ISSN: 3064-9846
Research Article
Journal of Agricultural, Earth and Environmental Sciences

Banded Eclogitization on Serpentinites – effect of Shock Wave Action

Evgenia Kozhoukharova

Geological Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria

[*]**Corresponding author:** Evgenia Kozhoukharova, Geological Institute, Bulgarian Academy of Sciences, Sofia, Bulgaria.

Submitted: 27 May 2025 **Accepted:** 02 June 2025 **Published:** 09 June 2025

https://doi.org/10.63620/MKJAEES.2025.1087

Citation: *Kozhoukharova, E. (2025). Banded Eclogitization on Serpentinites – effect of Shock Wave Action. J of Agri Earth & Environmental Sciences, 4(3), 01-14.*

Abstract
A rare case of rhythmic banded eclogitization of serpentinites in crustal conditions is interpreted as a possible effect of paleoseismic waves impact on serpentine structure. The serpentinites are a part of the Ophiolite Association in the Rhodope Massif, South Bulgaria. The Association is included in Lukovitsa Variegated Formation, which in the area of Avren village, consists of amphibolites, marbles and schists. Avren serpentinite body is in contact with leptite gneisses. The peripheral parts (30-40m) are affected by eclogitization. Bands of garnet-lherzolites (1-20mm), which are parallel to the contact, alternate with strips of unchanged serpentinite. The bands, close to the contact are more frequent and consist of pyrope-garnet, diopside, enstatite, olivine and spinel, crystallized under conditions of T = 560-820oC /P = 8-15 kbar. Moving away from the contact, the stripes become rarer and gradually disappear. Obviously eclogitization is associated with the contact between serpentinites and gneisses, which has been most probably a paleoseismic zone of friction. Every seismic event provokes emergence of shock body waves, whereas the longitudinal P-waves create spaces of delamination with rarefaction of the particles and spaces of compression. We assume that the weak Van der Waals bonds of the serpentine structure could break in the dilation zones during expansion and then layers of mobilized particles in chaotic motion occurred. The following S-waves enhanced the motion and increased the temperature and pressure in the layers. After crystallization of the mobilized particles, a striped texture of alternating bands of garnet-lherzolite and unchanged serpentinite was formed. The described case demonstrates the influence of seismic waves on crystallization processes and at the same time the appearance of HP metamorphism in situ in the middle levels of the crust.

Keywords: Eclogitization, Serpentinites, Seismic Waves, Rhodope Massif

Introduction

The discussion on the genesis and place of origin of the HP/UHP eclogite mineralizations is still topical and active. The dominant hypothesis launches the idea of subduction of a wedge of oceanic plate under the continental crust wherein an eclogite mineral association is crystallized and subsequently raised by exhumation to the higher levels of the Earth's crust [1-4]. The interpretation is based on the accepted metamorphic facial scheme according to which the place of eclogite mineralization is controlled by the Geothermal gradient and Confining (lithostratigraphic) pressure, respectively – the depth [5]. Thus, eclogite paragenesis containing microdiamonds and coesite, requires crystallization conditions of T=850-1000oC and P>4GPa, which should exist at infracrustal depth of 150-250 km. Hence HP/UHP rocks should be formed at the respective depths and returned to the crust according to the hypothetical subduction-exhumation mechanism. But while subduction is a really existing and proven movement, the so-called exhumation from the mentioned depths is always a matter of hypothetical views. The exhumation mechanism instead of giving a satisfactory explanation, poses a number of questions without sufficiently convincing answers. Furthermore, many of the eclogite findings are located in a geological setting, where traces of undergone subduction-exhumation zone do not exist as in the Rhodope Massif too.

Very often the decisions concerning eclogite genesis are actually assumptions based on the currently prevailing hypotheses and ideas, ignoring the real geological facts observed on the field and as well theoretical logic.

On the other hand, such a process depending only on depth, would have taken place provided that the Earth's crust is a homogeneous thermodynamic system in a completely calm tectonic environment. The real situation is just the opposite. The metamorphic complexes of the mobile belts, as in the Rhodope Massif as well, were crossed repeatedly by seismotectonic zones where kinetic energy was generated, creating a local thermodynamic environment of high temperature and pressure.

Traditionally, in the geological and especially petrological literature on metamorphism, the geothermal gradient and confining pressure are still considered as the main controlling factors. The energy factor friction and the seismic waves produced by it are completely ignored.

To find a plausible solution to eclogite genesis for each specific site, the geologist-petrographer is needed to consistently elucidate four issues: a. are eclogite bodies exotic blocks tectonically implanted or formed in situ? b. what is the energy source providing the high temperature and pressure required for eclogite crystallization?; c. what is the probable mechanism of crystallization of eclogite mineralizations?.

In our opinion the principles of geotribology and geotribometamorphism can offer a much more acceptable and reliable solution to the eclogitization in the Earth`s crust. Geotribometamorphism views eclogites and garnet-lherzolites as rocks formed in seismic zones, where friction creates a local thermodynamic environment of high temperatures and pressures [6]. The metamorphic textures are the key to understanding the mechanism of crystallization.

Here an illustrative example of a rare natural phenomenon of rhythmic banded eclogitization in situ on serpentinite is considered. A possible hypothesis is launched for its origin with the hope of drawing attention to the destructive and creative role of seismic energy in metamorphic processes.

Materials and Methods

In the Rhodope Massif is widespread a Neoproterozoic continental ophiolite association, composed of metamorphosed basic volcanites, metagabbros and serpentinites, located among the metamorphic complex of the Rhodope Mountains. The conditional geological mapping at a scale of 1:25 000 of the Rhodope massifs was carried out according to the lithostratigraphic method in 1948-1962 years, supplemented with stratigraphic correlations between different areas of the Rhodope Massif and thematic field research. The study was accompanied by laboratory microscopic observations and geochemical sampling. The results were summarized in a Geological Map of Bulgaria on a scale of 1:100,000, with descriptive Notes attached to it provided a complete picture of the distribution and the main petrographic characteristics of the serpentinites and amphibolites as well relationships between stratigraphic units and serpentinite bodies. The attached map (Figure 1-above) is the author's interpretation, based on additional field research [7].

Field studies on the eclogitized serpentinites were conducted by the author and included detailed mapping of the area (Figure. 1 below), tracing and describing the eclogitization zone, and collecting rock samples. The latter were laboratory processed by petrographic microscopy and chemical analysis. The main rock-forming minerals of eclogites were analyzed by laser scanning. Laboratory studies include petrographic microscopic observation of the mineral composition and structure of the metamorphic rocks, in parallel with geochemical analysis, which was carried out on thousands of samples in specialized laboratories. They provided information on the degree of metamorphism, metamorphic facies, sequence of metamorphic events, and rheological properties of the rocks and their absolute age.

The complex field and petrographic studies on the geological and stratigraphic position of ophiolites and their metamorphic changes led to the concept of a uniform heterogeneous ophiolite association undergoing regional metamorphism. The finding of eclogites in metamorphic rocks posed the problem of high-pressure metamorphism in Rhodope Massif [8-15].

Results

Geological Setting

Stratigraphic and Petrographic Overview

The Rhodope Massif is situated in the central part of the Balkan Peninsula on the territory of South Bulgaria and North Greece. The metamorphic basement of the Rhodope Massif is built of high-grade Precambrian metamorphic rocks divided into two supergroups named: Prarhodopian and Rhodopian of different age and petrographic composition [16, 17]. Several lithostratigraphic schemes have been proposed relating mainly to the Rhodopian one, which is subdivided into three groups or three complexes [18, 19].

An actualized version of lithostratigraphic division, based on geological mapping, general correlation and petrological analysis of the lithostratigraphic units and meanwhile with local corrections of some unclear tectonic relations is presented [7]. It is an attempt to restore the primary relationships and consistency between the lithostratigraphic units and to show the stratigraphic building in its primary form is a unified stratigraphic system [20]. We affirm with new arguments the existence of two complexes of different lithology and age: Prarhodopian and Rhodopian groups.

The lower Prarhodopian group (PRG) shows features of an ancient infracrustal continental complex, which may have been a fragment from some supercontinent such as Rodinia. It consists of biotite, leptite, migmatic gneisses and granite-gneisses represented into three lithostratigraphic units up to top: Boykovo Formation, Bachkovo Formation and Punovo Formation. The absence of marbles is a specific feature of PRG. Cadomian, Hercynian and Alpine granitoid magmas and several generations of aplite-pegmatite veins penetrated the rocks, causing local migmatization and reheating, and as result the hole rock complex obtained geochemical signature of granodiorite. The PRG builts up the core of anticlines and dome structures.

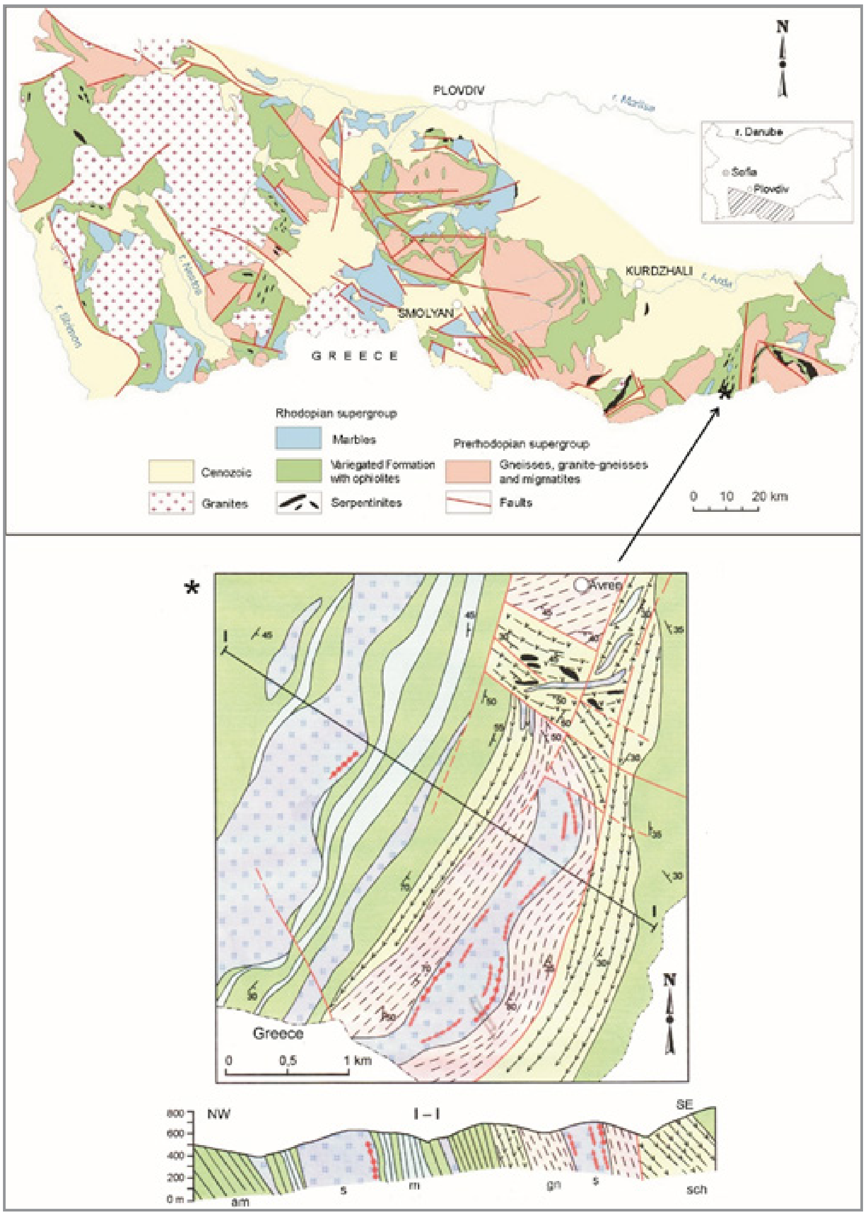

Figure 1: Geological map of the metamorphic complex of the Rhodope Massif.
Geological map of the Avren region, East Rhodopes.
am – amphibolites; s- serpentinites; m-marbles; gn-gneisses; sch- schists.

Above. Geological map of the metamorphic complex in the Rhodope Massif Down. Geological map of the Avren rayonq East Rhodopes. am-amphibolites; s-serpentinites; m-marbles; gn-gneisses; sch-schists. The upper Rhodopian group (RG) is a well stratified supracrustal variegated complex that has been transgressively deposited on the Prarhodopian group. It is represented by metamorphosed volcanogenic-sedimentary rocks: amphibolites, eclogites, garnet-lherzolites, schists, quartzites, marbles, serpentinites, grouped in three parts, up to top: Lukovitsa Variegated Formation, Dobrostan Marble Formation and Belashtitsa Calc-silicate Formation (Figure 2). Lukovitsa Variegaded Formation has been divided as an impotant stratigraphic level in the northern parts of the Central Rhodopes [8]. The presence of the same Variegated Formation was established throughout the Rhodope Massif nominated as: Chepelare Formation and Vucha Formation [21, 17].

Stratigraphic Scheme of the Metamorphic Complex
Belashtitsa Formation – calcareous schists

Rhodopian group	Belashtitsa Formation – calcareous schists
	Dobrostan Formation – marbles
	Lukovitsa Variegated Formation – mica schists, marbles, quartzites, ophiolites
Prarhodopian group	Punovo Formation – porphyroblastic gneisses
	Bachkovo Formation – leptite gneisses, migmatites
	Boykovo Formation – biotite gneisses, migmatites

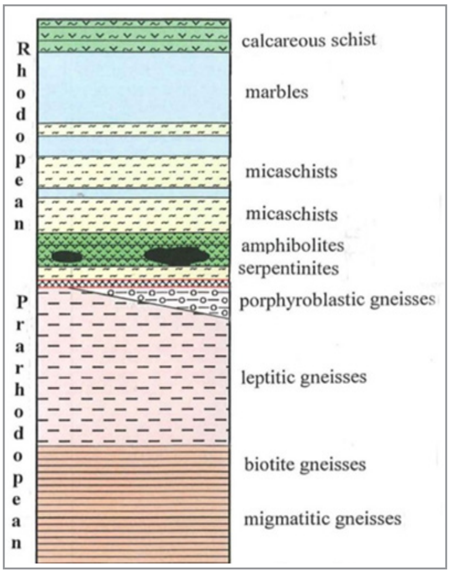

Figure 2: Stratigraphical coolumn of the metamorphic complex

An Ophiolite association occupies a clearly defined stratigraphic position in the lower levels of the Lukovitsa Variegated Formation [7, 22].

The Ophiolite association consists of: a. serpentinites; b. low potassium-high magnesium toleiites and their tuffs, metamorphosed into amphibolites; c. subintrusive bodies of metagabbros, metagabbrodiabases, metagabbronorites.

The serpentinites form elongated bodies, lenses and boudins in size from meters to 10-12 km in length. They are placed concordantly between the lower layers of the Lukovitsa Variegated Formation often directly on the gneiss sole of the Prarhodopian group. Thus the serpentinites mark the erosion level on the gneiss PRG complex and become a stratigraphic bench mark. The serpentinite bodies are covered and included of the amphibolites, schists and marbles. Discordant serpentinite wedges crossing metamorphic layers are not observed anywhere. It has been proved that high degree of serpentinization – 85-95% in lizardite and chrysotile is only possible in the ocean basins, where on the ultrabasic igneous rocks in the floor, an upper coat of serpentinite clay grows reaching a thickness of several kilometers [23].

The juxtaposition of all features of serpentinites leads to the conclusion that they were implanted by an obduction mechanism on the continental crust (Prarhodopian group) during closure of someone ocean. Between the continent and the ultrabasic oceanic plate a suprasubduction zone was probably developed. The serpentinite fragments were scraped off from the top of the already serpentinized oceanic plate and obducted on the erosion plane of gneiss continental crust (Figure 3). Some places with melt emerged along the frictional surface. The melt penetrated into the gneisses through channels and covered the serpentinites as lavas and tuffs, together with pelitic-carbonate sediments [24].

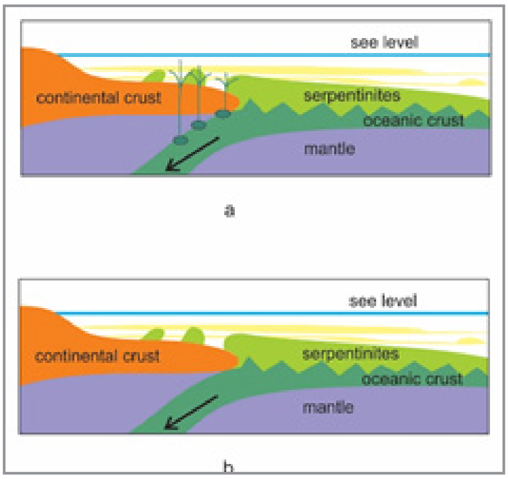

Figure 3: Interpretative drawing of a suprasubducted zone
subduction of an ocean plate and obduction of serpentinite fragments
melting and creations of authochthonous magmatism

Interpretative drawing of a suprasubducted zone: down - subduction of an ocean plate and obduction of serpentinite fragments; above - melting and creations of authochthonous magmatism.

The formation of the Rhodope ophiolite association had taken place in three stages: a. static – serpentinization of the oceanic ultrabasic plate; b. dynamic – ocean closure, plate tectonic movement and obduction of serpentinite fragments, scraped from the hydrated coat of the sliding ultrabasic plate; c. constructive – autochthonous subintrusive magmatism and SSZ-type volcanism including and covering serpentinite bodies. This determines the heterogeneous nature of formation of the ophiolite association – a combination of rock members appearing in different places at different times.

Later all ophiolite rocks underwent a regional metamorphism of amphibolite facies: basic volcanic rocks were recrystallized into amphibolites, subintrusive ones – into metagabbros or metadiabases. The large serpentinite bodies were only peripherally metamorphosed in antigorite and chlorite-actinolite schists, while in the inner parts they retained the lizardite-chrysotile composition. The incomplete replacement and preservation of lizardite-chrysotile indicate that the temperature of the regional metamorphism never exceeded 600oC. Otherwise all serpentinites would had become pyroxenites. The latter, being in the relatively dry continental crust, would never be serpentinized again.

The oldest ages according to U-Pb dating of zircons from the chromitites of the Dobromir serpentinite massif indicate Paleoproterozoic era - 2257 +/- 80 Ma and 1952 +/- 82 Ma, which is the age of the oceanic plate in the ancient ocean, from which the serpentinite fragments have been torn off [25].

The absolute age of the metamorphic basic rocks is determined by U-Pb dating on zircon as Neoproterozoic – 610 Ma in eclogites, 572 Ma in metagabbro and 566 Ma in metagabbro [26, 28]. These dates coincide with the time of ocean closure preceding the amalgamation of the Gondwana supercontinent.

Structural Overview

The Prarhodopian and Rhodopian groups were subjected to folding at least twice. In the general structural plan, the diapiric raised domes and linear positive structures are clearly outlined by layers of the Rhodopian group (Figure 1). The cores of anticlines are built of the Prarhodopian gneisses. The spaces between them are occupied by deeply sunk subvertical, inclined or lying synclines, filled by the rocks of the Variegated Formation with ophiolites and marbles. Regardless of the folding deformations the ophiolites preserve their position in the crystalline complex and serve as basic stratigraphic marker. Sutures and deep tectonic zones, marked by ophiolites or discordant serpentinite wedges, are not found anywhere in the Rhodope massif. Some ideas emerged, suggesting a new notion of the Rhodope massif as an Alpine structure of discordant sheet thrusts (“pile of thrusts“), other authors even report on discordant blocks with septas of Mesozoic rocks with fossils encountered among them [29-31]. However, the additional field explorations have not confirmed the reports and the authors themselves have not presented later publications with evidence of geological arguments proving their ideas such as maps, sections, outcrop photos, samples, etc. The idea of the presence of autochthonous, allochthonous, intermediate terrains, or upper, middle, lower allochthon without providing sufficient geological factual evidence from field mapping remain only as an interesting conceptual interpretation [32, 33].

In conclusion the geological data prove that the metamorphic complex in the Rhodope Massif is a Precambrian unified stratigraphic building with a relatively well preserved primary stratigraphic sequence. Phanerozoic events have left imprint mainly in fold tectonics, some shear zones and several rare small epidermal thrusts. Substance alterations are expressed as a. regional metamorphism in amphibolite facies: b. syn- and postmetamorphic geotribometamorphism as HPT eclogitization and c. reheating and feldspar metasomatism due to deeper anatectic manifestations and granite magmatism.

Eclogitization in the Rhodope Massif

Eclogitization in sensu lato as a highly thermobaric process, affects various rocks of the Rhodopian metamorphic group. The eclogites are formed on basic substance (amphibolites), pyroxenites and garnet lherzolites on ultrabasic ones (serpentinites), kyanite and phengite segregations in mica schists, and thin 1-2 mm layers of calciphyres on marbles or calcareous schists.

Eclogites

Eclogite bodies are found in all highly metamorphic terrains of South Bulgaria – the Rhodopes, Verila Mt. Sredna Gora Mt [12-15].Ograzhden Mt. [34-38]. Everywhere outside the Rhodope Massif eclogites are included in formations, analogous in rock composition to the Lukovitsa Variegated Formation. The eclogites associate with the amphibolites and form among them concordant thin layers and lenses up to 10-20 cm as well as rarely compact layers with a thickness of 1-1.5 m. The eclogites often appear on the contact with mica-poor leptite and aplitoid gneisses in geological setting indicating an old friction zone. Eclogites are encountered in cracks of 2-5cm, intersecting gabbronorites, which is the most convincing evidence for their formation in friction zones [38]. In rare cases small (1-1.5m) eclogite bodies are present among migmatized gneisses, which are close below layers of eclogitized amphibolites. They are considered to be fragments torn off during folding and sunken due to gravitational collapse.

The typical mineral composition of omphazite, garnet and rutile often includes kyanite, magnetite, ilmenite and as an exception glaucophane. The crystallization temperatures are most often within the range of 580-680oC at pressures of 1-1,6 to more seldom 2GPa. The temperature of 800-1100oC and pressure of 2-4GPa are recorded for the coesite and microdiamond containing eclogites [37, 39]. All eclogites are affected by alterations. The omphazite is replaced by symplectites of quartz, albite and diopside, garnet – by amphibole, which ultimately leads to complete replacement of eclogites by amphibolites.

The background regional metamorphism of the surrounding rocks is in amphibolite facies: T=480-560oC, P=0,5-0,7GPa. All features of the eclogites indicate that they are not exotic bodies, but are an integral part of the Lukovitsa Variegated Formation formed in situ along mobile zones on lithological contacts and shear zones.

Banded Eclogitized Serpentinites

Eclogitized serpentinites are found much rarely compared to eclogites. They are encountered mainly in the intensively folded Avren syncline, East Rhodopes [40]. Several strongly elongated serpentinite bodies (up to 1-5 km long and up to 250-300 m wide) are located there, concordantly among the steep to vertical layers of amphibolites and marbles of the Lukovitsa Variegated Formation. The serpentinites are composed of lizardite-chrysotile and antigorite. Along their contacts with gneisses, amphibolites and marbles, small pockets and lenses of pyroxenites are often observed, which consist of diopside, garnet, coesite, spinel, phlogopite, amphibole.

An instructive example of banded eclogitization was observed on a serpentinite body in the valley of the Dalbok Dol stream, 4.5 km south of Avren village, Krumovgrad district (Figure 1-detail). The body measuring 5 km long and 300 m wide follows a tectonic zone with a north-south direction, where it is in steep to vertical contact with leptite gneisses.

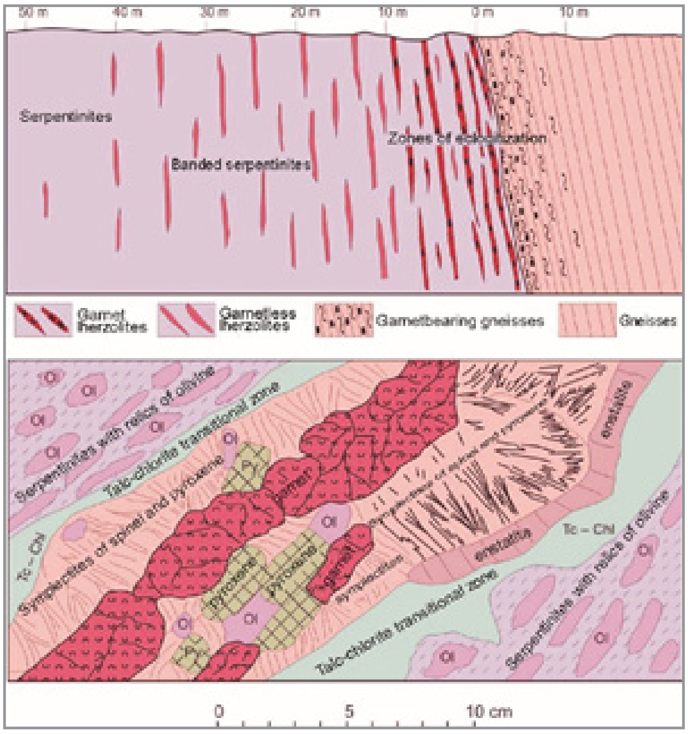

Figure 4: Skech of the Contact between Banded Serpentinites and Gneisses. Drawing after Microphotos of a Band of Garnet Lherzolites.

- Sketch of geotribological contact between banded serpentinites and leptite gneisses.
- Drawing of a band of garnet-lherzolites after microphotos.

The serpentinite body is built of lizardite-chrisotile with a typical mesh texture. Chrisotile forms thin veins around angular lizardite meshes containing strips of fine-grained magnetite. Antigorite occurs in single flakes or segregation mainly on the periphery of the body. Rare relics of olivine also appear in meshes. The serpentinite body is in contact with mica-poor leptite gneisses (Figure 4 above). On the peripheral parts of the body, thin 0.5-2 cm strips of garnet lherzolites parallel to the contact appear. These close to the contact are more frequent and they gradually disappear towards the interior of the body. Garnet, enstatite, diopside, olivine and spinel alternate with serpentine stripes. The high thermobaric banded segregation demonstrates a zonal texture (Figure. 4 down). The central part is occupied by a pyrope-garnet (Pyr50-55Alm27-29Grs16-18Sps1-2), followed by orthopyroxene – enstatite (En84-85Fs14-15Wo0,35-0,42), clinopyroxene (Wo49-51Fs4En46-47), olivine (Fo88Fa12) and spinel Cr-pleonaste. The myrmekite-like symplectites of diopside, spinel, enstatite and magnetite provide evidence for rapid crystallization. A transitional zone of cryptocrystalline talc-chlorite aggregate is formed between the new eclogite association and the serpentinite. The stripes are in conformity with the boundaries of the body and the contact. They alternate with strips of unchanged serpentinites (Figure 5).

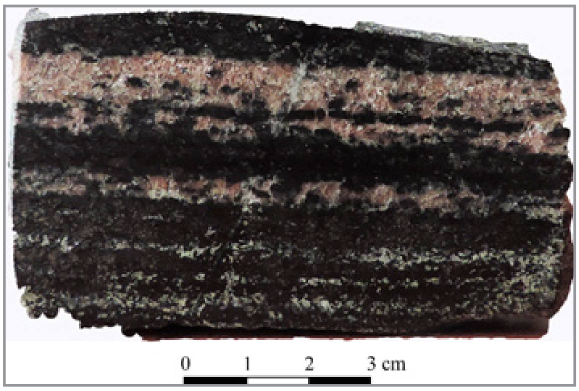

Figure 5: Photos of two Samples of Banded Serpentinites: Garnet Lherzolites (light bands) in Alteration with Serpentinites (Dark Bands).
Samples of banded eclogitised serpentitnites - Avren region.
Alteration of garnet-lherzolites (light rosy bands) with serpentinites (dark bands).

The conditions of crystallization in the zones vary within T =560-820oC/P = 0.8-1.5 GPa while the background metamorphism of the country rocks is medium pressure amphibolite facies – T = 480-540oC, P = 0.4-0.6 GPa, suggesting spatial anisotropy of the thermodynamic parameters.

The Lukovitsa Variegated Formation continues in North Greece and connects with the Kimi complex, where microdiamonds are found [41].

The conditions of crystallization in the zones vary within T =560-820oC/P = 0.8-1.5 GPa while the background metamorphism of the country rocks is medium pressure amphibolite facies – T = 480-540oC, P = 0.4-0.6 GPa, suggesting spatial anisotropy of the thermodynamic parameters.

Calcifiers are observed in many places among marbles as thin (0,5-3mm) layers, composed of fine-grained: garnet, scapolite, diopside, olivine, spinel, calcite, dolomite, phlogopite, plagioclase, titanite, quartz. The calculated crystallization conditions are: T=745-770oC, P= 0,5-1 GPa [42]. Similar thin layers of fine-grained calcite among marbles are often observed in areas subjected to interlaminar movements, which prove clearly and unambiguously that these mineralizations are results of sliding and friction.

Kyanite and phlogopite schists are found in zones of interlaminar sliding. Microdiamond-containing garnet porphyroblasts in gneiss schists of the Variegated Formation are encountered in the Chepelare region of the Central Rhodopes [39, 43]. T = 700-800oC, P = 3,5 - 4,6 GPa.

A similar case of banded eclogitization in ultramafic rocks has been described in the Dabie- Sulu region (China) [44]. The eclogites occure as sheared lenses, pods and layres within an association of foliated ultramafic blocks, metapelites, Gr-Q-Jd gneisses, kyanite quartzites and marble that represents a piece of continental crust. It were subducted to mantle debths greater than 80-100 km and then tectonically exhumed to the earth`s surface. Eclogites exhibit a banded texture of alternating garnet and omphacite stripes.Figure The formation of eclogites is represented as seismic reflection on a peridotite plate at the interface of rock walls.

Eclogitization sensu lato in the metamorphic complex in the Rhodope Massif affects different rocks: serpentinites, amphibolites, schists and marbles. It is manifested along seismic zones of movement and friction, mainly parallel to rock stratification and less often along transverse cracks. The chemistry of eclogite mineralizations is analogous to their host rocks. Their specific features define them as crustal products, emerging in situ in the middle sections of the crust at the level of the amphibolite facies.

Energy Source for Eclogitization

The considered problems are: a. what is the energy source that has provided the high crystallization temperature and pressure; b. its position in space and c. the mechanism of crystallization that has formed the contact banded structure of the eclogitized serpentinites.

The general geological setting and the relationships between the eclogite bodies and their host rocks definitely prove that they were formed in situ mainly along the contacts of the amphibolites and gneisses and at the level of the amphibolite facies in the middle parts of the Earth's crust. This means that the energy source should be sought for at the same levels.

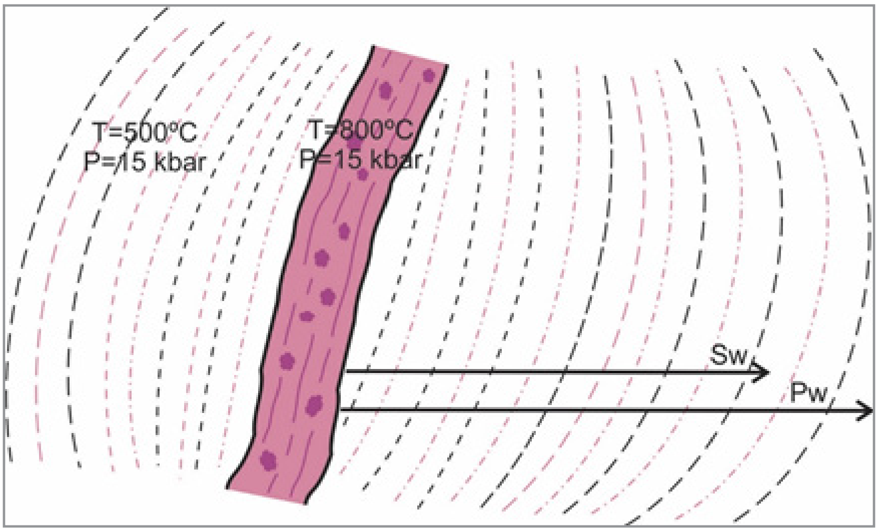

Figure 6: Scheme of geotribological zone: inner part of friction and outer part of the P- and S-seosmic waves of propagation. The friction phenomenon has been ....

Geotribological zone – inner part of friction and outer part of seismic wave propagation. The friction phenomenon has been known for millennia and in the last 500 years from the time of Leonardo da Vinci it has been an object of scientific research. Friction in its three modifications – sliding, rolling and impact, takes place between the contact surfaces of two bodies in relative motion. At the frictional contact, which we define here as geotribological zone, (Figure 6) processes of prelaminary displacement, stick-slip movements and redistribution of energy take place, which create a complex picture of the behavior of atomic particles [45].

Movement and resistance generate energy. It raises temperature and pressure in the contact space between the bodies in friction and produces mechanical body waves, propagating beyond that space. Numerous experiments prove that during friction, the matter in the contact space is disintegrated and temperature and pressure increase their initial values several times. In the Earth's crust friction occurs in the seismotectonic or geotribological zones, which emerge during different epochs and can be syn- or postmetamorphic in terms of regional metamorphism.

Brief Overview on Geotribological Processes in the Seismotectonic Geotribological Zones

The role of kinetic energy generated in seismotectonic zones of friction and propagating as body waves, is rarely and scarcely commented in geological literature. However, energy causes profound changes in the structure of minerals leading to deformation, destruction, melting and finally new crystallization of some specific type of HP metamorphic rocks.

Friction is a global natural phenomenon of transformation – generation and dissipation of the energy of external relative motion. It strictly obeys the energy balance equations, and in the most general case shows an adaptive-dissipative character. Numerous experimental studies explore the effect of friction on the physical-chemical properties of matter and formulate the thermodynamic principles of Tribology as the science of friction [46 - 51].

Geotribology is a branch of General Tribology and an interdisciplinary science of the group of Geosciences. Its object of study is the contact interaction concerning friction between blocks or layers in the seismotectonic zones within the Earth's crust and the transformation of rock and rock-forming minerals there under the influence of tectonic energy. The origin of tectonic zones in the Earth's crust starts always with fractures between blocks. When the tectonic stresses in a given section reach critical values, the rock blocks that have been in a state of quiescence or preliminary displacement are brought to a relative motion. The initial moment of relative motion is associated with a sudden and abrupt change of the state of quiescence to movement and is manifested as a shock of destructive effect, transforming the tectonic zones into seismic geotribological zones. In these zones a colossal amount of energy is generated, and it is completely sufficient to ensure the high temperature and pressure necessary for eclogite crystallization.

Three stages of development of processes are distinguished along the geotribozones: deconstruction, culmination of activity and crystallization.

At the first stage the deconstruction starts with elastic and plastic deformation, followed by brecciation, cataclasis and mylonitization. Point, linear and planar defects emerge also in the mineral lattice. The inner dislocations and translation of the crystal structure lead to fracture and fragmentation of minerals. In an advanced stage of deformation, the crystal chemical bonds are torn to complete decomposition of minerals, reaching to molecular and atomic level up to exoemission of ions and electrons and melt formation.

At the second stage of maximal activity of triboprocesses, specific thermodynamic conditions in the tribozone are established. The kinetic energy, delivered from tectonic movements, transforms to thermal one. The internal energy, entropy and enthalpy increase, the free energy decreases. Due to all mechanical-chemical (or tribochemical) processes the temperature, pressure and chemical activity of components increase considerably. The amounted effect of tribo-processes is possible to provoke realization of extremely high temperature and pressure only in the narrow-closed space of the geotribozone. The high concentration of energy into a narrow space, moreover with high velocity of friction, is possible for a brief moment to get to temperature "explosion" and during a second or microsecond the temperature to increase more than 1000oC. A specific feature of the triboprocesses is preservation of higher temperature and pressure only in the narrow space of a tribozone and beyond its boundaries they decrease rapidly. The tribozone may be considered as a closed or semiclosed system comparable to an autoclave, in which chemical reactions attain a local equilibrium.

At the third stage the melts crystallize in a new HTP mineral assemblage sometimes containing microdiamonds and coesite. In the shallow levels of the Earth`s crust due to rapid cooling of the melts glassy pseudotachylites may occur but in deeper levels the new rocks would show a granoblastic structure. The velocity of growth is much lower than that of melting. Temperature and pressure begin to decrease with a speed dependent on the depth level of the tribozone, although in any case much slower than the rapid, even in some cases, flash increase during the progressive stage of the tribological process.

At the same time the country rocks, out of the tribozone, are composed of lower thermobaric minerals. The new high thermobaric mineral assemblages may be synchronous but heterofacial to the mineral assemblages of the host rocks.

Wave Action

The influence of tectonic energy can be manifested not only following the direct friction between rock blocks within the frame of tribological zones but also outside them. It is known from geophysics that friction in its three modifications – sliding, rolling and impact, produces two types of body waves or seismic waves moving through solid rocks. The particles display intense vibration around their equilibrium positions. The first one, P-wave or primary longitudinal wave provokes mobilization with rarefaction and condensation of the particles, forming rhythmic zones of dilatation and compression. The second type – S- wave or secondary transverse, shear wave is slower than the P-wave, and the particles fluctuate in two directions, perpendicular to the first one and to the direction of propagation. The multiple consecutive energy wave pulses, moving at different speeds, are overtaken, superposed, increasing or decreasing their vibration amplitude, creating a complex interference pattern with a rhythmic character.

The current knowledge of the effect of mechanical body waves on the structure of minerals and rocks is scarce. The idea of the wave action on minerals is developed very slowly. Heinicke studying the impact of a metal ball on a softer surface, observes the formation of a thin layer of plastic flow below the surface of impact [47]. Chichinadze describes a layer beneath the friction surface with different physical properties, considering that this is due to distribution of stresses in depth [50].

During recent earthquake studies in Japan anomalous features have been identified in the Nojima Fault zone (SW Japan): hard foliated gouge between granite breccia and consolidated mudstone, charred routs of herbaceous vegetation, hard foliated rock layers, some of them showing a "flow structure" almost parallel to the fault, turbulent eddies of quartz [52-53]. Various phenomena such as increasing radon in water, electromagnetic wave noise, a funnel-shaped earthquake cloud, earthquake light, electronic exoemission were also registered. According to the work hypothesis of Enomoto.2005 the temperature at the epicenter area has reached 350-400oC and the minerals discharge unpaired electrons, called thermal exoelectron emission. Such phenomena are interpreted as an indication for destruction of the mineral structure to atomic and subatomic level in the hypocenter.

Parallel to the principal seismic slip zones, a bundle of thin cracks has been observed in the damage zone [54]. They cause this expansion of rocks outside the seismic zone, known as dilatancy. Similar thin fissures, accompanying the main friction zone, have also been found in geophysical experiments on seismic processes.Thin cracks parallel to the main friction zone indicate the influence of seismic P- and C-waves and the dissipation of energy.

Brantut et al. (2016) performed stick-slip experiment in sawcut samples of natural antigorite serpentinite during laboratory earthquakes and observed a rapid coseismic slip [55]. It caused a significant overheating of asperities along the sliding surface, sufficient to produce amorphization and melting. Furthermore, they registered a layer of the order of 1 to 3 μm of foam-like matrix in the internal structure of antigorite. The choice of the experimental material is not accidental. The 1:1 layered Mg silicate hydrated serpentine structure favors interlayer slip. Every layer consists of two sheets: Mg-rich trioctahedral sheet is tightly linked on one side to a single tetrahedral silicate sheet [56]. The two sheets are connected with strong covalent Si-O bonds, while the interlayer H-bonds are weaker. High-resolution TEM micrograph shows a flat crystal structure of lizardite with correct geometry of interlayer H-bonds. The basic structural unit is 0.72 nm thick [55]. Antigorite displays curved wave layers. The octahedral Mg-O sheet is continued and wavy while the tetrahedral Si-O sheet undergoes periodic reversal because of 3-5% dimensional disproportion between both sheets. In the interlayer space different components as Fe, Al, Ca, OH-groups may be present.

The serpentine is unstable to temperature and pressure and loses H2O in conditions of prograde metamorphism, it is successively replaced by talc, chlorite, olivine and at high pressure – enstatite.

All these phenomena testify to the possibility for disorder and destruction of the internal structure of minerals under the influence of mechanical (seismic) body waves and could be regarded as physicochemical aspects of an earthquake. However, the effect of mechanical (seismic) body 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. But 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 is presented here.

Meteor craters are an impressive illustration of the power and impact of seismic waves on rocks. They are often surrounded by concentric circles of hills that resemble frozen water waves. Between them, cracks form, filled with molten rock [57]. Their configuration repeats on a megascale the zones of dilation and concentration that occur during the movement of P-waves.

The totality of these phenomena associated with seismic waves convincingly shows that during their movement they cause plastic and rupture deformations of rock matter, similar to friction.

A Hypothesis for the Formation of Banded Texture on Avren Serpentinites

The search for a plausible interpretation of the origin of banded eclogitization on serpentinites is grounded on two basic ascertained facts: a. garnet-lherzolite strips are parallel contact structures to an old tectonic zone; b. gneisses and serpentinites from the zone are part of the stratigraphic sequence of the metamorphic complex. This proves that serpentinites have been eclogitized in situ and have not been exhumated from deep zones, where they would have been transformed to pyroxenites. In this case the enigma consists in the mechanism of formation of the unusual petrographic striped structure.

The eclogite bands indicate the occurrence of stresses close to the tectonic contact that have provoked the emergence of parallel cracks. The pattern resembles the phenomenon of dilatancy, which is characterized as an inelastic volumetric increase or a loosening process of extensive zones within the upper Earth`s crust due to the formation and propagation of cracks under tectonic stresses, related to earthquakes [58]. The dilatancy is described also as increase in volume of a granular substance when its shape is changed because of greater distance between the particles.

The seismic events cause the emergence of shock mechanical body waves, which propagate as longitudinal P-waves and transverse shear S-waves, provoking internal mobilization of particles. The longitudinal P-waves induce vibration of the particles along the direction of waves propagation and inflict spacing and condensation of particles (Figure 6, 7a). In the case of S-waves the particles fluctuate in two directions, perpendicular to the first one and parallel to the seismotectonic zone (Figure 7b). The mobilization of particles inflicts elastic and plastic deformations, as well as various defects and dislocations in the mineral lattice. Referring to Hook's law (F = -kx) for the proportionality between the acting force F and the degree of deformation, as well as to the Young's modulus of elasticity, the different deformation in gneisses and serpentinites should be noted. Gneisses as hard dense rocks react mainly elastically, while serpentinites respond plastically.

The serpentine with its specific layered structure and weak Van der Waals bonds in the interlayer space is particularly susceptible to wave impact. In the compression intervals the deformations are elastic or elastoplastic and occur in thickening of particles without crystal lattice destruction. On the contrary, in the dilatation zones the additional separation of the atoms may reach critical state leading to disruption of the weak bonds and disintegration of the mineral structure. In the dilatation zones bands or layers of released and mobilized in chaotic motion particles emerge (Figure 7). The propagating with a certain delay S-wave probably enhances their motion by interference. The rhythmic bands are perpendicular to the movement of the longitudinal P-wave and parallel to the contact of the serpentinite body (Figure 4). The friction and mutual collisions between the mobilized particles increase the internal energy, temperature and pressure. It could be assumed that the mobilized layer corresponds to a melt.

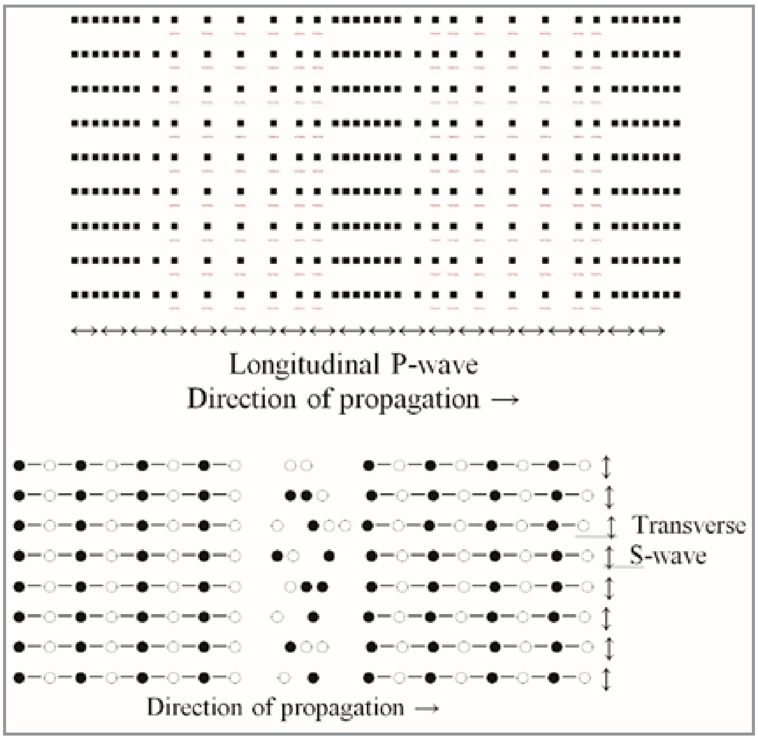

Figure 7: Deformation of the atomic structure during the propagation of the seismic waves: zones of dilatation and compression by the P-wave and rupture of bond by the S-way

After termination of the seismic event and energy supply, the chaotic mass tends to order. The melt is gradually cooled at a rate dependent on its quantity and temperature difference from the environment. In the case here we assume that the ambient temperature has never exceeded 580-600oC, that of antigorite stability, i.e. the smallest difference between the melt and surrounding rocks is in the range of 300-350oC. Reaching a threshold temperature, the melt in the strips crystallizes into a new ultrabasic metamorphic rock as garnet lherzolite, composed of high thermobaric mineral association: garnet (pyrope), enstatite, diopside, olivine and spinel. The structure of the new rock is granoblastic respectively to the estimated depth of about 20 km. The final effect is a banded texture of alternating layers of garnet lherzolites and unchanged serpentinite..

The described mechanism of deformation under wave energy impact is also relevant to the problem of delamination of matter in the vicinity of friction zones. Characterizing the effect of impact friction Heinicke indicates the emergence of a thin zone of plastic flow several millimeters under the impact surface [48]. Chichinadze (2001) also mentions fracture zones outside the direct friction zone, explaining the phenomenon with the action of adhesion forces [51].

Discussion

The same serpentinite body and the N-S tectonic zone continue to North Greece in the Kimi complex where microdiamond and formed coesite inclusions in garnet have been discovered in eclogites and metapelites [41]. According to the authors conclusion the rocks were metamorphosed in depths exceeding 220 km, probably by a sinking rock block. But the Kimi complex is not a separate block. It corresponds lithologically and by geological position to the Lukovitsa Variegated Formation and here it is directly prolonged in the Avren syncline and also in the whole Rhodopes. The Avren rock complex on Bulgarian territory and its corresponding Kimi complex on Greek territory may not have fallen into deep subcrustal or mantle levels.

There is also an opinion that the eclogite facies has been regionally developed and today's metamorphites, which are in amphbolite facies, are the result of general diaphtoresis that has changed all rocks, leaving only eclogites as relics from this previous metamorphism [42]. There are no facts supporting a similar idea about regional eclogitization but at the same time one refuting circumstance exists. In case of regional eclogitizarion all rocks would have been entirely eclogitized and serpentinites would have been transformed into pyroxenite massifs and they would have never regained their serpentinite appearance under the conditions of the dry Earth's crust.

Microdiamonds were found in pelitic gneisses from the Chepelare district in the Central Rhodopes. In the authors' opinion their genesis is related to collision and subduction of continental crust [39, 43]. But the geological structures in the Rhodope Massif do not correspond to such a vision. The eclogitization in the Chepelare district associated with a tectonic zone is incorrectly defined as a melange. There is also no data or prerequisites for the formation of a subduction zone in this region during metamorphism period.

The recommendable terminology is not HTP metamorphism but local mineralization. The geological setting, in which the eclogitized serpentinites of the Rhodope Massif are found, shows that the HP metamorphism was developed in situ and cannot be explained by a subduction-exhumation mechanism as supposed by some authors [39, 41, 43].

Conclusions

The Avren serpentinite body is a part of the Rhodopian ophiolite association, which keeps a definite stratigraphic level in the metamorphic complex. The serpentinites were integrated in the continental crust by Precambrian obduction in suprasubduction zone;

- The eclogitization on the serpentinites represents in situ metamorphic crystallization in crustal conditions;
- Seismotectonic zones are geotribological zones of friction. They produce body waves, provoking deformation, destruction and melting of minerals and subsequent recrystallization into new rocks. These zones within the middle levels of the Earth's crust generate huge amount of energy, which is sufficient to ensure T/P conditions for HP/UHP eclogite mineralizations. They are spaces with local particular thermodynamic conditions in the Earth's crust. This causes an uneven distribution of temperature and pressure, which in this case are not controlled by geothermal gradient and confining pressure, related to depth;
- The banded texture of alternating layers of unchanged serpentinite with garnet lherzolites is interpreted as a result of the impact effect of paleoseismic wave interference. The waves inflict mobilization of particles in the lattice and form rhythmic zones of dilatation and compression. In serpentine, a mineral with layered structure and weak Van der Waals bonds, the crystal lattice is destroyed in the zone of dilatation and the mobilized particles form layers of melt. After termination of the impact energy the mobilized mass is crystallized in bands of highly thermobaric mineral aggregates;
- The eclogitization, observed as thin stripes or layers in the crust, is local HP/UHP mineralization in situ and does not require depth but just enough energy. The formation of the banded eclogite mineralization on the serpentinites reveals the energy connection between the paleoseismic, petrological and mineralogical processes of the metamorphism from the middle levels of the Earth`s crust.
- The triad movement - friction - seismic waves is a powerful energy source and thermodynamic factor in the Earth's crust, which connects destructive (deformation) and constructive (crystallization) processes in a common sequence.

The advances of geosciences related to HP/UHP metamorphic terranes is to better understand the significance of real geological relationships between the eclogite bodies and hosted rocks, the processes of rock`s deformation, the petrological and mineral phase transformation in the geotribological zones of friction due the impact of generated kinetic energy there. When researchers found that HP/UHP mineralizations are formed in situ, all interpretations of the involvement of a subduction-exhumation mechanism become meaningless and the solution is directed to mobile friction zones in the Earth`s crust.

The Precambrian metamorphic complexes reveal the complicated geological processes occurring in the past. To study them comprehensively it is necessary to apply interdisciplinary methods and knowledge of geophysics, tectonics, stratigraphy, tribology, petrology, mineralogy, solid state physics and inorganic chemistry and joint research by specialists from the relevant sciences.

Funding
This reseach reseived no external funding.

Conflict of Interes
The author declare no conflicts of interest.

Acknowledgment
The author is grateful to all colleagues with whom she has worked together on the geology of the Rhodope Massif over the past 70 years.

References

1. Chopin, C. (2003). Ultrahigh-pressure metamorphism: Tracing continental crust into the mantle. Earth and Planetary Science Letters, 212, 1–14.
2. Pilchin, A. (2005). The role of serpentinization in exhumation of high– to ultra-high-pressure metamorphic rocks. Earth and Planetary Science Letters, 237, 815–528.
3. Dobrzhinetskaya, L. (2012). Frontier of ultrahigh-pressure metamorphism: A review. Gondwana Research, 21, 207–223.
4. Hacker, B., & Gerya, T. V. (2013). Paradigms, new and old, for ultrahigh-pressure tectonism. Tectonophysics, 603, 426–436.
5. Escola, P. (1921). On the eclogites of Norway. Videnskabelige Meddelelser fra Dansk Naturhistorisk Forening, 8, 118.
6. Kozhoukharova, E. (2025). Geotribometamorphism in the paleoseismic zones of the Earth's crust. In A. I. Kanli (Ed.), Advances in Earthquake Research and Engineering, Chapter 7, pp. 189–20).
7. Kozhoukharova, E. (2008). Reconstruction of the primary stratigraphy and correlation of the Precambrian metamorphic complexes in the Rhodope Massif. Geologica Balcanica, 37(1–2), 1–32.
8. Kozhoukharova, E., & Kozhoukharov, D. (1962). Untersuchungen über die Gesteine und den Bauplan der Nordrhodopischen Antiklinale im Gebiet von Assenovgrad. Bulletin of the “Strashimir Dimitrov” Geological Institute, Bulgarian Academy of Sciences, 11, 125–162.
9. Boyanov, I., Mavrudchiev, B., & Vaptsarov, I. (1963). On the structural and formational features of part of the Eastern Rhodopes. Bulletin of the Geological Institute of the Bulgarian Academy of Sciences, 12, 125–186.
10. Kozhoukharova, E. (1972). Precambrian metamorphosed basic volcanics from the Central Rhodopes. Bulletin of the Geological Institute of the Bulgarian Academy of Sciences, Geochemistry, Mineralogy and Petrology Series, 21, 167–174.
11. Kozhoukharova, E. (1984). Origin and structural position of the serpentinized ultrabasic rocks from the Precambrian ophiolite association in the Rhodope Massif. Geologica Balcanica, 14(4), 9–36.
12. Kozhoukharova, E. (1980). Eclogites in the Precambrian from the Eastern Rhodope block. Comptes rendus de l'Académie bulgare des Sciences, 33(3), 375–378.
13. Dimitrova, E., & Belmustakova, H. (1982). Relics of eclogites in the crystalline complex of Ihtiman Sredna Gora mountains. Geologica Balcanica, 12(1), 115–120.
14. Kolcheva, K., Zhelyazkova-Panayotova, M., & Dobretsov, N. P. (1984). Fragments of an ancient ophiolite association in the region of Ardino town (Central Rhodope, Bulgaria). Comptes rendus de l'Académie bulgare des Sciences, 37(2), 187–190.
15. Liati, A. (1988). Amphibolitized eclogites in the Rhodope Crystalline Complex, near Xanthi (N. Greece). Neues Jahrbuch für Mineralogie, 1, 1–8.
16. Vergilov, V., Kozhoukharov, D., Boyanov, I., Mavrudchiev, B., & Kozhoukharova, E. (1963). Notes on the Pre-Paleozoic metamorphic complexes in the Rhodopian Massif. Bulletin of the Geological Institute of the Bulgarian Academy of Sciences, 12, 187–211.
17. Kozhoukharov, D. (1984). Lithostratigraphy of the Precambrian metamorphics from the Rhodope Supergroup in the Central Rhodopes. Geologica Balcanica, 14(1), 43–88.
18. Kozhoukharov, D. (1988). Precambrian in the Rhodope massif: Lithostratigraphy. In Zoubek, V. (Ed.), Precambrian in Younger Fold Belts Wiley & Sons, pp. 726–746.
19. Zagorchev, I. (2008). Amphibolite-facies metamorphic complexes in Bulgaria and Precambrian geodynamic controversies. Geologica Balcanica, 37(1–2), 33–46.
20. Kozhoukharova, E. (2004). The Precambrian Metamorphic Complex in the Rhodope Massif – A Unified Stratigraphic System. Journal of Agricultural, Earth and Environmental Sciences, 3(6), 1–9.
21. Ivanov, Ž., Moskovski, S., Kolcheva, K., Dimov, D., & Klain, L. (1984). Geological structure of the Central Rhodopes. I. Lithostratigraphic subdivision and features of the section of metamorphic rocks in the northern parts of Central Rhodopes. Geologica Balcanica, 14(1), 3–42.
22. Kozhoukharova, E. (2025). Ophiolite association in the Rhodope Massif as indicator of the paleogeographical setting. Journal of Geography and Cartography, 8(1), 8816. https://doi.org/10.24294/jgc8816
23. Deschamps, F., Godard, M., Guillot, S., & Hattori, K. (2013). Geochemistry of subduction zone serpentinites: A review. Lithos, 178, 96–127.
24. Kozhoukharova, E. (2019). Obducted serpentinites in the Rhodope Massif and their stratigraphic, paleotectonic, and metamorphic significance. Review of the Bulgarian Geological Society, 80(3), 72–74.
25. Gonzales-Jimenez, J. M., Locmelis, M., Belousova, E., Griffin, W. I., Gervilla, F., Kerestedjian, Th., O'Reilly, S.-Y., Pearson, N. J., & Sergeeva, I. (2014). Genesis and tectonic implications of podiform chromitites in the metamorphosed ultramafic massif of Dobromirtsi (Bulgaria). Gondwana Research, 27(2), 555–574. https://doi.org/10.1016/j.gr.2013.09.020
26. Arkadakskiy, S. V., Bohm, C., Heaman, L., Cherneva, Z., Stancheva, E., & Ovtcharova, M. (2003). Remnants of Neoproterozoic oceanic crust in the Central Rhodope metamorphic complex, Bulgaria. Geological Society of America, Vancouver Annual Meeting, 2003, Isotope Geology and Geochronology, GS3: 62.

27. Carrigan, C., Mukasa, S., Haydoutov, I., & Kolcheva, K. (2003). Ion microprobe U-Pb zircon ages of pre-Alpine rocks in the Balkan, Sredna Gora, and Rhodope terrains of Bulgaria: Constraints on Neoproterozoic and Variscan tectonic evolution. Journal of the Czech Geological Society, 48(1–2), 32–33.
28. von Quadt, A., Peytcheva, I., Sarov, S., & Liati, A. (2010). Late Cretaceous subduction and magmatism in the Rhodopes: Geochronological and isotope-geochemical evidence. Bulletin of the Geological Society, National Conference "Geosciences 2010", 13–14.
29. Burg, J. P., Klain, L., Ivanov, Ž., Ricou, R.-E., & Dimov, D. (1996). Crustal scale thrust complex in the Rhodope Massif: Evidence from structures and fabric. Terra Nova, 8, 6–15.
30. Burg, J.-P. (2012). Rhodope: From Mesozoic convergence to Cenozoic extension – A review of petrostructural data in the geochronological frame. Journal of Virtual Explorer, 39(1–4).
31. Ivanov, Ž. (1988). Aperçu général sur l'évolution géologique et structural du massif des Rhodopes dans le cadre des Balcanides. Bulletin de la Société Géologique de France, 8(4), 2, 227–240.
32. Bonev, N., Ovcharova-Schaltegger, M., Moritz, R., Marchev, P., & Ulianov, A. (2013). Peri-Gondwanan Ordovician crustal fragments in the high-grade basement of the Eastern Rhodope Massif, Bulgaria: Evidence from U–Pb LA–ICP–MS zircon geochronology and geochemistry. Geodinamica Acta. http://dx.doi.org/10.1080/09853111.2013.858942
33. Froitzheim, N., Jahn-Ave, S., Frei, D., Wainwright, A. N., Maas, R., Georgiev, N., Nagel, T. J., & Pleuger, J. (2014). Age and composition of meta-ophiolite from the Rhodope Middle Allochthon (Satovcha, Bulgaria): A test for the maximum-allochthony hypothesis of the Hellenides. https://doi.org/10.1002/2014TC003526
34. Kozhoukharova, E., Ichev, M., & Pristavova, S. (1993). Eclogites in the Precambrian of Verila Mountain. Comptes Rendus de l'Académie Bulgare des Sciences, 46(11), 69–72.
35. Machev, P., Borisova, B., & Hecht, L. (2006). Metaeclogites from the Sredna Gora terrain – Petrological features and P-T path of evolution. Proceedings of the National Conference "Geosciences 2006", Bulgarian Geological Society, Sofia, 185–188.
36. Gaggero, I., Buzzi, L., Haydoutov, I., & Cartesogno, L. (2008). Eclogite relics in the Variscan orogenic belts of Bulgaria (SE Europe). International Journal of Earth Sciences, 98, 1863–1877.
37. Zidarov, N., Nenova, P., & Dimov, V. (1995). Coesite in kyanite eclogite of Ograzden Mt., SW Bulgaria. Comptes Rendus de l'Académie Bulgare des Sciences, 48(11–12), 59–62.
38. Nenova, P., & Zidarov, N. (2008). Eclogites from Maleshevska Mountain, S.W. Bulgaria. In 80th Anniversary of Geology, Sofia University (pp. 109–114). Sofia University Press.
39. Collings, D., Savov, I., Maneiro, K., Baxter, E., Harvey, J., & Dimitrov, I. (2016). Late Cretaceous UHP metamorphism recorded in kyanite-garnet schists from the Central Rhodope Mountains, Bulgaria. Lithos, 165–181.
40. Kozhoukharova, E. (1996). Eclogitized layered serpentinites in the East Rhodope block. Comptes Rendus de l'Académie Bulgare des Sciences, 49(6), 69–71.
41. Mposkos, E. D., & Kostopoulos, D. K. (2001). Diamond, former coesite and supersilicic garnet in metasedimentary rocks from the Greek Rhodope: A new ultrahigh-pressure metamorphic province established. Earth and Planetary Science Letters, 192, 497–506.
42. Georgieva, M., Cherneva, Z., Hekimova, S., & Petrova, A. (2009). Petrology of marbles from the Arda tectonic unit, Central Rhodope, Bulgaria. Proceedings of the National Conference "Geosciences 2009", 43–44.
43. Petrik, L., Janak, M., Froitzheim, N., Georgiev, N., Yoshida, K., Sasinkova, V., Konecny, P., & Milovska, S. (2016). Triassic to Early Jurassic (c. 200 Ma) UHP metamorphism in the Central Rhodopes: Evidence from U–Pb–Th dating of monazite in diamond-bearing gneiss from Chepelare (Bulgaria). Journal of Metamorphic Geology. https://doi.org/10.1111/jmg.12181
44. Ji, S., Saruwatari, K., Mainprice, D., Wirth, R., Zhigin, X., & Bin, X. (2003). Microstructures, petrofabric and seismic properties of ultra-high-pressure eclogites from Sulu region, China: Implication for rheology of subducted continental crust and origin of mantle reflections. Tectonophysics, 370, 49–76.
45. Assenova, E., & Kozhoukharova, E. (2022). Friction and deformation at convergent contact in geotribological systems. Tribology and Materials, 1(3), 120–127.
46. Thiessen, P. A., Meyer, K., & Heinicke, G. (1966). Grundlagen der Tribochemie. Abhandlungen der Deutschen Akademie der Wissenschaften, KI Chemie, Geologie und Biologie, 1, 194 pp.
47. Kragelsky, I. V. (1978). Friction, wear and lubrication (Vol. 1). Moscow: Machinery. (in Russian)
48. Heinicke, G. (1984). Tribochemistry. Berlin: Akademie Verlag, 495 pp.
49. Hedba, M., & Chichinadze, A. V. (1989). Handbook in Tribotechnics. I. Theoretical Bases. Moscow: Mashinostroenie, 397 pp. (in Russian)
50. Tkáčová, K. (1989). Mechanical Activation of Minerals. Elsevier Science Publishing Company, 154 pp.
51. Chichinadze, A. V. (2001). Fundamentals of Tribology (Friction, Wear, Lubrication). Moscow: Mashinostroenie, 664 pp. (in Russian)
52. Enomoto, Y., Asuke, F., Zheng, Z., & Ishigaki, H. (2001). Hardened foliated fault gouge in the Nojima Fault zone at Hirabayashi: Evidence for earthquake lightning accompanying the 1995 Kobe Earthquake? The Island Arc, 10, 447–456.
53. Enomoto, Y. (2005). Geotribology of earthquakes. Journal of Japanese Tribology, 50(5), 513–521.
54. Shipton, Z. K., Evans, J. P., Aborcrombie, R. A., & Brodsky, E. (2006). The missing sinks: Slip location in fault damage zones and seismic energy budget. Geophysical Monograph Series, American Geophysical Union, 1–6.
55. Brantut, N., Passelègue, F. X., Deldicque, D., Rouzaud, J.-N., & Schubnel, A. (2016). Dynamic weakening and amorphization in serpentinite during laboratory earthquakes. Geology, 44(8), 607–610.
56. Evans, B. W., Hattory, K., & Baronnet, A. (2013). Serpentinite: What, why, where? Elements, 9, 99–106.

57. Spray, J. G. (2010). Frictional melting processes in planetary materials: From hypervelocity impact to earthquakes. Annual Review of Earth and Planetary Sciences, 38, 221–254.
58. Alekseev, A. S., Tsibulchik, G. M., Kovalevsky, V. V., & Belonosov, A. S. (2010). Elements of active geophysical monitoring: Theory. In Handbook of Geophysical Exploration: Seismic Exploration, 40, 55–71.