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CONTACT, FRICTION AND SEISMIC WAVES DURING SEISMOTECTONIC PROCESSES IN THE EARTH'S CRUST

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Abstract: *Based on the general concepts of tribology as interdisciplinary science, the paper regards the contact interaction as most general transfer process. Surfaces bonding in contact represent an encounter of various scale elements, and the Contact as a mechanical system is a medium with structure of clusters of different size and scale, density, and energy distribution variation. The paper reconsiders some basic notions on contact interaction in tribological systems and the behavior of the contact. Regarding natural tribosystems, the friction contact interfaces, e.g. the shear zones of geological seismotectonic fault systems, involve phenomena similar but not equal to those of the mechanical tribological contact. The triad: movement (tectonics) - friction - seismicity is a powerful energy factor in the Earth's crust. Frictional rock bodies undergo various deformations and destructions depending on their spatial relationships, rheological properties, etc. The immense energy generated during seismotectonic processes causes changes in rocks and minerals and in contact systems. In the geotribological zone of friction between the rock blocks, temporary local thermodynamic system of high temperature and pressure is created, at which the rocks are deformed, disintegrated and melted, and after the tectonic event, recristalize into new highly thermobaric minerals. The article focusses on the evolution of energy in the shear zones of friction and the connection between destructive tectonic processes and creative material transformations. The aim of the article is to draw the attention of tribologists to geotribological natural objects, to the comparison between tribological - natural geotribological and seismic objects, and to the role of seismic waves as destructive and creative agents in the relevant triboprocesses.*

Keywords: *contact interaction and structure, geotribological friction zones, friction and seismic waves, destructive and recrystallization processes in Earth's crust*

1. INTRODUCTION

1.1 Contact. Outline the new aspects.

Due to the amazing growth of our knowledge, research in the various sciences has become extremely complex and varied. In the last decades of the past century, a trend has emerged: what used to be separated in order to be considered in isolation and analized, is now re-immersed in the wholeness [1]. This will also be the challenge of our century. Complex structures and processes can be observed from macro- down to the atomic level. New thinking is felt in the various aspects in the study of systems integrity and complex contact systems, involving the description of the interface bonding, and the forming of the contact. To describe the function of the contact body it is necessary to know the elementary constituents and the functional atomic groups, as well as to unravel the interaction of the clusters and the groups in the molecules.

1.2 Friction. Tribology and geotribology.

The return of the holistic idea charts the path of the new spirit in science hints to one of the most interesting interdisciplinary sciences – tribology. Genealogically, tribology lies at the border of many sciences. Its object – the contact, cannot be considered in isolation; it exists only through its neighbors and through the environment in which it is immersed. Contact is not only a bridge, through which bodies exchange substance, energy and information, it is also a part of their source. It is a complex open nonequilibrium system. Tribology, as intellectual and scientific pursuits, can be defined as the science of the structure and forms of contact and the accompanying interactions and phenomena.

The great interest to tribological phenomena, e.g. friction, wear, lubrication of surfaces and interfaces, involves great theoretical and practical attention to the contact body. [2] The surface layers and surface elements forming the zone of contact interaction between frictional bodies differ strongly in properties, phase and chemical content from the bulk solids, forming a layered network of interconnected interacting elements of a material with variable in plain and depth content and properties. The paper considers some basic notions on contact interaction in tribological systems and the behavior of the contact and the contact system. A contact system is denoted as a combination of elements, elementary contact links, in a specific mutual relationship, which gives the combination a quality of entity. The contact is considered both as relation and a real object with complex behavior. Being a relation, contact implies the interaction between system's interface elements. As an object, contact is as a multiphase discrete system of contact microlinks with complex behavior. The macro- to nano-scale features merge gradually in the passage bulk-interface, so that establishing a threshold size is arbitrary. Research of the contact body needs interdisciplinary tools of studying complex multiscale nonequilibrium systems.

The same applies to the contact system and the triboprocesses developing in interfaces in the course of the chain: rest – deformations - microslips – friction onset. Friction, the resistance to movement, is a global natural phenomenon of energy transformation and dissipation during the joint synergy work of two surfaces in contact. It is the process of static contact, preliminary micro-displacements, deformation, initial jump of kinetic friction, and damaging between tribo-couple surfaces, and passage to material recrystallization/ regeneration. Friction results of two opposite simultaneous trends [3,4]*:* accumulation of potential energy by the deformable contact and release (dissipation) of that energy. The first defines the effect of deformation and damage. The second - the heat effect of friction. It reveals trends to the constructive recrystallization of new minerals.

Integrity and interdisciplinarity are characteristic of research and interpretations in geotribology. Geotribology is a branch of the Overall Tribology and a separate interdisciplinary field in the Earth's sciences. Geotribology examines in a new perspective the processes of contact interaction and friction between earth blocks and layers and their influence on the internal structure, deformation, destruction, substance regeneration and physicochemical changes of geological objects. [5]

Geotribology, the most interdisciplinary new branch of the Earth's sciences, relates tribology to natural, e.g. geological tribosystems in the Earth's crust. As a subject of study, it covered geological processes associated with **friction** in all its forms: sliding, rolling and rotation, impact and compression, characterizing deformations, and structural and material changes of rocks.

By tracing various geological structures, tracks and relicts, geotribology discovers new objects that can be successfully interpreted as a result of the driving power of the triade: movement - friction - seismicity. Earthquakes, for example, are seismic phenomena of release of energy accumulated by tectonic movement loading, providing a number of friction shear zones (seismiotectonic tribozones) in the rock systems. In the paper is considered the triade: movement - friction - seismic waves, acting as a powerful energy factor in the friction shear zones of the Earth's crust.

Seismic waves are an indispensable element in any tribological and geotribological system. They appear at the beginning of friction between the contacting bodies. Until recently, seismic waves were the subject only of physics and geophysics, and were associated with their destructive effect in earthquakes. They were not considered as a result of friction and an essential element of tribological systems.

On the other hand, studies of geological processes, where friction and tribological principles find their most vivid application, also did not pay attention to seismic waves, as a concomitant element of tectonic movements and metamorphic transformations of rocks. In geological literature, various geotribological objects are of various names: fault, thrust, subduction zone or meteor crater, suture, etc. But they were mainly considered as architectural structures of the relief and only after 1960, with the new paradigm of plate tectonics, was movement included as an active factor. Even then, no attention was paid to friction induced seismic waves and their impact on tectonic, seismic and petrological processes. Seismotectonic shear zones of the Earth`s crust produce an enormous amount of kinetic energy as a result of inter-block friction and seismic waves. The kinetic energy causes destructive deformations and activation of the rock system and its shear zones, which transform later into constructive creative processes, e.g. crystallization in new rocks from the damaged broken mass.

1.3 Aims

To reconsider some basic notions on contact interaction and the essence and behavior of the contact and contact systems resulting from the contact interaction. To illustrate these concepts regarding natural tribosystems with the friction contact interfaces, e.g. the shear zones of geological seismotectonic fault systems, which involve phenomena similar but not equal to those of the mechanical tribological contact.

An important purpose of the article is to draw the attention of tribologists to geotribological natural objects, to the comparison between tribological, natural geotribological and seismic objects and underline the role of seismic waves both as destructive and creative factor in the relevant processes.

2. METAMORPHIC COMPLEXES, METAMORPHISM AND FAULTS

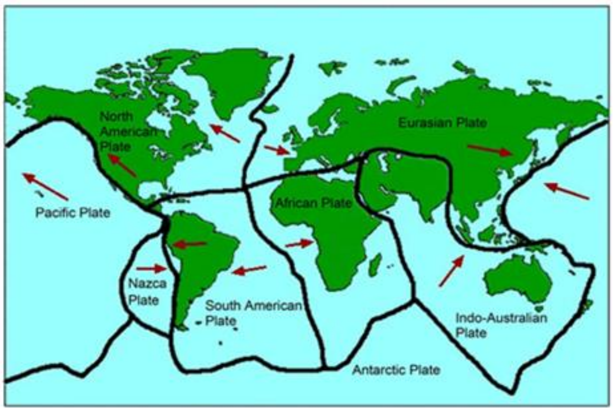

Figure 1. Tectonic plates map of the world

Precambrian metamorphic complexes form the basis of continental plates. (Fig. 1). Formed over hundreds of millions of years under different conditions, today's surface exposures allow us to trace the path of material transformation in the Earth's crust. It is an established fact that the main controlling factors of material changes are temperature T, pressure P and fluids penetrating through the rocks.

During periods of tectonic calm, temperature and pressure depend on the Earth's internal heat and increase smoothly with depth, measured by the temperature gradient Gt and the lithostatic pressure Pc. In the continental crust, Gt averages 2.85°C/100 m, and Pc varies approximately by 2.50-2.60 kbar/10 km. Based on these parameters, in 1921 Pentti Eskola developed the concept and graphical scheme of metamorphic facies. [6] Large areas of the Earth's crust can be considered as relatively equilibrium thermodynamic system with horizontal isotropy and a gradual increase in TP parameters with depth.

During periods of tectonic activity, however, shear zones arise in the earth's crust (geotribological zones), in which friction occurs in all modifications - sliding, rolling and impact. This significantly changes the distribution of TP conditions and their dependence on the geothermal gradient and lithostatic pressure largely loses its controlling significance. In the space of geotribological zones local thermodynamic systems are established, which shows another direction of development of the structural and material processes of metamorphism.

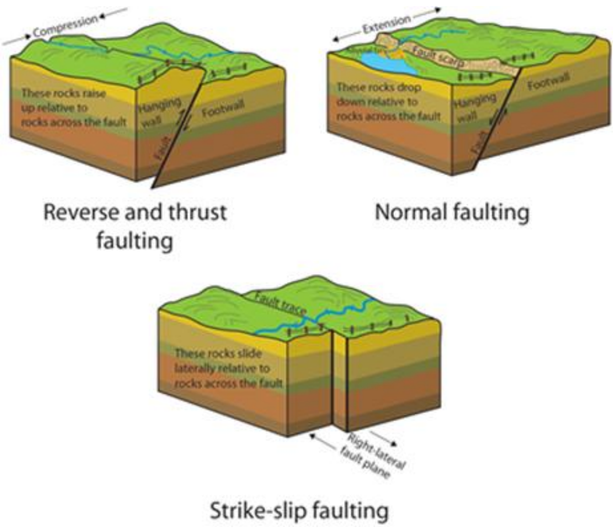

Figure 2. Types of geological faults according to the direction of movement [7]

A fault is a fracture or zone of fractures between two blocks of rock. (Fig. 2) Faults allow the blocks to move relative to each other. This movement may occur rapidly, in the form of an earthquake - or slowly, in the form of creep. Faults may range in scale length from a few millimeters to thousands of kilometers. Most faults produce repeated displacements over geologic time. During an earthquake, the rock on one side of the fault suddenly slips with respect to the other. The fault surface can be horizontal or vertical, or some arbitrary angle in between. Exploring and knowing frictional mechanisms in faults could help forecasting of earthquakes and/or other subsurface phenomena caused by the increasing human intervention.

3. THE GEOTRIBOLOGICAL CONTACT ZONE

3.1 Origin and types

A geotribological zone is a contact system consisting of two rock bodies in relative motion along a contact surface. In the Earth's crust, geotribological zones are often created as subduction zones in the contact along the convergent boundaries between tectonic plates. [7] They are localized along lithological contacts between rocks of different composition and rheological properties, and in interblock tectonic faults. Geotribological zones are also zones with micro- and submicro-sizes, those in the crystal structure of minerals, dislocations.

Object of geotribology is the transformation of rocks in the seismic-tectonics zones, i.e. the geotribological zones, which are friction zones in Earth`s crust during various (based on the movement) faults : a) reverse and thrust faults, b) normal faults, c) strike-slip faults, etc. (Fig.2)

3.2 Movement and friction evolution

Main characteristic of a geotribological zone is the movement between both contacting bodies. In periods at rest, the zone is a tectonic zone of normal structure. In case of tectonic movement, friction processes between the contacting surfaces transform the rupture zone of the fault in a geotribological zone.

Static friction. A body is at rest (its state is apparently static) when it is in contact with with a counterbody under the force of gravity G and the reaction N of the interaction. However, when a tangential external force F is applied to the body and it is smaller than the frictional resistance T, the body is still apparently stationary until F < T. T is the static friction force required to start sliding. This phase is a state of preliminary (microscopic) displacement of the body, in which energy accumulates as potential energy in the frictional interface and its density increases. During that period, individual contact links in the interface are charged with energy and are torn apart when the body tries to move.

Kinetic friction. At the moment when the driving force F overcomes the resistance and F ≥ T, the body suddenly, with a "jump", starts moving and begins to visibly slide. It is the onset of kinetic friction. The beginning of the movement is under the influence of an energy impulse with a strong deformation effect. In the Earth's crust, this is a seismotectonic event and creation of the geotribological zone.

Stick-slip effect or interrupted rhythmic movement. The relative sliding of contacting bodies is rarely uniform, and consists of numerous interruptions that create a rhythm of movement. At the micro- and submicroscale, the preliminary displacement described above is multiplied with a jump-like start, and accordingly, numerous energy microimpulses are produced. The stick-slip phenomenon has been the subject of research and analysis for only about several dozen of years, and acceptable models for its various manifestations have not yet been created. The modeling of stick-slip in geological sites is related to the movement and development of faults and the foreshocks in earthquakes. One of the manifestations in geology is the creation of some striped rhythmic metamorphic structures.

4. PROCESSES OF EVOLUTION IN GEOTRIBOLOGICAL CONTACT ZONES

4.1 Internal geotribological zone

In the interface and third body between the two contacting surfaces forms the internal geotribological zone.

During the evolution of a contact system, three main stages are outlined (Fig. 3): 1. Initiation and progressive development of destruction, 2. Culmination, and 3. Regressive constructive development, ending with consolidation and formation of a new structure.

The geotribological zone is initiated by a seismo-tectonic event, which brings into relative motion and friction two rock contact surfaces and triggers a series of destructive processes in the contact. These are elastic, plastic and rupture deformations, which damage or destroy the contact surfaces of the rock bodies. The rupture deformations, in turn, go through fragmentary, granular, powder and molecular/atomic disintegration, in the final stage reaching melting of the material. The contact body or third body contains the destroyed material, the parts of which are also set in motion. They rub against each other, activate and produce numerous additional active contact zones. The crystal structure of minerals acquires defects such as vacancies, dislocations, etc. As a result of all deformations, additional energy is generated, part of which is spent as work on destruction, and another part increases the internal energy of the system: temperature, pressure, entropy and enthalpy increase. The destruction process is endothermic.

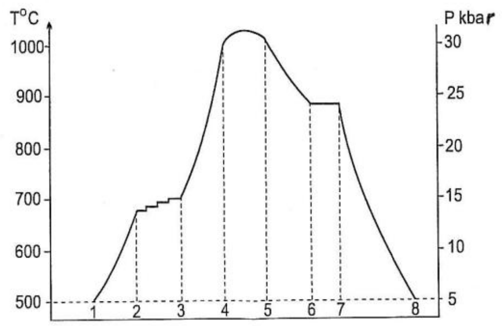

Figure 3. Termobaric scheme of geotribological process evolution

1 – 4 **destructive stage** with phases:
1-2 deformation, 2-3 disintegration,
3-4 activation; 4 - 5 **culmination stage**;
5 - 8 **constructive stage** with phases:
5-7 cooling, crystallization,
7-8 retrograde metamorphism

The culmination moment in the evolution of the various geotribological systems is different. In case the kinetic energy introduced by the seismotectonic event was small and friction was short, the rocks destructive processes reach fragmentary destruction, and the third body is a cataclased rock or tectonic breccia. In case of long and strong energy aggression, the third body contains finely dispersed nanomylonite to molecular or atomic level or a viscous to liquid mass, and in extreme cases – a gas-liquid plasma. The melt also differs depending on the surrounding conditions – it can remain within the geotribological zone and crystallize, fusing the fragmented material or, under lateral tectonic pressure, be squeezed out of the zone and accumulate in adjacent permeable spaces, where it can form new bodies and solidify as igneous rock.

The regressive/constructive development of the geotribological zone begins after the movement between the bodies ceases and the supply of kinetic energy is interrupted. Then the system switches to a mode of energy dissipation, the temperature and pressure gradually decrease, the entropy and enthalpy decrease, and recrystallization of the melt begins. In contrast to the progressive first stage, the process is now exothermic. A new mineral association of high-thermobaric, anhydrous silicate and oxide minerals is created, which fuse the fractured zone and mark its location.

4.2 External geotribological zone

An important fact is that the tectonic energy influences not only directly friction between rock blocks in the tribological zones but also outside them. Friction produces mechanical waves that propagate beyond the contact body, and the internal geotribological zone. [8] The formation of the geotribological zone is a seismic event and the waves are seismic waves (Figs 4 & 5). The energy generated during friction is transferred through the seismic waves to the rocks surrounding the internal zone and increases the amplitude of oscilla rocks and minerals particles. The energy pulses from the seismotectonic event have complex characteristics, so weak crystallochemical bonds between particles are broken and the structure of some minerals, e.g. serpentine, is destroyed, which has been proven experimentally. [9]

5. SEISMIC WAVES SEEN BY GEOTRIBOLOGY

A seismic wave is a mechanical wave of acoustic energy that travels through the Earth or another planetary body. It can result from an earthquake, volcanic eruption, magma movement, a large landslide and a large man-made explosion.

The essence of the wave process is the temporary forced energetic activation of the substance particles, which begin to oscillate with increased amplitude around their equilibrium points. Only energy and momentum are transmitted in the mechanical wave process, and no matter is transferred.

On the other hand, seismic waves are an inseparable element of the triad: motion - friction - seismic waves. Any motion between bodies in contact causes friction, which in turn produces seismic waves. Although fast seismic interface ruptures are tolerably described by the fracture mechanics models, the deep mechanisms that drive them, especially for the onset of friction (preliminary displacement, stick-slip) and the slow ruptures, are not fully understood .[10]

The propagation velocity of a seismic wave depends on medium properties, as well as on the type of wave. According to geophysical terminology, seismic waves are generally divided into body waves and surface waves. (Figs. 4 and 5)

Body waves travel through the interior of the Earth along paths controlled by the material properties, varying with temperature, composition, and material phase. Two types of particle motion result in two types of body waves: Primary and Secondary waves.

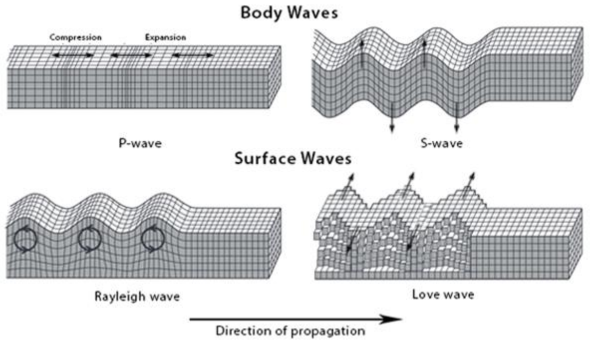

Figure 4. Types of seismic waves

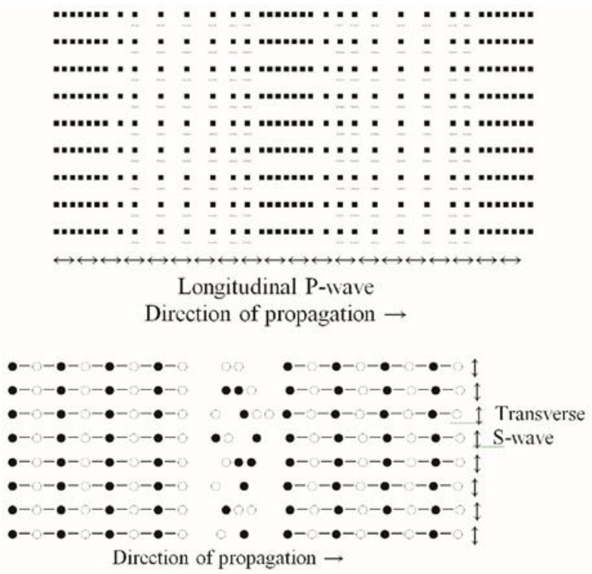

Figure 5. Schemes: Longitudinal P-wave with zones of dilatation and compression, and transverse S-wave

Primary waves (P waves) are longitudinal waves, where the particles vibrate in direction of the wave's motion. Mobilization with rarefaction and condensation of the particles is provoked, forming rhythmic zones of dilatation and compression: particles move apart (dilation) and come closer together (compression), which is how the wave propagates. P waves travel faster (at the speed of the sound) than other waves through the earth to arrive first (where does the name Primary waves come).

Secondary waves (S waves) are shear waves **transverse** in nature. Following an earthquake event, S waves arrive at seismograph stations after the faster-moving P waves and displace the ground perpendicular to the direction of propagation. In shear waves, the particles vibrate perpendicular to the wave propagation, cutting the dilation zones (Fig. 4). As a result, thin cracks appear parallel to the main seismic geotribological zone.

Surface waves are similar to transverse waves but travel along the boundary between the Earth's surface and air, i.e., through the crust. They have a lower frequency than body waves. They are responsible for the high damage and destruction caused by earthquakes. The particles in a surface wave move in a circular or elliptical motion. Surface waves occur only in the uppermost layers of the crust and the surface. Two common types of surface waves are the Rayleigh wave and the Love wave.

Rayleigh Waves (R-waves): The motion of Rayleigh waves is a combination of longitudinal, compressional, and dilatational. As a result, the particles move elliptically in a vertical plane. These waves are dispersive, and the amplitudes generally decrease exponentially with depth in the Earth. They are the most destructive.

Love Waves (L-waves): The particles of Love waves jerk back and forth perpendicular to the direction of wave propagation, similar to S-waves. The motion of particles of the Love wave makes a horizontal line perpendicular to the direction of propagation. The energy of Love waves spreads from the source in two directions. The amplitude often decreases rapidly with depth. Love waves travel faster than Rayleigh waves. They cause rupture of land masses and opening of deep trenches.

It is known from geophysics that friction in its three modifications: sliding, rolling and striking/impact, produces mechanical waves, i.e. seismic waves. Propagating outside the contact zone, they cause mobilization and vibration of the particles around their equilibrium positions.

The seismotectonic event provides shock body waves, which propagate as longitudinal P-wave and a transversal shear S-wave. Longitudinal P-waves form rhythmic zones of dilatation and compression, which result in rarefaction and condensation of particles. The second type – S wave or secondary transverse shear wave, is slower than the P-wave. The particles fluctuate in two directions: one perpendicular to the first ones and the other to the direction of propagation.

The mechanical vibrations and waves caused by friction, lead to deformation and instabilities in the components of a tribosystem. Thanks to the energy of tectonic process in geological systems, vibrations and seismic waves from outside the contact zone affect friction in the contact between geological plates and result in further instabilities and dynamic behavior in bulk and contact zones. On the other hand, waves caused by friction have also reverse impact upon the contact intensifying the instabilities in the contact system.

In general, friction evolution influences mechanics, thermodynamics and physico-chemistry, as well as the whole energy conditions of the **Earth's crust**.

Much research work and experiments testify to the possibility for disorder and destruction of the internal structure of minerals under the influence of seismic waves and could also be regarded as physicochemical aspect of an earthquake. However, the impact of seismic waves is traced theoretically only in the first destructive stage of the geotribological process. Seismology studies examine only the surface damages and those in the hypocenter remain inaccessible for direct geological observation. However, eroded Precambrian metamorphic complexes provide some natural examples of old consolidated seismotectonic zones where recrystallization of destroyed or melted rocks into a new mineral association can be observed. A similar example of an eclogite crystallization on serpentinite body in an ancient seismotectonic zone were found [9]. Nevertheless, the current knowledge of the effect of seismic waves on the structure of minerals and rocks is still scarce. The impact on rocks and minerals from friction originated waves is poorly studied and is not present in the geological literature as a developed topic.

6. CONCLUSION

With the justification of examples of geotribological processes and the general concepts of tribology as interdisciplinary science, some basic notions on contact interaction in tribological systems and the essence of the contact and contact systems are reconsidered.

Geotribological frictional behavior is found as an excellent example of an entity of various contact behavior between rocks. Geotribology studies the processes and products in the shear zones of friction between adjacent geological rocks and plates in the Earth's crust during seismo-tectonic movements in a wide extent of conditions. Geotribology is over again recognized as an important branch of the overall tribology and an interdisciplinary field of the Earth Sciences, in which geotribological objects and processes prove the principles of tribology.

Geotribological zones in the Earth's crust are seismotectonic zones where friction occurs between rock blocks or layers. They are spaces of energy activity and material transformations and of seismotectonic waves arising.

A continuous energy connection between seismotectonic events and frictional processes is traced in the sequential development of destructive and constructive changes in rock matter, reaching the final geotribo-metamorphic products as new rocks and minerals.

Studies of friction in geotribological zones outline interdisciplinary tasks encompassing the evolution of energy and preservation of existence and functionality of the geological system through recrystallization into new mineral associations.

Research on geotribological processes provides an opportunity to find new solutions in geology, e.g. for the genesis of new high-thermobaric rocks.

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