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SEISMOGENIC FRICTIONAL MELTING AND ITS ROLE IN THE REDISTRIBUTION OF MATTER IN THE METAMORPHIC COMPLEXES OF ZAVALLIA

Roman Minkevich, *Postgraduate Student of the Faculty of Geology*
Roman.Minkevych@lnu.edu.ua
https://orcid.org/0009-0000-0486-3557

Nataliia Bilyk, *Assistant Professor at the Department of Mineralogy, Petrography and Geochemistry named after Professor Orest Matkovskyi*
nataliya.bilyk@lnu.edu.ua
https://orcid.org/0000-0002-9684-195X

Leonid Skakun, *Candidate of Geological and Mineralogical Sciences, Associate Professor at the Department of Mineralogy, Petrography and Geochemistry named after Professor Orest Matkovskyi*
https://orcid.org/0000-0002-2338-6562

Kostiantyn Alferiev**,** *Student of the Faculty of Geology*
kostiantyn.alferiev@lnu.edu.ua
https://orcid.org/0009-0004-2910-1187

Ivan Franko National University of Lviv,
4, Hrushevskoho St., Lviv, Ukraine, 79005

Using the example of the Zavallivske graphite deposit (Ukrainian Shield), the role of palaeoseismic activity in the formation of hydrothermal systems and ore zones is examined. A marker of ancient earthquakes is pseudotachylites – black vitrified rocks, represented by slip films and thin veins. Pseudotachylites are products of frictional melting in fault zones. Their formation is accompanied by the localisation of thermal energy, rapid cooling and the formation of an amorphous glass-like substance, as confirmed by X-ray diffraction studies.

Microprobe analysis of the pseudotachylites revealed a high SiO_2 content (up to 73.84 wt. %) and significant variations in FeO (from 5.56 to 34.79 wt. %) and MgO (3.62–11.61 wt. %). Calculations of the oxides indicated the presence of water (up to 36 wt. %), which acted as a kind of flux and a melting point depression factor.

The source of water was likely the dehydration of minerals under conditions of rapid heating during seismic events. This is evidence of a close link between friction melting processes and the mobilisation of fluids in the fault zone. As a result, a local environment enriched with volatile components was formed. About 10 % of the volume of the studied rocks consists of fragments of primary rocks and minerals that either did not melt completely or were entrapped by the melt during formation.

Pseudotachylites formed at the transition boundary from plastic to brittle deformation, at depths of 10–12 km, corresponding to the conditions of the amphibolite facies of metamorphism. Mylonites formed below this boundary, and cataclastic rocks – above it. Friction melting processes were accompanied by the dehydration of the surrounding primary rocks, the formation of fluids and fracture systems. The fluids, in turn, facilitated the migration and redistribution of chemical elements. And the extensive fracture systems facilitated the circulation of hydrothermal solutions and the development of vein-type mineralisation.

Pseudotachylites are an important indicator of palaeoseismic activity and a trigger for hydrothermal processes. Hydrothermal fluids played a significant role in the formation of ore mineralisation at the Zavallivske deposit, particularly in the redistribution of material and the formation of graphite deposits.

Key words: pseudotachylites, friction melting, hydrothermal processes, fluid, graphite, fault zone, Zavallivske deposit, Ukrainian Shield.

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Statement of the problem. Paleoseismic activity is an important factor in the conditions governing the formation of ore zones. One of the indicators of ancient earthquakes is the presence of pseudotachylites in zones of disjunctive deformation. The specificity of the conditions for the formation of pseudotachylites lies in the fact that the process is accompanied by the dehydration of the surrounding rocks. This leads to a redistribution of matter in the contact zones. Analysis of these processes and their influence on the formation of areas with elevated concentrations of ore elements makes it possible to identify certain patterns in the formation of ore zones.

The Zavallivske graphite deposit in the Ukrainian Shield is a region of unique geological significance. The discovery of pseudotachylites here provides grounds for re-evaluating the role of hydrothermal fluids in the formation of graphite. The extensive system of fractures and their diverse mineral fillings indicate variability in both the chemical composition of the fluids and the physical conditions under which the mineral associations formed. Unfortunately, the pseudotachylites of the Ukrainian Shield have not yet been sufficiently studied, making it difficult to fully comprehend their influence on hydrothermal processes, which, in turn, shifts the focus of attention away from research into the fluid component of graphite genesis towards more conservative interpretations.

Review of research. It was not the first time that pseudotachylites had been discovered and studied within the granitic formations of the Vredefort crater in the Republic of South Africa. In particular, the British scientist S. J. Shand described veins of dense black rock in granites in 1916 and first used the term *pseudotachylite* [3]. In 1972, geophysicists and seismologists demonstrated the possibility of rock melting along fault planes and identified the conditions necessary for this [2]. Three years later, the New Zealand structural geologist R. Sibson directly linked pseudotachylites to zones of ancient seismic activity [4].

However, subsequent studies revealed the relatively limited distribution of these formations and the specificity of the conditions for their formation, namely: the limited distribution of pseudotachylites compared to earthquakes [5], anomalous pressure and temperature readings, and the localisation of seismic energy within a narrow layer (often < 2 mm). There is also the problem of preserving samples and their interpretation, as such formations are often not given sufficient attention and are classified as basalts.

In 2021, the journal «Geochemistry, Geophysics, Geosystems» published the findings of a large group of scientists who studied Chilean pseudotachylites and linked their formation to hydrothermal activity [1].

The research purpose of our work is to investigate the influence of the region’s seismic activity on hydrothermal activity and, on this basis, to identify the link between the redistribution of matter and the formation of pseudotachylites.

One of the world’s largest, and simultaneously the largest in Ukraine and Europe, graphite ore deposit of the same name is located in the vicinity of the village of Zavallia (Holovanivskyi

District, Kirovohrad Oblast) (Fig. 1). The first studies and development of graphite began here around 100 years ago. Currently, the deposit's production capacity stands at around 30,000 tonnes of graphite per year. The deposit is mined using open-pit methods, and the ore is enriched using the flotation method. Zavallia graphite is high-quality, flaky graphite, with flake sizes ranging from 2 to 4 mm. An associated mineral is an abrasive substance, namely garnet.

The deposit consists of a complex of Precambrian metamorphic rocks dating back approximately 2.5 billion years, which belong to the Khashchuvato-Zavallivska Group of the Bug Series within the Ukrainian Shield. It is represented by a fault zone between carbonate rocks in the southern part (mainly calciphyres) and silicate rocks (predominantly enderbites) in the northern part. Between them lies a sub-lateral zone of graphite-garnet and graphite-pyroxene schists and skarns [6]. Calciphyres, skarnoids, amphibolites, quartzites, magnesian skarns, migmatized granites and granitic pegmatites are also present.

The rocks of the deposit have undergone repeated deformations. The first phase consisted of deformations under conditions of the granulite facies of metamorphism at depths of over 20 km. This was followed by a phase of deformation under amphibolite facies conditions at a depth of 10–12 km. This phase is characterised by a transition from mylonites to cataclastic rocks, and it is with this phase that the formation of pseudotachylites is associated.

Fig. 1. Quarry at the Zavallivske graphite deposit

During field studies at the Zavallivskyi quarry and its surroundings, numerous samples of fractured rocks of various compositions were collected. Among them were samples with thin (several millimetres) black films with a vitreous lustre (Fig. 2).

The material from the selected samples was analysed using a range of methods. X-ray studies were carried out in the X-ray structural analysis laboratory of the Faculty of Geology at Ivan Franko National University of Lviv (analyst A. Dvorianskyi, DRON-3 diffractometer, CuK_α -radiation, U = 40 kV, I = 25 mA, recording speed – 1 degree/min). Polished sections were prepared for electron probe microanalysis and scanning electron microscopy. Microanalytical studies of the sections were carried out in the Laboratory of Physics and Technology of Nanostructures at the Department of Solid-State Physics, Faculty of Physics, Ivan Franko National University of Lviv (analyst R. Serkiz) using a REMMA-102-02 scanning electron microscope (Sumy, Ukraine), equipped with an EDAR energy-dispersive analyser.

Fig. 2. A block of fractured glassy rock

The diffractograms obtained during X-ray analysis of the selected samples clearly show the absence of peaks. This indicates the amorphous nature of the substance and provides grounds for interpreting it as glass.

Table 1 presents the results of the chemical analysis of pseudotachylite glass. As can be seen from the table, pseudotachylite glass may contain a relatively high proportion of silica – 33.60–73.84 wt. %. There are significant fluctuations in the content of iron and magnesium oxides, and in some samples (where SiO_2 is comparatively lower) the content of these components is quite high: FeO – from 5.56 to 34.79, MgO – from 3.62 to 11.61 wt. %. Recalculations of the analysis results revealed a fairly significant water content in the studied formations – from 12.53 to 36.71 wt. %.

Fragments of primary minerals have been identified in the pseudotachylite samples; these either did not melt completely or were entrapped by the melt during formation. Such fragments account for approximately 10 %. They are predominantly garnet (Fig. 3), as well as biotite, hornblende and pyroxenes.

Table 1

Results of chemical analysis of pseudotachylite glass, wt. %

Components	Sample and analysis number					
	Zv–Ar2–1	Zv–Ar2–3		Zv–Pth		
	12	6	15	1	2	3
SiO_2	33.60	64.75	66.29	42.04	37.78	38.10
TiO_2	0.04	0.12	0.05	0.22	0.11	0.04
Al_2O_3	2.52	0.27	0.17	1.46	1.14	1.29
Cr_2O_3	0.33	N. d.*	N. d.	N. d.	N. d.	N. d.
FeO	18.03	6.55	8.67	34.79	31.32	32.42
MnO	0.43	0.00	0.19	1.07	1.16	1.22
MgO	6.19	5.45	11.61	5.42	4.96	4.50
CaO	1.69	0.04	0.00	0.85	0.86	0.64
Na_2O	0.47	0.00	0.27	0.35	0.35	0.45
K_2O	0.00	0.22	0.22	0.15	0.11	0.30
Total	63.30	77.40	87.47	86.35	77.79	78.96

Components	Sample and analysis number						
	Zv–Pth						Zv–Ar2–5
	5	8	11	12	14	17	11
SiO_2	42.21	38.60	42.40	39.92	39.55	34.20	73.84
TiO_2	0.00	0.05	0.07	0.07	0.00	0.00	N. d.
Al_2O_3	2.35	2.44	1.86	1.53	3.08	0.45	0.02
Cr_2O_3	N. d.	N. d.	N. d.	N. d.	0.00	0.64	N. d.
FeO	31.49	30.92	30.25	34.18	29.99	29.90	5.56
MnO	1.06	0.82	0.99	0.98	0.99	1.15	0.19
MgO	6.58	5.28	7.25	5.65	5.81	3.62	5.94
CaO	0.34	0.13	0.70	0.31	1.38	0.41	0.00
Na_2O	0.39	0.29	0.58	0.19	0.69	0.00	0.35
K_2O	0.11	0.35	0.00	0.18	0.00	0.06	0.43
Total	84.53	78.88	84.10	83.01	81.49	70.43	86.33

* N. d. – not determined.

An analysis of previous studies and our results suggest the following mechanism for the formation of pseudotachylites. As a result of seismic activity, blocks of primary rocks rapidly shifted relative to one another. This occurred at a depth of approximately 10–12 km, which is typical for the hypocentres of major earthquakes. It is precisely this depth, according to the geothermal gradient, that corresponds to the onset of quartz plasticity and the transition from plastic to brittle deformation. Mylonites form below this threshold, and cataclasites – above it, with pseudotachylites serving as a marker of this transition.

As a result of the rock's extremely rapid displacement, the blocks are subjected to crushing and grinding. This is accompanied by the release of an enormous amount of energy. The concentration of energy within tiny cracks prevents the heat from dissipating quickly, leading to the melting of the material that has been ground to dust. As soon as the seismic displacement ceases, heat generation stops. This leads to the melt cooling very rapidly, resulting in the formation of an amorphous rock. The presence of a significant amount of water in the system contributes to a reduction in the melting point – from 1,700 to 900 °C.

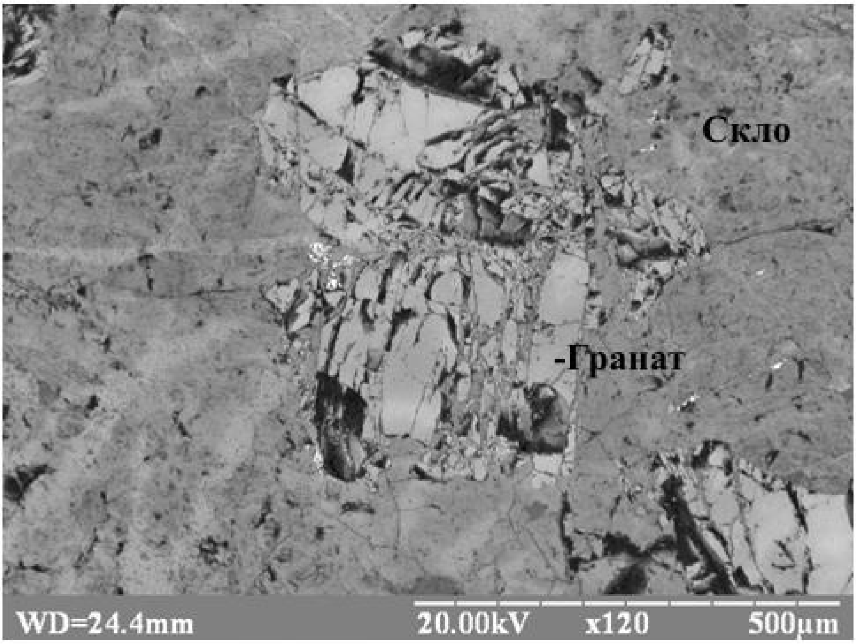

Fig. 3. A fragment of a garnet crystal in pseudotachylite glass

Conclusions and prospects for further research. Pseudotachylites serve as a marker for the uplift of rock complexes and the transition from plastic to brittle deformation. This facilitated the formation of numerous fracture systems necessary for the movement of hydrothermal fluids. Furthermore, the seismic thermal shock contributed to the dehydration of surrounding minerals. The resulting fluids leached certain chemical elements from the host rocks, transported them through the fracture systems and redeposited them as hydrothermal vein associations. This is evidenced by the large number of veins varying in age and mineral composition.

Thus, at a depth of about 10–12 km, during the transition from mylonitization to cataclasis, frictional palaeoseismic melting occurred, resulting in the formation of pseudotachylites. The transition to the zone of brittle deformation and the formation of pseudotachylites contributed to the formation of fracture systems and the «initiation» of hydrothermal processes.

One of the main agents of the hydrothermal fluids was carbon, as evidenced by the presence of numerous veins filled with carbonates in the rocks. The active involvement of carbon in the hydrothermal system of the Zavallia ore zone is the factor that compels scientists to pay greater attention to the vein mineralisation of the region, as well as to investigate the influence of hydrothermal systems on the formation of deposits in one of the world's largest graphite fields.

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СЕЙСМОГЕННЕ ФРИКЦІЙНЕ ПЛАВЛЕННЯ ТА ЙОГО РОЛЬ У ПЕРЕРОЗПОДІЛІ РЕЧОВИНИ В МЕТАМОРФІЧНИХ КОМПЛЕКСАХ ЗАВАЛЛЯ

Роман Мінькевич, Наталія Білик, Леонід Скакун, Костянтин Алфер'єв
Roman.Minkevych@lnu.edu.ua

Львівський національний університет імені Івана Франка,
вул. М. Грушевського, 4, Львів, Україна, 79005

На прикладі Заваллівського родовища графіту (Український щит) розглянуто роль палеосейсмічної активності у формуванні гідротермальних систем і рудних зон. Маркером давніх землетрусів є псевдотахіліти – чорні склуваті породі, представлені плівками ковзання та прожилками невеликої потужності. Псевдотахіліти – продукти фрикційного плавлення в зонах розломів. Їх утворення супроводжується локалізацією теплової енергії, швидким охолодженням і формуванням аморфної склоподібної речовини, що підтверджено рентгеноструктурними дослідженнями.

Мікрозондовим аналізом у псевдотахілітах визначено високий вміст SiO_2 (до 73,84 мас. %) та значні коливання FeO (від 5,56 до 34,79 мас. %) і MgO (3,62–11,61 мас. %). Перерахунки оксидів засвідчили наявність води (до 36 мас. %), яка була своєрідним флюсом і певним чинником зниження температури плавлення. Джерелом води, імовірно, були процеси дегідратації мінералів за умов швидкого нагрівання під час сейсмічних подій. Це є доказом тісного зв'язку між процесами фрикційного плавлення та мобілізацією флюїдів у розломній зоні. Унаслідок цього формувалось локальне середовище, збагачене леткими компонентами. Близько 10 % об'єму досліджуваних порід представлено уламками первинних порід і мінералів, які або остаточно не розплавились, або ж були захоплені розплавом у процесі утворення.

Псевдотахіліти сформувались на межі переходу від пластичних деформацій до крихких, в інтервалі глибин 10–12 км, що відповідає умовам амфіболітової фації метаморфізму. Нижче від цієї межі утворювались мілоніти, вище – катаклазити. Процеси фрикційного плавлення супроводжувались дегідратацією навколишніх первинних порід, утворенням флюїдів і систем тріщинуватості. Флюїди, своєю чергою, забезпечували міграцію й перерозподіл хімічних елементів. А розгалужені системи тріщин сприяли циркуляції гідротермальних розчинів і розвитку прожилкової мінералізації.

Псевдотахіліти – важливий маркер палеосейсмічної активності та тригер гідротермальних процесів. А гідротермальні розчини відігравали суттєву роль у формуванні рудної мінералізації Заваллівського родовища, зокрема, у перерозподілі речовини та утворенні графітових покладів.

Ключові слова: псевдотахіліти, фрикційне плавлення, гідротермальні процеси, флюїд, графіт, розломна зона, Заваллівське родовище, Український щит.

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