{S}} \xrightarrow[k_{\mathrm{ST}}]{H} (\underset{\substack{\downarrow\\ \mathrm{F}}}{\dot{\mathrm{Cl}}_\mathrm{d}}\ \dot{\mathrm{M}}\mathrm{g^+})^{\mathrm{T}}\,.$$

Here, $(\mathrm{Cl_d^-}\ \mathrm{Mg^{2+}})$ is the initial state of the dislocation trapped by the $Mg^{2+}$ ion ($\mathrm{Cl_d^-}$ stands for the ion element of the dislocation, and the dots denote unpaired electrons). The direct transfer of the electron $e^-$ creates a spin nanoreactor in the singlet S state; F denotes liberated dislocations leaving the nanoreactor.

The dislocation liberation is limited by the rapid reverse spin-allowed electron transfer, returning the dislocation to the initial trapped state, which occurs in the spin nanoreactor (created in the singlet spin state due to the preservation of zero spin during electron transfer). The magnetic field causes the spin conversion of the nanoreactor from the short-lived singlet state to the long-lived triplet T state, from which the reverse electron transfer is spin-forbidden. This means that the magnetic field liberates the dislocation from the Coulomb attraction and increases the lifetime of the 'Coulomb-switched off' state, i.e., increases the depinning probability.

The magneto-induced rate of dislocation liberation is proportional to the nanoreactor population in the T state. This state is populated with the rate constant of singlet–triplet conversion: $k_{\mathrm{ST}} = |\Delta g \beta H|$. Here, $\Delta g = g_1 - g_2$ is the difference of the $g$-factors of partners in the spin nanoreactor, $\beta$ is the Bohr magneton, and $H$ is the magnetic field strength. For the usual value of $\Delta g \approx 10^{-2}$ in the field of $H = 500$ mT, the value of $k_{\mathrm{ST}}$ amounts to $\approx 1.5 \times 10^8\ \mathrm{s^{-1}}$. Note that the spin nanoreactor is created in a purely diamagnetic crystal without any paramagnetic impurities. This circumstance considerably expands the boundaries of magnetoplasticity as a universal phenomenon.

The spin origin of magnetoplasticity and the existence of spin nanoreactors have been reliably proved experimentally. It was conclusively proved, both theoretically and experimentally, that the mobility of dislocations, mechanics, and plasticity of diamagnetic crystals depend not only on static magnetic fields but also on microwave electromagnetic fields [54, 55].

Resonance microwave fields with frequencies $g_1 \beta H$ and $g_2 \beta H$ cause the reorientation of the electron spins in the nanoreactor and transfer it from the **S** state to the long-lived triplet state. In other words, the resonance microwave pumping of Zeeman transitions increases the lifetime of the Coulomb-switched off nanoreactor, thereby increasing the probability of dislocation depinning. As a result, the dislocation range and plasticity increase at these pump frequencies. This phenomenon has been reliably proved in experiments [56, 57].

The lifetime of a spin nanoreactor in the stopper–trapped dislocation system is determined by the rates of two competing processes: the reverse electron transfer, and depinning; as a rule, this lifetime ranges $10^{-8} - 10^{-9}$ s. This time interval corresponds to spin transition rates (frequencies) in the nanoreactor in the range from 10 to $10^2$ MHz. Therefore, all the nonresonance microwave fields, oscillating at lower frequencies, act on the nanoreactor as slowly varying static fields, and their action is similar to that of a constant nonoscillating magnetic field.

## 6. Microwave stimulation of the seismic focus plasticity

A decrease in the lifetime of trapped dislocations and the acceleration of their depinning in a constant magnetic field (300–500 mT) and microwave fields (resonance and nonresonance) have been conclusively proved experimentally [57]. It should be noted that the microwave depinning of dislocations also exists in Earth's field [58], i.e., in the seismic focus. The deformation of rocks in the focus generates dislocations with various chemical structures. In conjunction with the chemical variety of stoppers, this produces a huge chemical ensemble of stopper–trapped dislocation systems and, therefore, a huge set of spin nanoreactors with a broad distribution of $g$-factors and Zeeman frequencies. The irradiation of a seismic focus by low-amplitude (low-power) microwaves in a broad megahertz frequency range (which can be easily performed) can stimulate simultaneously the resonance and nonresonance depinning of dislocations. Their acceleration increases plasticity and provides the energy relaxation of the focus. The slow relaxation of the stress energy to slow plastic deformation keeps the focus in the subcritical regime, thus preventing a catastrophe. The quantitative evaluation of this effect is a special problem, requiring the construction of physical models capable of connecting the microscopic level (stimulated motion of dislocations) with macroscopic effects.

Magneto-induced dislocation depinning can phenomenologically lead to two opposite effects. The microwave irradiation of a weakly stressed seismic focus makes it even safer. On the contrary, stimulated depinning for a strongly stressed focus, which is in the critical regime, can trigger a catastrophic energy dump through deformation. This is a case where microwave irradiation can induce an earthquake.

Indeed, studies of variations in seismicity in seismically active regions in Kazakhstan and Kirghizia in periods before and after magnetic storms (generating microwave fields, as is well known), which were considered in an excellent monograph [15], showed that the number of earthquakes after storms in some regions increased (positive effect), while in other regions it decreased (negative effect). It was pointed out in Ref [15] that the found influence of magnetic storms on seismicity had a trigger, or threshold, character. These observations are, in principle, consistent with the predictions of the concept of the magneto-induced depinning of dislocations.

## 7. Conclusion

The author understands that the concept proposed here can be accepted ambiguously (or not accepted at all). It should be realized, however, that there is no other way if we wish to reduce the risk of dangerous earthquakes. Within the framework of the formulated physically realistic concept, the existing and well-developed monitoring system finds its logical place: it is focused on finding and outlining the seismic focus contour and on controling, at least approximately, its evolution (through the signs called precursors). The next stage consists in irradiating the seismic focus by a system of microwave sources optimized in their power and direction. This can be achieved with the help of permanently operating low-power and low-frequency sources stimulating the focus magnetoplasticity.

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