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Research article

Stress-State and Sliding Between Colliding Plates in the Subduction Zone

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A B S T R A C T

Understanding of friction is important for tribological processes ranging from engineering contact systems to the nonmechanical inorganic tribosystems of Earth's seismo-tectonic zones. A common but little-studied case is the combination of interaction, sliding and counter-pressure (collision) between plates and rock blocks, which develops specific deformations and energy and material changes. Above friction processes depend on the geometry, the spatial relations between the crustal plates, their material, especially rheological properties, and the energy transformations. The subduction zone has been regarded as place of renewal processes of energy and material. The role of the intensive friction processes in the increase of temperature and pressure in the subduction zone is shown, and the resulting both internal, external deformations and material changes of the rock material. A hypothesis is presented for the formation of the so-called "Deformation Arc" observed in the Alps, the Chilean segment of the Andes and the Nepalese zone. A contribution to science represents the application of tribological principles in the interpretation of natural, in this case geotribological processes, which leads to mutual enrichment of both tribology and geology.

1. INTRODUCTION

Last decades a new thinking, specifically the focus on the interdisciplinary and multiscale aspect of systems behavior, conduct us to the main features of tribology [1-5]. The study of contact and friction processes involves complex and interdisciplinary tasks. Tribology is a clearly interdisciplinary science: the formulated principles and elaborated tribology models have found application and expand its importance enriching a number of other sciences - chemistry, biology, geology, ecology, sociology, etc., which, in turn, contribute significantly to development of tribology [5-9].

Tribology began its development for the practical purpose focused on the technical and technological specifics of machinery and equipment. It expanded further providing study of processes in the natural sciences and humanities, affecting also ecology and life quality problems by the green tribology. Nature provides various cases and examples highlighting the collaboration and favorable mutual influence between tribology and earth's sciences. Emphasizing the interdisciplinary, multiscale and energy aspects of contact interaction, one of the newest tribological fields was born: geotribology. It is a branch of General tribology and a new interdisciplinary field in Earth Sciences [9-12].

The interdisciplinary perspective in geotribology is based on fundamental and practical concepts from physics (deformation, diffusion, gravity, wave propagation, thermodynamics, fracture mechanics), material science (rheology, material transformation), geology and geophysics (plate tectonics, gravity, seismology, earthquakes), and tribology (contact interaction, stress/strain, friction, selforganization and dissipative structure formation) that are essential to multiple topics in Earth and Planetary Sciences.

More specifically, geotribology applies the principles and models of tribology for the contact interactions while explaining geological processes in rock friction zones. It also examines the geotribological products that appear during the evolution and transformation of minerals and rocks due to friction. Following the synergy work of friction rock surfaces, the adaptation, energy dissipation, and self-organization in friction zones, geotribology enables the study of the contact during tectonics and seismicity with tracing geological formations from their birth up to the metamorphically recrystallized geoproducts. A special feature of geotriboproducts is the possibility to trace the development of triboprocesses over a very wide range of scale levels: from micro / nano-level in the crystal lattice of rocks to mega- (or geological, planetary) level in the contact zones of geological plates in the Earth's crust.

The paper focusses on the behaviour and characteristics of a subduction geotriboloogical zone as both tribological state combining sliding and collision.

Through the eye of tribology, new moments in subduction zone friction processes to be outlined, such as: the role of generation and dissipation of friction energy in the geotribozones, especially the subduction zones; the increase of temperature in the tribozones; the destructive and constructive effects of friction processes; connecting tribological behaviour with rock/plate tectonic motions and seismicity.

2. GENERAL CHARACTERISTICS AND NOTIONS OF ROCKS

Earth is the planet with voluminous felsic continental crust, operating in a plate tectonic mode. Tectonics considers processes that control structure and properties at/near Earth's crust and its evolution through time, as well as the ways the rigid plates interact with each other. The tectonic mode promotes interaction between the deep interior and the surface of Earth fundamentally shaping and affecting the environment in which we live [13,14].

For a deformable body (a rock) under stress, the dependence of strain ε vs stress σ reflects material behavior from elastic to plastic deformation and rupture, as well as the mechanical evolution of the deformations.

Rocks undergo stress: a force applied to a given area (compression, tension or shear) which generates a deformation in rocks, known as strain**.** Stress and strain create complex geotribological contact structures deforming the Earth's crust, like folds and faults, and unconformities (e.g. related to erosion breaks and gaps).

Under compressional forces, i.e. under applied compressional stress, rocks are pushed together. Tensional forces operate when rocks pull away from each other. Simple shear force is created when rocks collide moving past each other in opposite directions.

The deformation or the strain that results from applied stress depends on many factors. This includes the type of stress, the type of rocks or blocks, i.e. their rheology, the pressure and temperature conditions, the extent of time the rocks are subjected to the stress, as well as all forms and conditions of friction (static friction, sliding, rolling, rotation and impact friction). To understand how rocks deform through the slow movement of tectonic plates, or rapid movement occurring during an earthquake, we need to consider the internal deformation of the rocks.

Rheology reveals the behavior of a rock when a force is applied to it. Usually (in mechanics), it tells how forces are applied to particles or blocks (considered as perfectly rigid bodies), what is their resulting displacement and what is the velocity of this displacement. In geotribology, the focus is to how a rock or a mineral deforms internally when forces are applied at its boundaries. So, in the place of force we consider the stress**,** which is defined as the force applied over an area. In the place of displacement, the strain is considered, defined as the change in shape or size of a rock relative to the original shape or size. Instead of velocity, we consider the strain-rate, which is defined as the change in strain with respect to time. To consider how an object deforms internally we have to consider the rheology of the material, the orientation and distribution of the applied forces, and where these forces are applied.

The surface of the Earth is divided into rigid blocks, called tectonic plates, bounded by narrow regions of high deformation called plate boundaries. Tectonic plates comprise both crust (oceanic or continental) and mantle rock. Tectonic plates have various shapes and sizes and are continuously changing shape, either through the addition of new crust and lithosphere at mid-ocean spreading centers, or through the loss of material at subduction zones. Tectonic plates move at rates of a few centimeters per year.

The motion of tectonic plates is driven by convection in the mantle, i.e. dissipation of heat from the mantle is the original source of energy needed to drive plate tectonics. In convection, the dense, cold things sink, and warm things rise. In the Earth, the cold sinking things are slabs (subducting plates) and the warm buoyant things are ridges, or just rising material from deeper in the mantle.

3. FRICTION AND BASIC GEOTRIBOLOGICAL STRUCTURES

3.1 Sliding friction structures

Generally speaking, the formation of geotribozones follows two paths: the case of a spontaneous occurrence of a crack in a single rock block followed by horizontal, vertical or oblique frictional displacement – faults and shear zones; or the case of joining of different rock bodies.

A variety of geological structures containing the geotribozones follow-up the stress acting on rocks, their type, movement, contact interaction and types of friction. Any geotribological zone at rest is a simple tectonic fault, however when the bodies begin to move, frictional interaction occurs, high friction energy and seismic waves are generated, and the zone may become seismic.

Sliding friction of rock blocks, minerals and strata is the most common type of geotribological activity.

Sliding of the rock bodies takes place under the action of driving and resistance forces parallel to the frictional surface, at moderate velocities of the contact interaction. The built geological structures on frictional macrolevel can be as follows: a) According to the line of movement and the direction, fault structures around a crack between rock blocks appear as normal, reverse, oblique or strike-slip fault, transform fault, horst and graben. b) Broken lithological contacts, in the case of layered rock complexes in a sloping position. c) Thrust structures - sliding of a package of rocks on a relatively stationary horizontal subsurface. d) The structures on micro- and nanolevel built around the dislocations in the crystal lattice of minerals.

3.2 Friction at high velocities: impact, collision and high compression forces

Collision or impact between opposite high velocity moving bodies is an instance of one moving object striking violently against another. Instantaneous or short-term frictional contact is produced. The driving force is perpendicular to the frictional contact plane. Huge amount of energy is transferred during the contact interaction. Examples are the collisions between meteorites and Earth surface and the resulting meteorite craters [9,13].

High compression parallel forces between opposite moving towards one another bodies like in the convergent sliding of rocks and plates produce high-energy interaction and long term frictional contact with noticeable amounts of stress and strain. [11-13] This case is related to orogeny (mountain building), e.g. to tectonic processes on the convergent margins of continents when the plate motion compresses the margin. Orogenic belts develop at the compressed plate crumples and are uplifted to form a mountain or a mountain range. Characteristic geotribological structures are the sutures, i.e. "seams" or "stiction" between large rock blocks. The most famous planetary megasuture is the Ural mountain range, which stuck the European and Asian continental plates. In plate tectonics, sutures are closely related to the subduction zones.

4. THE SUBDUCTION ZONE

A subduction zone is a megageotribological tectonoseismic structure, often planetary in nature. It is formed at convergent contacts between tectonic plates, when two plates sliding in opposite motion meet and one of them, usually the heavier one, is pushed under the other and slides along an inclined surface (Figure 1). The distribution of forces at the moment of the encounter and the subsequent action is a combination between the compression or impact forces, perpendicular to the frictional contact surface and at the same time tangential forces - parallel to the inclined surface.

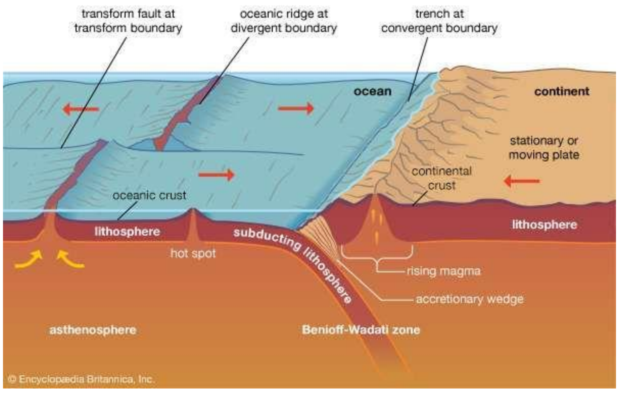

Fig 1. Subduction zone, Andean-type: oceanic to continental convergent contact.

The main forces that determine the rate at which tectonic plates move as part of the mantle convection system (Figure 2) are, as follows [14]:

1) viscous drag: the force opposing motion of the plate and slab past the viscous mantle underneath or on the side;
2) slab pull: the force due to the weight of the cold, dense sinking tectonic plate;
3) ridge push: the force due to the buoyancy of the hot mantle rising to the surface beneath the ridge.

According to the type of the plates, three main variants of subduction zones along the convergent boundaries form geotribological structures [9, 11-13]:

a) Oceanic under oceanic plates, resulting of a transform fault at the ocean floor; island arcs subsequent the friction between both plates, e.g. the Japanese islands.

b) Continental under continental plate, with well-known example the Alpo-Himalayan system, along which numerous local subduction zones were formed: the African plate under the Alps, the European plate under the Carpathians, the Indian plate under the Himalayas and others, everywhere marked by the most active orogeny on the planet.

c) Oceanic under continental plate, e.g. the Pacific plate of Nazca under the Andes. Characteristic of this type is the combination of orogeny and volcanism, observed in the section of the Chilean Andes. In this case, two options are possible:

- the oceanic plate sinks under the continental plate, bringing with it sediments from the ocean floor;
- the oceanic plate splits, if it is two-layered, e.g. covered with softer serpentinite layers. Fragments of the softer mantle are then scraped off and obducted onto the continental surface [15].

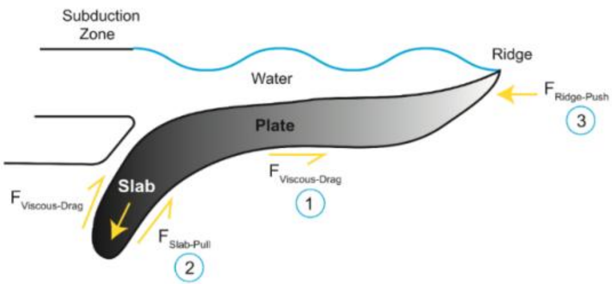

Fig 2. Forces driving plate motion, adapted from M. Billen [14].

The movement of plates in the crust, which begins with horizontal sliding, is due to the action of deep mantle convection flows, which in turn are a reflection of the cyclic eccentric displacement of the heavy earth's core. The emergence of transform and rift zones in the earth's crust, followed by the drifting of tectonic plates in different directions, causes the opening and closing of ocean basins. The subduction configuration occurs when ocean basins close. The energy of friction between the heavy tectonic plates is colossal and it is reflected in significant orogenic deformations and physicochemical changes of the rock material, which led to its disintegration and melting. All subduction zones are hotbeds of strong earthquakes. They have long lifespans that can last for hundreds of millions of years.

5. DEFORMATION AND MATERIAL CHANGES IN THE SUBDUCTION ZONE

The subduction zone is a space loaded with very high energy, which provokes processes in two directions: deformation and material changes of the rock material.

5.1 Deformation changes

a) In the contact space between the tectonic plates, friction mainly occurs, which destroys their walls and the entrained material from the ocean floor. At the beginning, large rock fragments prevail, which are rolled, crushed and disintegrated until their complete mylonitization. The temperature and pressure in the subduction zone rapidly increase and reach the thresholds for rock melting at higher (shallow) levels than those if they were only under the control of the temperature gradient. It can be assumed that magma hotbed centers originate at less than 50 km below the Earth's surface.

b) Orogeny above the subduction zone - Due to the compression forces acting on the upper plate, if it is more ductile, it folds and lifts, following the rheology influence on deformation and strain between a rigid body and a more ductile conterbody in convergent contacts [9,11]. Mountain ranges are formed on the surface of the crust above the subduction zone: Alps, Himalayas, Andes, Rocky Plain, Carpathians, etc.

c) Deformation arc - The surface roughness and the contact body discontinuity between the tectonic plates in the subduction zone lead to nonlinearity of contact stress distribution. Meanwhile, elevations in the overriding plate are affected by topographic changes, depending on the rheology and resilience of both overriding and subducting plate. As the horizontal opposite forces continue to act, Similar arcs are well expressed on the territory of Chile, where the Nazca oceanic plate runs into the Andes, in the Nepalese zone between India and the Himalayas, the Apennine peninsula towards the Western Alps, the Arabian plate towards Anatolia, etc.

5.2 Material changes

It is believed that the rocks from the sliding down oceanic crust, in addition to deformation changes undergo various geochemical changes. Sinking down, rocks fall into an environment of increasing temperature and pressure. Due to the accompanying friction, the increase in temperature values should be greater than that of the temperature gradient in the crust. While the average temperature gradient in the crust is 2.5-3^{o}C/100 m, in open tribological systems A.V. Chichinadze [16] measured 1000^{o}C/cm. However, a number of authors suggest that cold rock materials from the ocean floor, sediments and serpentinites, cool the frictional space of the subduction zone to a significant depth, which we consider implausible.

The supposed material changes fall into three types:

a) Dehydration of sediments and serpentinites: Reaching earth levels with temperatures above 200^{o}C, dehydration of the clay minerals and serpentinites containing OH group occurs.

b) Successive recrystallization of all minerals and their replacement by higher thermobaric ones corresponding to the increasing temperature and pressure, as well as occurrence of HP/UHP metamorphic rocks such as eclogites.

c) Gradual melting of the rocks in depth, appearance of magma foci in the frictional contact and the channels crossing the overriding plate (continental or oceanic plate) along which the magma rises. On its way, the magma forms subintrusive chambers, and reaching the surface – volcanoes.

6. DISCISSION

As a global geological structure in the Earth's crust, result of the movement of tectonic plates, the subduction zone is the subject of long-term geological research and interpretations of the supposed processes in it [17-19].

The subduction zone is the place where geological processes, considered in the aspect of geotribology, clearly demonstrate the unified energy relationship between movement, friction, deformation and material changes [9,11,15,20,21] and many other. In reality, however, individual phenomena are considered in isolation in different sciences such as seismogeophysics, tectonics, petrology, mineralogy, geochemistry, so that above unified relationship and mutual dependence is lost from the researcher's view. Therefore, for some geologists, the claim that seismic processes are the cause of the emergence of new metamorphic rocks sounds absurd. We believe that the lack of a generalizing theory is the reason for the unsatisfactory interpretation of high-thermobaric (HP/UHP) processes in the Earth's crust, such as eclogitization. The latter is a typical example of a cause-and-effect energy connection between tectonoseismic and material petrological-mineralogical processes in the rocks.

The subduction zone is related to the formation of the ophiolite associations above it, and in this sense, it becomes a suprasubduction zone [21]. In the Rhodope massif, a three-stage building of the ophiolite associations has been established [15], which includes obduction of serpentinites, subintrusive and volcanic magmatism, as result of the sliding of tectonic plates and the effect of friction on the transformation of the rock material.

The finding of HP/UHP metamorphic rocks among midhigh-thermobaric rocks opened a long-standing dispute about their place of formation [22]. It is widely believed that eclogites formed in the subduction zone rise (exhumed) tectonically [17,23] or pieces of them are carried out by the ascending magma and fall into higher levels on the crust where we find them. We definitely reject this idea as unrealistic and contrary to the laws of physics. It is really possible to create conditions for the formation of eclogites in the subduction zone, and they remain in this place. It is even more illogical to believe that large and heavy serpentinite masses that fell into the subduction zone could rise into the high crustal levels.

7. CONCLUSION

1) The subduction zone is a global geotribological and seismic structure in the Earth's crust, which arose because of the collision of two tectonic plates in the eras of closing oceans.
2) The subduction zone has been regarded as place of renewal processes of energy and material. The role of the intensive friction processes in the increase of temperature and pressure in the subduction zone is shown, and the resulting both internal, external deformations and material changes of the rock material. The internal deformations are manifested in fragmentation and crushing (mylonitization) of the rocks, and the external ones in the orogenesis above the subduction zone, often with creation of a deformation arc.
3) Material physicochemical changes have been considered in the subduction zone including dehydration, recrystallization, and melting of rocks. Recrystallized rocks are the result of HP/UHP geotribometamorphism, a famous example of which are eclogites staying in situ at the site of formation. Above the subduction zone of the continent-ocean plate type, ophiolitic associations are built up, including subducted serpentinites and magmatism.
4) Contribution to science: the application of tribological principles in the interpretation of natural, in this case geological geotribological processes, leads to mutual enrichment of both tribology and geology.

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