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Friction and deformation at convergent contacts in geotribological systems

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Abstract

Geotribology reveals the application of a tribological approach to natural, e.g. nonmechanical inorganic tribosystems in the Earth's crust. It aims an integrated view over frictional phenomena in the Earth's crust and tracks the interweaving between the immense seismotectonic energy brought in and generated in the geotribological zones, and the evolution of destructive and constructive contact processes ending with the emergence of new mineral structures preserving system's life. A tribological application concerns the convergent contact deformations in geological objects with different rheology, in the movement of tectonic plates, leading to the emergence of obduction relief structures. Convergent geotribological contacts are places of tectonic collision between large rock plates forming the planetary zones of most active, both seismic and volcanic activity. A typical example is the obduction and subduction zones of two ongoing rock plates, one pushing under the other. Studies of the contact process in geotribozones provide an opportunity for tribology to explain new phenomena in the variety of contact deformations and their full cycle of evolution. Considering the necessity of using a tribological approach to geology when describing friction-induced deformations, the role of rheology, mechanisms of preliminary contact displacement and distribution of energy and energy density in the contact body is shown.

1. Introduction

Tribological processes of friction and wear are the subject of intensive, multifaceted and detailed research over a wide range of contact mechanisms, conditions and scale levels [1-5]. A broad-minded and comprehensive view of the energy processes during friction is however needed, as, for example, in the thermodynamic and energetic approach in tribological studies [6-9]. Contact interaction, contact deformation and friction, as global phenomena of energy transformation and dissipation during the interaction of contacting objects accompany any contact system in nature and technology. Being open systems exchanging materials, energy and information with the environment (external contacts) and between system components (internal contacts), the tribosystems have the ability to "forget" external disturbances by building new self-organized dissipative structures [10]. Away from equilibrium, new aggregations as mega-, meso-, micro- and nano-clusters arise, because of the flows of mass, energy and information to and from the system. The deformable contact body evolves, adapts, destructs, and forms new structures (secondary/dissipative structures) during friction. It shows well-defined stages of adaptation and dissipation in its evolution [8-10]. In this way in a tribosystem, as a complex adaptive system [11], the set of interconnected components work together with a common goal: adapting to the changing conditions and transforming to satisfy a vital need – survival of the functioning tribosystem. Contact interaction and friction [12], subject matters of tribology, become objects of study in different natural, technical and social sciences, each of which contributes with various enrichments to themselves and to tribology.

An illustration is the study of friction phenomena, widespread in Earth's crust geological systems leading to an interdisciplinary science called Geotribology [13-15]. Geotribology is one of the natural sciences where principles of tribology apply successfully to the consideration of geological processes. Friction is manifested in various geological processes: Earth's surface formation of the relief, seismic events of sliding between rock blocks and layers, meteorite impacts, etc. Geotribology is a branch of overall tribology and an autonomous interdisciplinary field in geosciences. The object of study of geotribology is the transformation of rocks under the influence of kinetic energy, generated in the seismotectonic tribozones of the Earth's crust. The progressive stage starts with an energy impulse from an external source, while the constructive stage is related to self-organized evolution relevant to the latent energy in the contact body [9,15].

Several aspects in the friction behaviour of geological objects are revealed by combining mechanical standpoints in tribology and a general geological point of view [16-18]. The high pressures together with shift deformation characterising frictional interaction deliver immense energy to the material in contact, accompanied by high reaction velocities. These are the main components of the friction process in geological objects too.

Induced deformations and dissipation structures are highly affected by multiple agents: rheology of bodies, topography of the contacting surfaces (including the micromodel conception of the contact, e.g. asperity-scale), type and ageing of contact, supplied external energy, energy density distribution in contact, etc., each of them participating in a combined synergy action of all agents. A feature of these effects is their manifestation on different scales: from mega-transcontinental geotribozones as obduction and subduction to the nanolevel as defects and dislocations in the crystal lattice. The contact interaction between bodies on different length scales reveals new connections between the processes of friction, deformation, destruction and adaptation in the contact evolution and the creation of dissipative structures of diverse character.

The paper focuses on the deformation effects in convergent and divergent contacts occurring when sliding bodies move against each other. Greater attention is paid to the state of contact and deformation in the contact zone of the friction pairs. Convergent contacts of moving tectonic plates leading to the appearance of new obduction relief structures are used for illustration.

2. Preliminary displacement, redistribution of energy and material in contact

2.1 Contact deformations and friction evolution

The deformation of a body is a change in its shape and properties under the influence of external and internal forces. From the point of view of tribology, the corresponding impact is friction induced: it comes from an energy impulse by the friction between bodies in sliding, rolling, rotation and collision kinematics.

Friction creates waves that transfer energy to the micro-constituents of the contact lattices, and increase the vibration amplitudes of the latter. Some of the particles leave their equilibrium place, migrate and create vacancies, dislocations and volumetric defects that damage the crystal structure. The bodies react elastically, plastically or destructively. The activated matter changes many of its physical and chemical properties: lowering melting points, phase transitions, increasing physico-chemical reactivity, etc. [19-22]. The type and intensity of deformation depend on roughly three main factors: dynamics of the energy impact, matter characteristics of the interacting bodies, and environmental conditions.

Concerning the contact deformation, the specifics of the contact body are highlighted. The real contact area (many times smaller than the nominal contact area of the contacting bodies) is formed in the contact zone from the areas of the contacting asperities during deformation on the mesoscale level contacts, which is the most popular scale level in tribology research. The contact stresses on the asperities are high, which leads in general to a fast transition to plastic deformations. The energy density, the dissipated energy and the frictional heat are highly concentrated in the small real contact area.

Contact deformation and friction, as global phenomena of energy transformation and dissipation during the interaction of contacting objects, accompany any contact system in nature, technology and society. The deformable contact body develops, adapts, destructs, and forms new structures (dissipative structures) during friction. It shows well-defined stages of destruction, adaptation, dissipation and healing in its evolution [8,14,15].

2.2 Preliminary contact displacement during friction

Friction, a typical process and phenomenon of contact interaction, is interpreted as the resistance of the environment to the behaviour of the contact system, e.g. resistance to the movement of the system. From the common mechanical point of view, friction is a force, which resists the motion of a solid body over another one under the action of normal and tangential (traction) forces. The major source of friction between the contacting surfaces is the attraction (adhesion), and friction force forms already at zero tangential force. Two types, kinetic and static friction, are usually considered. The value of static friction varies between zero and the smallest traction force needed to start visual motion. This smallest force to overcome static friction is always greater than the force required to continue the motion or to overcome kinetic friction.

One of the aspects of friction that has been understudied is the onset of kinetic friction [23,24]. Understanding the transition to macroscopic sliding is central to many different fields of physics and material science including tribomechanics of fracture, geotribology of earth faults and earthquakes, etc. The period after the application of an increasing tangential force, while this force is lower than the maximum frictional resistance and before the beginning of the macroscopic (visible) movement of the slider is the stage of preliminary displacement.

The macroscopic or kinetic sliding is preceded by the propagation of discontinuous/discrete fronts (the forefronts) in the contact, covering part of the microcontacts at the interface and changing the real contact area, the contact pressure and the distribution of energy in the contact spots. For sliding to begin, the microcontacts have to be fractured. Under the action of external forces, the individual contact elements, the microcontacts (at the micro level) in the contact body, accumulate greater energy and energy density, deform and tear apart during the preliminary movement, while the actual/macro sliding of the body has not yet occurred. At the macro level, the body is at rest. At the micro level, the contact body is not at rest; the precursor fronts or precursors of kinetic sliding propagate in it. This leads to contact instabilities; nonlinearities and instabilities are formed in the behaviour of the contact body, similar to the instabilities of a stick-slip macro-motion [25]. The behaviour of the antecedents/precursors of the sliding depends on many factors, but especially on the general synergistic interaction of the contact elements. With a sufficiently large amount of accumulated energy (a sufficient number of destroyed and newly created microcontacts, expressed in the fact that the magnitude of the tangential force has exceeded the so-called static friction force), a common front of micro displacements is formed in the contact body, after which the actual sliding of the body begins.

The study of the transition from static friction to sliding, i.e. of the preliminary displacement and the precursor's dynamics may be important for many tribological tasks, e.g. about the predictability of material failure under shear stress in contact bodies, as it is in the geotribological zones during and after seismotectonic movements [26,27].

Among the variety of factors influencing the forefronts propagation in the shear zones are the ageing of microcontacts, respectively the rheology of the materials, the redistribution of energy and energy density, and the resulting deformations and ruptures in the contact bodies.

2.3 Redistribution of forces and energy – convergent and divergent contact

As shown in the previous subchapter, during the preliminary displacement under the action of an external tangential force, energy, energy density, forces and pressure in the contact are redistributed, involving contact deformations, deformation changes and damages. Due to the redistribution of energy and material in convergent and divergent contacts, a preliminary displacement (a micro-shift) in tangential direction and deformation in the elemental contacts occur in the contact body before the real/visible sliding, as well as in the characteristics and properties (especially rheological) of the surfaces in contact. Figure 1 illustrates the material deformation during the ongoing moving of bodies of different rheological properties.

A convergent contact reflects the coming closer of the frontal, forepart, e.g. of a harder body with a soft counter-surface. As a result, deformation occurs, the energy in the contact is compressed (its mass/gravimetric energy and energy density increase) and material is shifted or spilt from the soft body as if the harder one is scraping down or edging it (Fig. 1b). At the rear of the harder body, a divergent contact of the harder body with the softer surface is formed (Fig. 1a).

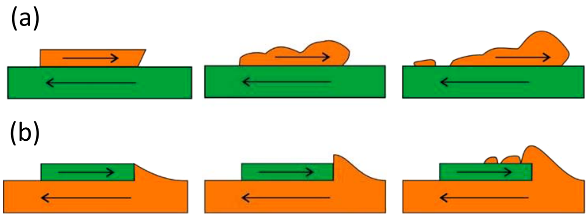


Figure 1. Contact and sliding friction of bodies with different rheology by ongoing movement: (a) divergent contact (disruption of the rear part of the softer body on the harder counter-body) and (b) convergent contact (deformation of the softer counter-body by the harder body)

3. Convergent and divergent contacts in geotribological zones

3.1 Geotribozones

The Earth's crust is a living organism in a state of eternal movement. Tectonic processes like earthquakes, collisions, folding, faulting, thrusting, subduction, and obduction provide the formation of a great number of shear zones of friction where various triboprocesses are developing. The shear zones of friction are known as geotribozones. They are created during tectonic and seismotectonic movements as a result of critical stress being reached in some sections of the rock systems. The geotribozones are located between rock blocks or lithological layers with homogeneous or heterogeneous petrographic composition, which also determines their rheological properties. The formation of the geotribozone follows two paths: a spontaneous occurrence of a crack in some single rock block followed by horizontal or vertical displacement – faulting or folding (Fig. 2); or joining of different rock bodies.

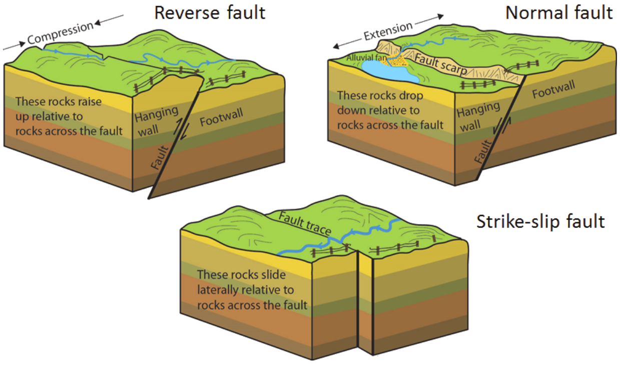


Figure 2. Depiction of reverse, normal, and strike-slip faults; reprinted from Earle [28], licensed under CC BY 4.0

The geotribozones in the Earth's crust manifest various scale lengths: transcontinental megazones over 1000 km long; regional macrozones with tens to hundreds of kilometres lengths; mesozones with meter and decimeter lengths, observable on rock outcrops; microzones with microscopic dimensions; submicro (nano) zones in the crystal lattices.

Two more kinds of geotribozones are distinguished: internal tribozone, which spans the space between two rubbing bodies, and outer geotribozone, where seismic waves affect minerals and rocks.

3.2 Processes in the geotribozones

The movement and friction between rock bodies cause billions of crystallographic bonds in the mineral lattice to break, releasing a large amount of energy. It acts as a powerful energy impulse that amplifies the oscillations of the particles in the matter, internal deformations appear in the crystals such as vacancies, dislocations and volumetric voids, and the rock body undergoes successively elastic, plastic and fragmental deformations. At the same time, in the closed geotribozone, the temperature and pressure increase, reaching high values where the matter passes through a liquid, gas or plasma state. Entropy and enthalpy also increase.

Ending motion between rock bodies interrupts the supply of kinetic energy to the tribozone. Temperature and pressure gradually reduce. The rock system moves to a mode of restoration of damaged matter, with the release of energy to the environment and crystallization of the disintegrated material with the formation of new minerals and rocks.

At full development, the evolution of rock transformation during friction includes three main stages of the contact processes, namely: (a) progressive destructive stage of elastic, plastic deformation and material melting; (b) culmination stage of complete disintegration of matter at very high temperature and pressure; (c) regressive constructive stage of crystallization with the formation of dissipative structures and new associations of minerals and rocks [14,15]. The progressive stage starts with an energy impulse from an external source, while the constructive stage is related to self-organized evolution relevant to the latent energy in the contact body [8,9,15].

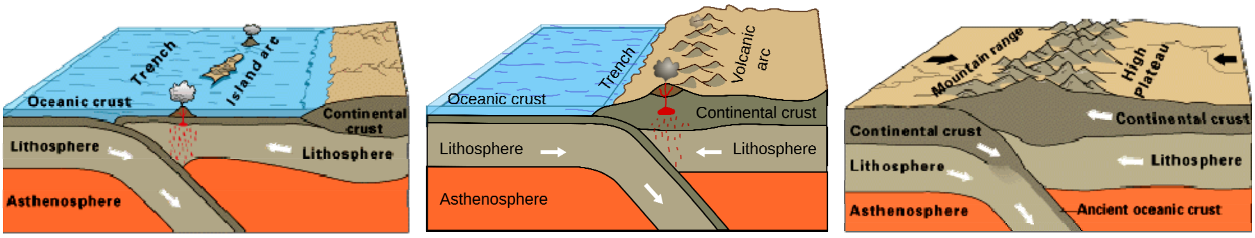
3.3 Hierarchy of deformations and autonomy of structural elements in rock systems

Geological systems offer a favourable opportunity to observe and study tribological processes at different levels – from planetary scales to nanolevels in the crystal lattice. This circumstance, characteristic of geological processes, determines the position of the observation as an important criterion for geological interpretations. It is established for example, that in a geological structure of a high regional order covering tens of kilometres, observed on a scale of 1:1,000,000, no deformations are manifested. If, however, the same structure is considered at a lower level, folds already appear, i.e. plastic deformations too. Upon direct observation of the rock outcrop, the researcher will notice numerous small folds and tectonic faults, and under a microscope, he will detect fragmentary deformation of a variety of ductile micro-folds and various fracture structures: displaced, cracked, split, sheared, rotated, fragmented minerals. In this way, it is possible to arrive at incorrect and contradictory interpretations about the geological characteristics of the researched terrain – the regional geologist will decide that it is a stable crust block, while the petrographer microscopically examining a sample, will conclude that the same terrain is highly tectonized and is part of a thrust fault.

The deformations considered in such an aspect show a clear hierarchy dependence on the state of the observer and at the same time relative independence. The overall structure shows the behaviour of a single undisturbed body, but its constituent parts behave as independent units forming internal plastic and rupture deformation structures. Such systems are defined as internally granular rock bodies [29]. Subordinate structural elements and particles show greater mobility in deformations, causing internal plastic flow.

The nonuniformity of the body movement manifested in a stick-slip phenomenon emphasizes the autonomy of structural units even more clearly. When the movement of the sliding body stops, the internal structural (building) elements continue the movement by inertia for some time, condensing the mass and energy in the frontal part of the body, while at the rear part the energy dissipates and the mass thins out and fragments. An expressive example is the territory of Canada, where friction sliding to the west has created the Rocky Mountains, and the eastern part is flat and torn by numerous bays, lakes and tectonic faults (Fig. 3).

Figure 3. Deformations in geotribological convergent (west) and divergent (east) contacts in Canada; reprinted from Wikimedia Commons, licensed under CC BY-SA 3.0



Oceanic-oceanic convergence **Oceanic-continental convergence** **Continental-continental convergence**

Figure 4. Three main variants of Earth's crust convergent plate boundaries; reprinted from Wikimedia Commons, licensed under CC public domain

3.4 Friction and deformations in obduction and subduction zones

The nature of the contact as well as the distribution of energy and mass is determined by the material properties and the mutual spatial arrangement of the geotribocouples in the frictional system. Contacts between bodies can be divided into three main interaction types.

Pure sliding. Two parallel geological bodies to which tangential forces of opposite directions are applied slide against each other relative to a common frictional surface. Interaction velocity is relatively low and contact life during the preliminary displacement is relatively long. The convergent contact is realised in the frontal part of the ongoing bodies, and the divergent one in the rear part (Fig. 1). Examples of geological structures of this type are thrust faults, block and interlayer seismic slips, etc. (Figs. 2 and 4).

Collision impact and pressure. Two bodies meet head-on at a point or area under normal forces when collision velocity is relatively high and contact life during the preliminary displacements is relatively short. High dynamics of contact bodies changes. Typical examples of collision impact results are the meteorite structures, and of pressure – the sutural structures such as the Ural chain, which had joined the European and Asian continents together.

Combined action of sliding and compression pressure. It happens between two bodies in contact on an inclined plane. Subduction and obduction contact processes between tectonic plates refer here. Geotribological structures form the contact interaction of the two ongoing rock plates, with one pushing under the other (Fig. 4). Three main variants of the structure can be separated: (a) two homogeneous oceanic plates, e.g. the Pacific volcanic island arcs; (b) oceanic under the continental plate, e.g. the Pacific plate of Nazca under the Andes; (c) two continental plates, e.g. the Hindustan peninsula under the Himalayas. These contacts are convergent. The formation of mountains is a deformation in the upper body under the pressure of the lower one. In the case of the large difference in hardness and rheology between the contacting bodies, a "scraping" of the softer body may occur and fragments may be transferred to the upper body surface – a process known as obduction. An example is the soft serpentinite coat scraped by the edge of a hard continental plate and fragments are thrown on the continental surface. Later, they are covered by sediments and become part of the stratigraphic sequence of the rock complexes [30].

Turning to processes of Earth's deep past epochs, the creation of obduction and subduction zones with convergent contacts was the consequence of the movement of plates at the closing of the oceans, preceding the amalgamation of the future supercontinents. We evaluate them today by the relict rock products, as well as by the stratification of rock complexes revealed on the surface after blocks' rise and erosion.

4. Conclusion

Friction, contact interaction and deformation between natural (e.g. geological) bodies are the least studied phenomena in tribology and tribomechanics. Besides, the enormous impact of friction in the shear zones between rock plates during and after seismotectonic movements is almost not handled in geology, which leaves unresolved many unexplained and controversial problems.

The present study is an attempt to fill gradually these gaps in both tribology and geology, through the above-highlighted topics, i.e. the frictional and deformation processes in convergent and divergent contacts between natural formations of Earth's crust, as follows.

Friction followed by various deformations are widely spread processes in geological rock systems from transcontinental megascale to the microscale in the crystal lattice. They develop in geotribological zones during and after seismotectonic movements of sliding between rock plates, blocks and layers.

Friction causes a rupture of the crystal's chemical bonds in the mineral structure, during which a large amount of energy is released affecting, deforming and destroying the geotribological zones.

The movement of rock bodies is usually uneven and irregular, with a variable velocity and multiple stops and starts. Deformation processes during the stage of preliminary contact highlighted in the paper, cause changes in energy and energy density in the contact body, increasing them in the front side of the contacting bodies – the convergent contact and decreasing them in the rear side – the divergent contact.

The type and intensity of internal and external deformations depend mainly on the change in energy density in contact, the rheological properties (petrographic composition) of the rock bodies and the spatial relations and associations during friction's sliding, impact and combination.

In the case of geological systems examined at different levels, the hierarchy of deformations, as well as their relative independence, are clearly visible. For example, if a body during friction retains its external shape and integrity unchanged, i.e. reacts elastically, the internal building components, being relatively independent, can exhibit plastic or even fragmentary internal deformations.

Regarding future development, geotribological studies serve not only as the interdisciplinary bridge of transferring bilateral information for both tribology and geology applications. New opportunities are through tribology assistance and energy concepts application to break the traditional idea of geology as purely observational and field investigation science, and to direct geology methodologies deeper into the aspects and models of physics and chemistry. Furthermore, as the empirical methods of geology provide huge amounts of data, the physical and energetic relations can lead to quantitative assessments and the application of informational and big-data computational methods in geology.

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