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The Telšiai and Drūkšiai-Polotsk Deformation Zones: petrography and U/Pb geochronology

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VILNIAUS UNIVERSITETAS

GAMTOS TYRIMŲ CENTRO
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Telšių ir Drūkšių –Polocko deformacijos zonos: petrografija ir U/Pb geochronologija

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INTRODUCTION

Relevance of work. The Telšiai deformation zone (TDZ) and the Drūkšiai-Polotsk deformation zone (DPDZ) in the crystalline basement of Lithuania are important structures, belonging to the wide Polotsk-Kurzeme fault belt in the western part of the East European Craton (EEC). Petrographic and microstructural features of their rocks, pressure-temperature conditions and geochronological data help to unravel tectonic processes and timing of the TDZ and DPDZ development. The TDZ and DPDZ were reactivated several times in the Proterozoic and Phanerozoic times. These movements can be capable to affect the formation of natural resources like hydrocarbons and geothermal energy, but also cause hazards.

Thus, the understanding of the deformation evolution of these fault zones is important both from the scientific and practical points of view. Their correlation with similar deformation zones of the Baltic Shield in Sweden and Belarus provides new insights into the regional structure and evolution of the East European Craton around the Baltic Sea.

The object and aim of the research. The main **objects** are rocks of crystalline basement within the Telšiai and Drūkšiai-Polotsk deformation zones in northern Lithuania. The principal **aim** is to constrain the development history of the TDZ and DPDZ using petrographic, microstructural, geothermobarometry and geochronological data.

Tasks:

-to characterize and classify the TDZ and DPDZ rocks petrographically;

-to characterize microstructures, deformation and metamorphism of the TDZ and DPDZ rocks;

-to estimate pressure and temperature conditions during deformation (mylonitization) of the TDZ rocks;

-to obtain magmatic, metamorphic and deformation ages of the rocks composing the DPDZ and TDZ.

Originality of work:

- For the first time, petrographical-microstructural classification of the TDZ and DPDZ rocks has been performed and their deformation mechanism is proposed.

- For the first time, the age of the magmatic activity, metamorphism and deformation within theTDZ and DPDZ has been determined employing SHRIMP and TIMS techiques for the U/Pb isotope zircon and titanite datings, respectively.
- For the first time, the Early Carboniferous (350 Ma) and Mesoproterozoic (1622 and 1580 Ma) magmatic granitoids have been found in the TDZ and DPDZ using the SHRIMP technique for U/Pb isotope zircon dating.

Defended highlights:

1. The Telšiai and Drūkšiai-Polotsk Deformation Zones are characterized by mylonites of various degrees of ductile deformation (protomylonite, mesomylonite and ultramylonite) as well as breccias and pseudotachylites formed under brittle conditions.
2. The Telšiai Deformation Zone was developed along with repeated ductile deformation during phases D1 (<1622 Ma) and D2 (ca. 1450 Ma). Brittle deformations (phases D3 and D4) were manifested mostly in the Phanerozoic.
3. The major ductile deformation within the Drūkšiai-Polotsk Deformation Zone (phase D1) took place at 1534 Ma and continued at 1511-1460 Ma (phase D2), whereas brittle deformation occurred along phase D3 in the Late Proterozoic and in the Phanerozoic.
4. The regional Polotsk-Kurzeme fault belt in the western part of the East European Craton, to which the Telšiai and Drūkšiai-Polotsk Deformation Zones belong, thus began forming in the Mesoproterozoic between 1622 and 1534 Ma, recurrently activated from ca. 1460 Ma up to the present.

Practical use. The TDZ is a site of natural resources particularly of hydrocarbons and geothermal energy, which are strategically important for the Lithuanian economy. The geological knowledge of the DPDZ is important for the closure of the Ignalina Nuclear Power Plant, for the long-lived waste radioactive disposal and for the choice of a new building place.

Approbation of results. Results were published in two articles of ISI Master Journal List and ISI Web of Science journals. The results were presented at the 33rd International Geological Congress (IGC) Oslo, Norway (2008) – and at the 12 international conferences: Goldschmidt, Praque, Czech Republic (2011); 20th General Meeting of International Mineralogical Association (IMA) Budapest, Hungary (2010); European Geosciences Union General Assembly, Vienna, Austria (2010); 53rd Scientific

Conference for Young Students of Physics and Natural Sciences, Vilnius, Lithuania (2010); SIMS Short Courses on Microstructures 2010: Microstructures and Physico-Chemical Properties of Earth and Planetary Materials, Verbania, Italia (2010); MAPT (Micro-analysis, processes, time), Edinburgh, UK (2009); European Geosciences Union General Assembly, Vienna, Austria (2006); the Nordic Geological Winter Meetings: 26th Uppsala, Sweden (2004); 27th Oulu, Finland, (2006); 28th Aalborg, Denmark (2008); 29th Oslo, Norway (2010).

Structure of the thesis. The thesis consists of the Introduction, Explanation of terms, 4 chapters, Conclusions and a List of references. Overall, there are 130 pages of the text, 40 figures and 12 tables.

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1. THE GEOLOGICAL OUTLINES OF THE CRYSTALLINE BASEMENT IN LITHUANIA AND THE TELŠIAI AND DRŪKŠIAI DEFORMATION ZONES

1.1. Geology of the crystalline basement in Lithuania

The crystalline basement of Lithuania represents a part of the western East European Craton (EEC). The crust in Lithuania was formed between 1.9 and 1.8 Ga along with the amalgamation of the EEC and is subdivided into several tectonic domains (Fig.1). They have different structural and geophysical patterns, crustal composition and evolution. The major domains are the West Lithuanian Granulite Domain (WLGD) and East Lithuanian Domain (ELD), which are adjoined along the Mid-Lithuanian Suture Zone (MLSZ), and partly the Belarus-Podlasie-Granulite Belt (BPGB) in southeastern Lithuania (Skridlaite and Motuza, 2001). The Paleoproterozoic crust in Lithuania is completely overlain by the Phanerozoic sedimentary cover ranges from 200 m in the east to 2300 m in the west. It can be studied only by means of drilling and geophysics. Understanding of the structure and tectonic evolution of the lithosphere in Lithuania has been considerably improved due to seismic profiling: Sovetsk–Kohtla–Järve (Ankudinov et al. 1994), *POLONAISE* and EUROBRIDGE (Yliniemi et al. 2001, Czuba et al. 2002; Bogdanova et al., 2006, and other).

Several E-W-striking, crustal-scale deformation zones (e.g. the Telšiai and the Drūkšiai-Polotsk deformation zones of this study) cut sharply the mostly NS- and NW-trending Palaeoproterozoic structural pattern and indicate some lateral displacements (Fig.1). The narrow Akmenė deformation zone is identified to the north of the TDZ (ADZ, Čechanavičius et al., 1974; Stripeika, 1990; Apirubytė, 1974; Suveizdis, 2003; Motuza, 2004). A negative magnetic anomaly lineament corresponds to the Šilutė deformation zone (ŠDZ, Suveizdis, 1978, 2003; Motuza, 2004) to the south of the TDZ and coincides with the Nieman-Polotsk of the Polotsk-Kurzeme fault belt (Fig. 1, inset). There the southernmost Prieglius deformation zone is also near Kaliningrad (Pačėsa et al., 2005). According to the available geophysical and geological data, we assume that the E-W trending network of deformation zones takes a wide place for more than 100 km in the WLGD. This continues all the way to the east where the DPDZ occurs.

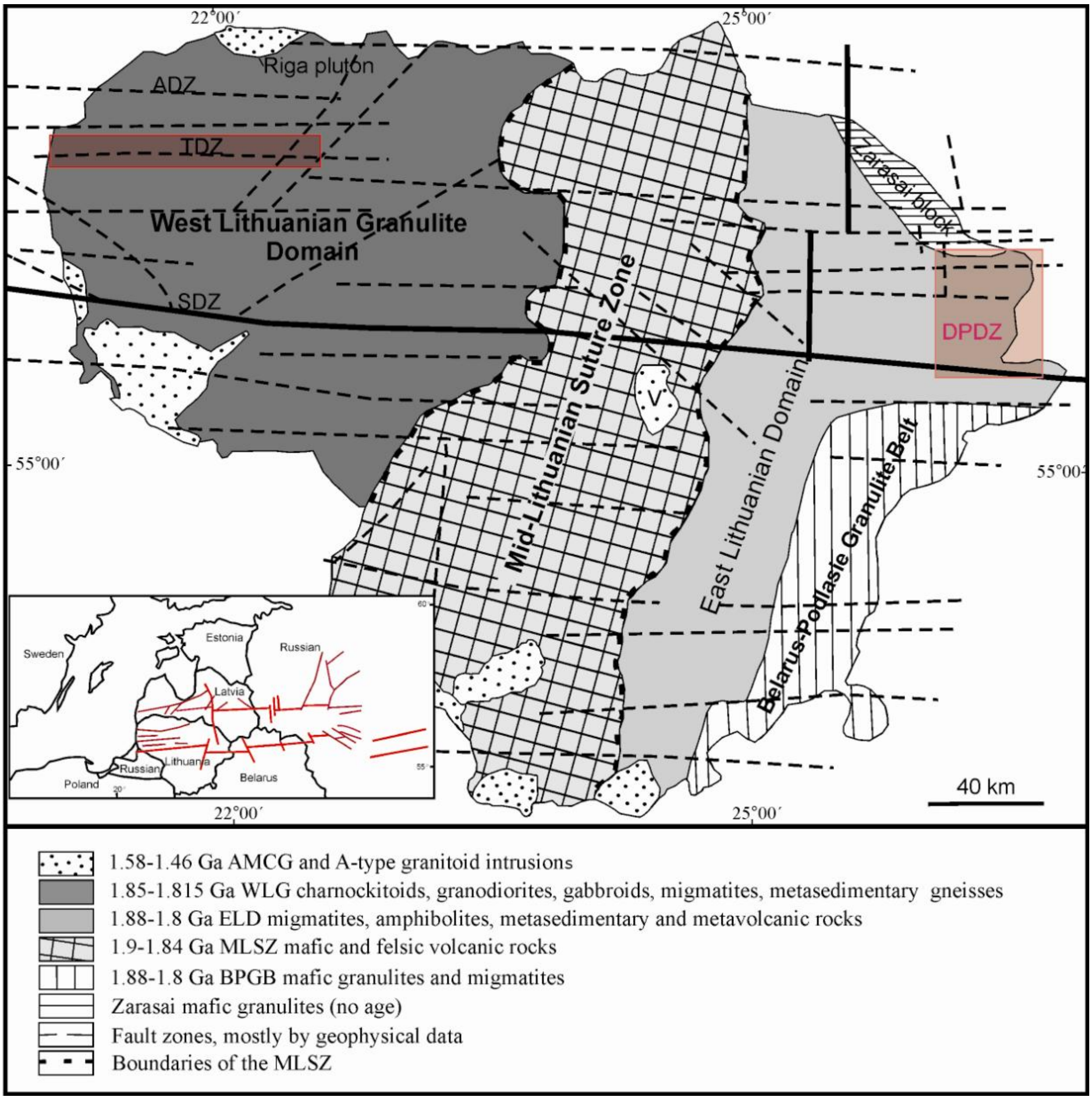


Fig. 1. Major tectonic subdivisions of the Precambrian basement in Lithuania (modified after Motuza, 2004). The letters are: ADZ – Akmenė Deformation Zone; DPDZ – Drūkšiai-Polotsk Deformation Zone; SDZ – Šilutė Deformation Zone, TSZ – Telšiai Deformation Zone; V – Vepriai gabbro intrusion. The red squares show the study areas. The sketch in the left indicates the position the Polotsk-Kurzeme fault belt (Garetsky et al., 2002). Its bounding Nieman-Polotsk fault zone corresponds to the SDZ and the southern boundary of the DPDZ fault zone in the present study.

The wide Polotsk-Kurzeme fault belt (Garetsky et al., 2001, 2004) apparently overlaps these deformation zones and was repeatedly activated until the present time. It is bounded by sublatitudional Nieman-Polotsk fault in the south and Liepaya-Lokno one in the north and extends approximately 800 km being 120-160 km wide. The Polotsk-Kurzeme fault belt is considered as extension structure formed simultaneously with the other Mesoproterozoic (Riphean) rifts of the EEC (Garetsky et al., 2001).

The studied TDZ and DPDZ are important structures of the crystalline basement in Lithuania within the Polotsk-Kurzeme fault belt (Fig.1) and characterize its deformational history.

1.2. Geological features of the Telšiai and Drūkšiai-Polotsk deformation zones

The Telšiai Deformation Zone (TDZ), a Precambrian ductile shear zone occurs within the western part the Polotsk-Kurzeme fault belt in Lithuania, transecting the northern WLGD in E-W direction. It is approximately 15-20 km wide as mirrored by a belt of linear gravity and magnetic lows. The TDZ rocks are mostly charnockitoids, granitoids and metapelites deformed to various degrees. The petrographic analysis of about 40 drill cores shows that the TDZ as the crystalline basement structure, can be traced to Palanga city at the Baltic Sea shore and continues to the east to the Tryškiai village. However, there are not enough wells to identify the eastern continuation of the TDZ. By gravity and magnetic anomaly data it is not clear whether the TDZ turns on to the northeast, as well as the Telšiai fault in the sedimentary cover, or continues to the southwest joining to other EW- trending deformation zones in eastern Lithuania. The northern boundary of the TDZ is indicated by the deformed charnockitoids, which are found in Tūbausiai-1 (Motuza, 2004), Vydmantai-1 (Skridlaite and Motuza, 2001) and Vydmantai-2 wells, and its southern boundary is marked by weakly deformed rocks in the drill cores of Žutautai, Mikoliškės and Kuliai wells.

The Drūkšiai-Polotsk deformation zone (DPDZ) transects the East Lithuanian Domain (ELD) in eastern Lithuania close to the Belarus border. It is 35-40 km wide and comprises two subparallel E-W trending belts, which are marked well by linear low gravity and magnetic anomalies. According to the gravity field modelling, the DPDZ can penetrate the crust to the depth of 20 km (Šliaupa and Popov, 1998). The crystalline rocks within the DPDZ are granitoids and mafic rocks such as amphibolites and metagabbros, also some migmatites. Because of ductile shearing at an early stage, weakly deformed rocks, mesomylonites and ultramylonites were produced along the DPDZ, while tectonic breccias and pseudotachylites were formed by later brittle deformation.

2. MATERIALS AND METHODS

The studies of the Lithuanian deformation zones is complicated because the crystalline basement is covered by sedimentary cover and there is no azimutal location of drill cores known only in few wells in southern Lithuania.

Mesoscopic examinations of the drill core materials (totally 42 drill cores) have been carried out at the Lithuanian Geology Museum in Vievis. I have examined of the TDZ rocks from the following drill cores: Eitučiai–1; Genčiai–2, 3, 4, 5, 6, 7, 8, 10, 11; Girkaliai–1, 2, 3; Kretinga–1, 2, 3, 4; Kuliai–1; Mamiai–1; Mikoliškės–1; Nausodis–2, 3, 5; Pabalvė–1; Tryškiai–73, 74; Toliai–1, 2; Vėlaičiai–1, 2, 3; Vydmantai–1, 2; Žutautai–1. The rocks from the DPDZ were studied from 8 drill cores: Drūkšiai–324, Kazimirovo–6, Novikai–1, Schedai–3, Stankovičiai–4, Šaškai–2, Tverečius–336 and Visaginas–5. Microscopical analyses have been performed using optical microscope at Vilnius University and Lund University. 775 thin sections from the TDZ and 70 from the DPDZ were studied. Polished thin sections were analyzed at the electron microprobe laboratory of the Department of Earth and Ecosystem Sciences, Lund University, Sweden where a Hitachi S-3400 with backscattered detector and *INCA* microanalysis system has been used. Pressure (P) and temperature (T) parameters of metamorphism have been calculated using "Thermobarometry" Program by Frank S. Spear and Matthew J. Kohn (2001) for the following TDZ drill cores: Girkaliai-2, Girkaliai-3, Tryškiai-73 and Vydmantai-2.

U/Pb isotope geochronology has been carried out on zircon using the Sensitive High Resolution Ion Microprobe (SHRIMP) at the Korean Basic Science Institute (KBSI), Ochang, South Korea and on titanite using the Thermal Ionisation Mass Spectrometry (TIMS) technique at the Institute of Precambrian Geology and Geochronology (IPGG), St. Petersburg, Russian in cooperation with E. B. Salnikova.

3. PETROGRAPHY AND DEVELOPMENT OF THE TELŠIAI AND DRŪKŠIAI-POLOTSK DEFORMATION ZONES

In regard to deformation shear zones are subdivided into major types: brittle, brittle-ductile and ductile (Van der Pluijm, Marshak, 2004). Mylonites, typical rocks of ductilly deformed crust, are strongly foliated rocks of which original textures have been modified with accompanying reduction in grain size. A well developed foliation of rock defined by elongate minerals such as quartz ribbons and porphyroclasts or layers in a fine grained matrix are common feature in mylonites. The formation of mylonites occurs in zones of high strain deeper than 15 km in the crust and in the upper mantle. Zones of mylonitization are located along major faults, and can vary from milimetric scale to several kilometeres in wide. Thus, mylonitic rocks are reliable indicators of ductile deformation zones. In the present study, mylonites are classified according to the percentage of recrystallized matrix as compared to porphyroclasts (Passchier and Trouw, 2005): protomylonites (10-50% matrix), mylonites (or mesomylonites, 50-90% matrix) and ultramylonites (over 90% matrix). By appearance, mylonites can resemble migmatites such as in the DPDZ and are difficult to be recognized. In the brittle fault zone of the upper crust, above the ductile shear zone, the brittle fault rocks such as cataclasites and breccias are formed by fracturing. In the transition brittle-ductile shear zone pseudotachylites can be formed by local melting of host rocks along a fault in response to earthquakes.

3.1 THE TELŠIAI DEFORMATION ZONE

3.1.1. Petrological-microstructural classification of deformed rocks in the Telšiai deformation zone (northwestern Lithuania)

Rocks of the West Lithuanian Granulite Domain within the Telšiai deformation zone (TDZ) have experienced polymetamorphism and multiple deformations under metamorphic conditions reaching the upper amphibolite- and granulite facies. The temporal and spatial relationships of the TDZ rocks are poorly constrained because the crystalline basement is entirely overlaid by the Phanerozoic sedimentary cover. The studied rocks according to their protolith compositions are subdivided into three groups: *charnockitoids* (weakly deformed, protomylonites, mesomylonites and ultramylonites), *granitoids* (weakly deformed, mesomylonites) and *metapelitic rocks* (ultramylonites).

Charnockitoids: weakly deformed, protomylonites, mesomylonites and ultramylonites

The crystalline basement in the northwestern part of the WLGD contains synorogenic charnockitoids, granitic intrusions and migmatites (Motuza, 2004). The charnockitoids according to mineralogical composition are subdivided to various types: charnockite, enderbite, opdalite, mangerite and jotunite (Motuza et al., 2008). Postorogenic intrusions are mainly composed by pyroxene granodiorite and opdalite (Motuza, 2004). In this work, the charnockitoids are grouped by degree of their deformation into *weakly deformed, protomylonites, mesomylonites* and *ultramylonites.*

The weakly deformed charnokitoids are present in the Kuliai-1, Žutautai-1, Vydmantai-1 and -2, Mikoliškės-1 (Fig.2. A and E) and Toliai-2 drill cores. They are usually grey medium-to-coarse grained magmatic rocks composed by plagioclase (An_{29-50}, 30%), quartz (25%), K-feldspar (7-10%), hypersthene (10-15%), biotite (10-15%) and garnet (almandine, 10-20%). Accessory minerals are magnetite, apatite, ilmenite, zircon, monazite and hercynite. These rocks show a little evidence of deformation. Large plagioclase grains (2.4-3 mm) are usually subhedral with polysynthetic twins, but sometimes recrystallized at the margins to 0.1-0.4 mm grains. Quartz forms large grains (2-2.4 mm) with undulose extinction and lobate boundaries. Large garnet contains numerous symplectites of biotite, magnetite and quartz (Fig.3. G). Also garnet corona textures are well visible around magnetite. Biotite is of two generations: 1) reddish-brown biotite looks as spots with irregular bounadries (Fig.3. J), and 2) green-brown biotite has flake shape. Large crystals of hypersthene (Fig.3. J) commonly include zircon. Also small grains of metamorphic hypersthene are visible as a late generation. Zircon was dated by U/Pb isotope method.

The charnockitic protomylonites have coarse grains within <50% fine grained matrix. They contain narrow zones of fine-grained ultramylonites. The protomylonites were discovered in 15 drill cores from these areas: Eitučiai, Toliai, Genčiai, Kretinga, Mamiai, Nausodis, Vėlaičiai and Vydmantai. The charnockitoid protomylonites consist

Fig. 2. Macroscopic classification of the investigated rocks within the TDZ: **Weakly deformed rocks:** A) Charnockitoid (Mikoliškės-1); B) Pegmatite (Genčiai-6); C) Fine grained granite (Genčiai-6); **Mylonites:** D) The contact of charnockitic mylonite with weakly deformed fine grained granite (Genčiai-6). Black arrow shows a top of drill core; E) The contact of weakly deformed and mylonitised charnokitoid(Mikoliškės-1); F) Augen mylonite of charnockitoid (Kretinga-4); G) Augen mylonite of charnockitoid composition with boudinaged veins of granite composition (Kretinga-1); H) Coarse grained granitic mylonite (Genčiai-6); I) The contact of a mylonitised charnockitoid with coarse-grained granite (Genčiai-6). Black arrow shows a top of drill core; J) Mylonite of charnockitoid with ribbon structure (Nausodis-3); K) Metapelitic ultramylonite (Girkaliai-2); **Cataclasites and pseudotachylite**s: L) Breccia with pseudotachylite in charnockitoid (Kretinga-3); M) Pegmatite with pseudotachylite (Girkaliai-2); N) Cataclased charnockitoid (Genčiai-11); O) The brecciated contact of the charnockitoid with the Cambrian sandstone (Genčiai-3). The diameter of drill cores is 7.8 cm.

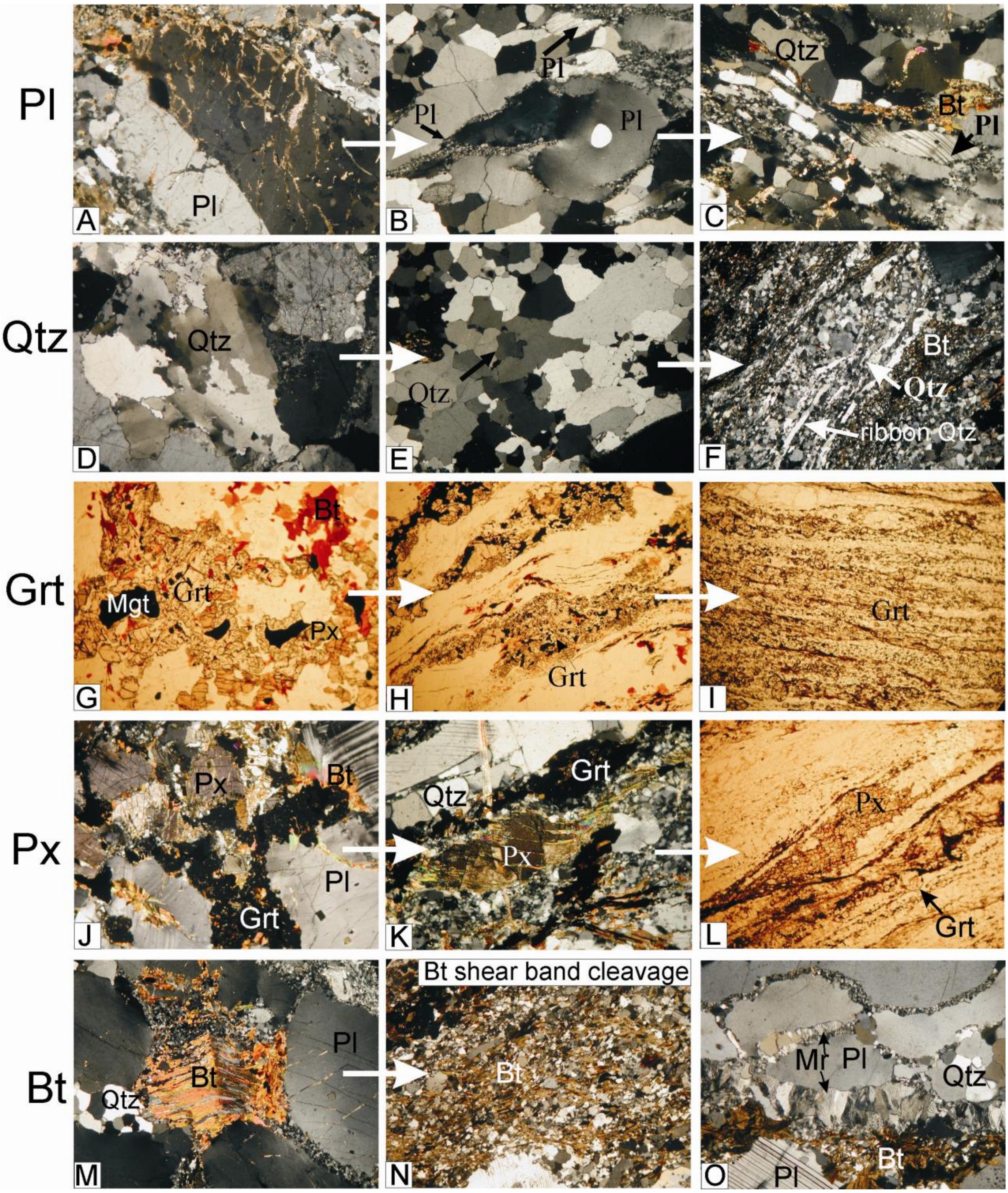


Fig. 3. Microtextures of the investigated rocks from the TDZ demonstrating different degrees of ductile deformation: A) Relict of plagioclase with simple twin showing magmatic origin of charnockitoid (Genčiai-10), CPL; B) Plagioclase with undulose extinction and rotation in the charnockitic mesomylonite (Nausodis-5), CPL; C) Strongly elongated plagioclase (in the centre) in the charnockitic mesomylonite (Nausodis-2), CPL; D) Elongated subgrains of quartz in a deformed charnockitoid (Mamiai-1), CPL; E) Quartz with irregular boundaries formed by grain-boundary migration recrystallization in the charnockitic mesomylonite (Genčiai-4), CPL; F) Near-completely recrystallized plagioclase to new grains in the charnockitic ultramylonite (Girkaliai-3). The mylonitic appearance is defined clearly by the ribbon quartz grains, CPL; G) Large garnet with magnetite and biotite inclusions in the weakly deformed charnockitoid (Eitučiai-1), PPL; H) Large garnet partly recrystallized to small fragments along mylonitic foliation in the charnockitic mesomylonite (Nausodis-2), PPL; I) Completely recrystallized garnet to new grains in the charnockitic ultramylonite (Girkaliai-3), PPL; J) Weakly deformed charnockitoid composed of plagioclase, K-feldspar, pyroxene, biotite and garnet (Vydmantai-1), CPL; K) The asymmetry of the pyroxene

grains shows sinistral shear sense, which implies that this grain rotated in the charnockitic mesomylonite (Nausodis-2), CPL; L) Orthopyroxene recrystallized to new small pyroxenes in the charnockitic ultramylonite (Girkaliai-3), PPL; M) Kinked crystal of biotite that rim has been partly neocrystallized to much smaller new grains of biotite in the augen mylonite (Genčiai-4), CPL; N) Crenulation cleavage structure formed by biotite growth during compression in the charnokitoid ultramylonite (Girkaliai-3), CPL; O) Quarter structures of myrmekite along plagioclase boundaries in the augen mylonite of charnokitoid (Genčiai-4), CPL. Abbreviations: Plagioclase (Pl), quartz (Qtz), garnet (Grt), pyroxen (Px), biotite (Bt), magnetite (Mgt), myrmekite (Mr), Cross-polarized light (CPL), plain-polarized light (PPL). Width of view of pictures is 3 mm. The white arrows show the increasing deformation.

of plagioclase (An_{29-55}, 30%), microperthitic K-feldspar (10%), quartz (25%), hypersthene (10-15%), biotite (10-15%) and garnet (almandine, 10-15%) with magnetite, apatite, ilmenite, zircon, and monazite as accessory minerals. The foliation in these rocks is almost vertical (90-80°) or 60-40° dipping relatively to the drill core axis. Protomylonites often have augen structure and prominent foliation. Mostly these augens are feldspar megacrysts or of granitic composition and up to 7-8 cm long (Fig.2. F and G). Both protomylonites and mesomylonites show abundant elongated porphyroclasts with well-developed symmetric and asymmetric tails.

Microscopically, some large porphyroclasts (~1 cm) of plagioclase have simple twinnning (Fig.3. A). Other plagioclase grains are elongated and banded, showing intracrystal deformation Plagioclase (andesine) porphyroclasts display a core-mantle structure. The mantle is composed of fine grained plagioclase (andesine or oligoclase) and quartz grains caused by recrystallization. Myrmekite is found along plagioclase boundaries and forms quarter structures (Fig.3. O). The core-and-mantle structures and myrmekite in feldspar indicate the metamorphic temperature during the deformation around 500-600º C (Tullis and Yund, 1991). Some curved regions of plagioclase break into a microshear zones composed of small K-feldspar and plagioclase grains, which formed by sliding of grain boundary and subgrain rotation (Fig.3. B and C). Quartz grains are with deeply indented boundaries and undulose extinction showing dynamic recrystallization (Fig.3. D and E). Garnet grains have inclusions of quartz, biotite and magnetite. Large biotite grains are locally kinked (Fig.3. M). Large crystals of hypersthene are deformed and elongated. Zircon was dated by U/Pb isotope method.

The charnockitic mesomylonites are coarse-grained between 50-90% fine grained matrix. They are the dominant rocks. The mesomylonites were discovered in 26 drill cores from these area: Genčiai, Girkaliai, Kretinga, Mikoliškės, Nausodis, Pabalvė, Tryškiai, Vėlaičiai, Vydmantai, Laužai and Žarėnai. The mesomylonites consist of plagioclase (An_{30-55}, 30%), K-feldspar (10-15%), quartz (25%), hypersthene (10-15%), biotite (10-15%) and garnet (almandine, 10-15%) with magnetite, apatite, ilmenite, zircon, and monazite as accessory minerals. The foliation in these rocks dips relatively to the drill core axis both vertical and 60-40°, excepting the Mikoliškės-1 drill core with horizontally dipping foliation. The mesomylonites have often highly extended quartz and feldspar grains (Fig.2. J), and look like as striped gneisses. They resemble ribbon mylonites (Hanmer et al., 1995).

Microscopically, some large porphyroclasts (4 mm) of plagioclase have synthetic twinning. Plagioclase porphyroclasts display a core-mantle structure. The mantle is composed of fine grained plagioclase and quartz grains caused by recrystallization. Other plagioclase grains are elongated (Fig.3. C) and banded, showing intracrystal deformation, with or without fracturing. This elongate plagioclase is part of a core-and-mantle structure (Hanmer, 2000). Quartz grains are of three kinds: large older grains with deeply indented boundaries and undulate extinction, medium polygonal grains and ribbons. Large quartz grains are transformed into an aggregate of small recrystallised grains and subgrains along irregular boundaries (Fig.3. E). Medium grained quartz grains are with straight boundaries and are strain free. In mesomylonites, quartz has undergone dynamic recrystallization, mainly by grain boundary migration and subgrain rotation. Quartz ribbons have straight boundaries and wrap around rigid porphyroclasts indicating grain boundary migration recrystallization. Garnet grains have different morphology: all large grains are with symplectites and inclusions of quartz, biotite and magnetite. The other ones are rotated or elongated in the shape (Fig.3. H), sometimes show asymmetric pressure shadows on both sides of the crystals and lie parallel to the foliation (Fig.3. N). Large biotite grains are locally kinked, some of them have been partly neocrystallized to much smaller new grains at the margin of the large biotite grains. Generally, these small grains are parallel to the foliation. Large crystals of hypersthene are elongated and/or with asymmetric trails (Fig.3. K).

The charnockitic ultramylonites ware discovered in 2 drill cores in Girkaliai and Kretinga only in the western part of the TDZ. The rock suffered with essential grain-size reduction and has typically highly extended quartz and feldspar grains, and looks like as striped gneisses. This ultramylonite consists of plagioclase (An_{2-16}, 30%), K-feldspar

(10%), quartz (20%), hypersthene (10%), garnet (almandine, 10%), biotite (10%), ±clinopyroxene (0-5%) and accessory magnetite, zircon and apatite.

The abundant, elongated polycrystalline quartz ribbons have straight boundaries, suggesting grain boundary migration recrystallization (Fig.3. F). Coarse plagioclase porphyroclasts are elongated (Fig.3. C), with undulose extinction and rotation (Fig.3. B). They are rounded with recrystallized margins and well developed “tails” of fine-grained recrystallized grains of equal shape and random fabric as a result of grain boundary area reduction. Plagioclase is often fully recrystallized to polygonal fine-grained aggregates (Fig.3. F). Garnet crystals are different in size ~2.1-2.5 mm and ~0.15-0.2. Major garnet grains vary from elongated to elliptical and oriented along the foliation plane. Individual grains of them have been recrystallized to many small (0.4 mm) grains in the highest strain areas (Fig.3. I). They were formed like isolated layers in high strain zones. Garnet grains often contain inclusions of biotite and opaque minerals. Asymmetrically elongated large crystals of hypersthene are banded. On its sheared rims, tails of small grains of hypersthene, clinopyroxene and plagioclase often developed parallel to the foliation (Fig.3. L). Statically recrystallized pyroxene and plagioclase with straight boundaries were formed at high temperature and slow rate of deformation (Hanmer, 2000). Biotite is dominant in the high strain areas. Also, both biotite and opaque minerals compose the shear band cleavage transecting the main foliation with gentle inclination (Fig.3. O). Zircon was dated by U/Pb isotope method.

Granitoids and pegmatite: weakly deformed and mezomylonite

The weakly deformed granitoids have been found in 4 drill cores in the Girkaliai, Genčiai, Kretinga and Vydmantai areas in the western part of the TDZ.

A slightly deformed granite forms a 10 cm wide veins in the charnockitoid mylonites. The contact between the granite and the host charnockitoid is straight and shows an angular unconformity (Fig.2. C and D). It is medium to fine grained and consists of microcline (32%), plagioclase (30%), biotite (5%), and quartz (31%). Accessory phases include monazite, zircon and opaque minerals. K-feldspar is 0.8-1.4 mm in size with the cross-hatched twinning. Plagioclase grains (1.5-2 mm) are euhedral and subhedral. They are altered and completely replaced by sericite and carbonate. Quartz grains are about

0.8-2.5 mm in size with undulose extinction. Biotite is brown and strongly altered. Zircon was dated by U/Pb isotope method.

Pegmatite veins are pink coarse grained and range from few centimetres to metre wide with a little evidence of deformation. Pegmatites were founed in the Girkaliai and Genčiai areas (Fig.2. B and M). The pegmatites consist of K-feldspar (45%), quartz (35%) and biotite (10-15%). The contact with charnockitoid is sharp. Pseudotachylites occur in these pegmatites.

The mesomylonites of granitic composition were found in 12 drill cores in the Girkaliai, Genčiai, Kretinga, Kuliai, Laužai, Nausodis, Pabalvė and Vydmantai area i. e. around the southern margin of the Riga pluton. It is coarse-grained red granite composing about 2 m wide dykes with vertical foliation (Fig.2. H and I). Their contact with the host charnockitic mylonite is straight. The granite consists of plagioclase (30%), K-feldspar (27%), quartz (25%) and biotite (7%) and single garnet grains (6%). Magnetite, apatite, ilmenite, zircon and monazite are accessory. Large sized (1-2.5 cm) plagioclase, microcline and quartz crystals are strongly extended and form separate, about 1 cm wide bends. Plagioclase exhibits signs of alteration that developed sericite in its core. The newly-formed microcline fine grains are set up at the margin of large microcline. Quartz occurs as aggregates of subequel grains and elongated subgrains. They have undulose extinction and lobate boundaries. Also, polycrystalline ribbons of quartz are common. Garnet is rare, only few grains are visible, which slightly retrogressively chloritised. Garnet crystals are fractured and oriented along the foliation. Biotite is in small flakes and altered to chlorite. Together with ilmenite garnet and magnetite it occurs like few millimetres dark stripes surrounding large feldspar grains (Fig.2. H). Zircon was dated by U/Pb isotope method.

Metapelitic rocks

A metapelitic ultramylonite was found in the western part of the TDZ, in the Girkaliai and Mikoliškės areas, in 2 drill cores (Fig.2. K). It is characterized by strong foliation and the presence of large garnet (almandine) grains (10-15%) in fine grained matrix composed of K-feldspar, quartz, plagioclase, sillimanite, biotite, garnet, spinel, magnetite, and ilmenite. Quartz forms ribbons and irregular granoblastic aggregates, suggesting dynamic recrystallization. Plagioclase (oligoclase) and feldspar with some bent twins, all have undulose extinction. Hercynite, sillimanite, biotite, magnetite and fine grained garnet appear to follow foliation. Some hercynite grains are associated to the garnet rims.

Breccias

Breccias of the charnockitic (Fig.2. L and N) granitic and metapelitic rocks have been studied from the drill cores Girkaliai-1, 2, Genčiai-3, Kretinga-1, 2, 3, Žutautai-1, Mikoliškės-1, Laužai-1, Žarėnai-1, Pabalvė-1. A breccia is located in the contact of the charnockitoids with the Cambrian sandstone in the Genčiai-3 drill core (Fig.2. O). This breccia contains the angular fragments of both rocks. The largest core interval of breccias is about 50 m in the Girkaliai area. Also fractures (Fig.2. N) and slickensides with different directions were found. Some fractures are healed by epidote, chlorite or chalcedony (Motuza, Vejelyte, 2005).

Pseudotachylites

Pseudotachylites are in the charnockitoids and pegmatite in Girkaliai-1 and -2, Genčiai-8 and -10, -11, Kretinga-3, Kretinga-4 and Kuliai-1 drill cores (Fig.2. L and M). It occured as few millimetres to 1 centimetre wide veins and have the sharp contacts with charnockitoid or pegmatite. The vein is composed by a brown glassy matrix with inclusions of quartz.

Pseudotachylite can be formed by local melting of the rock along a brittle fault plane when rapid frictional sliding occurred in the upper or middle crust. They are associated with seismic activity. The melting temperature ranges from 750°C to 1700°C (O‘ Hara 1992, Passchier and Trouw, 2005).

Summary. According to the present petrographic-microstructural study, two phases of ductile deformation (D1 and D2) are recognized in the TDZ.

D1 deformation was partitioned within the entire TDZ and rocks of different degree of deformation are variously distributed. The mylonites were formed in the upper amphibolite-to granulite facies and contain the mostly anhydrous mineral assemblage of orthopyroxene+plagioclase+garnet+quartz+K-feldspar±clinopyroxene±amphibole. The analysis of microstructures has showed the great importance of grain-reduction processes, which were affecting the pristine magmatic plagioclase, quartz, K-feldspar, garnet and pyroxene during progressive ductile deformation. The structures such as core-and-mantle, kink and undulose extinction indicate dynamic recrystallization. They were formed during subgrain rotation and grain boundary migration recrystallization processes. The later static recrystallization partly overprinted previous structures. Grains with straight boundaries show the post-deformational phase at high temperature conditions and a relatively slow cooling rate. Feldspar fracturing can be formed at 400-500°C during the late D1 phase. The metapelitic mylonites were also developed at this phase. The crenulation cleavage transecting the main foliation in charnockitoid ultramylonites is interpreted as D2 phase. It was partitioned locally only in the western part of the TDZ. It could have been the last ductile compressive phase in the TDZ and related to the 1460 Ma granitoid magmatism in the West Lithuanian Granulite domain. The latest deformation (D3 and D4) took place under conditions of brittle deformation.

3. 1. 2. P-T conditions in the rocks of the Telšiai deformation zone

An attempt has been done to assess pressure and temperature (P-T) conditions of metamorphism during deformation. The most relevant rocks are high grade charnockitoids showing newly formed and fine grained mineral assemblages of plagioclase, biotite, hypersthene, clinopyroxene, garnet, quartz, K-feldspar and amphibole, which are related to deformational textures (Fig.4. A and B). In the metapelitic rocks, syn-shearing mineral assemblages include garnet, sillimanite, biotite, plagioclase, K-feldspar and quartz (Fig.4.C).

Temperatures were calculated using the garnet-biotite (Grt-Bt) Fe-Mg exchange thermometer by Ferry and Spear and pressures were estimated using the garnet-biotite-plagioclase-quartz (GBPQ) of Hodges and Spear for charnockitoids and metapelitic rocks. P-T calculations made using Program “Thermobarometry” (Frank S. Spear and Matthew J. Kohn, 2001). For the calculations, analyses of individual garnet grains were taken in different positions: across garnet-biotite boundaries, across garnet-plagioclase boundaries, and across garnet-orthopyroxene contacts. The absence of reactions between these minerals indicates that they were in equilibrium state allowing the P-T calculations. We used Fe 3+ - uncorrected data.

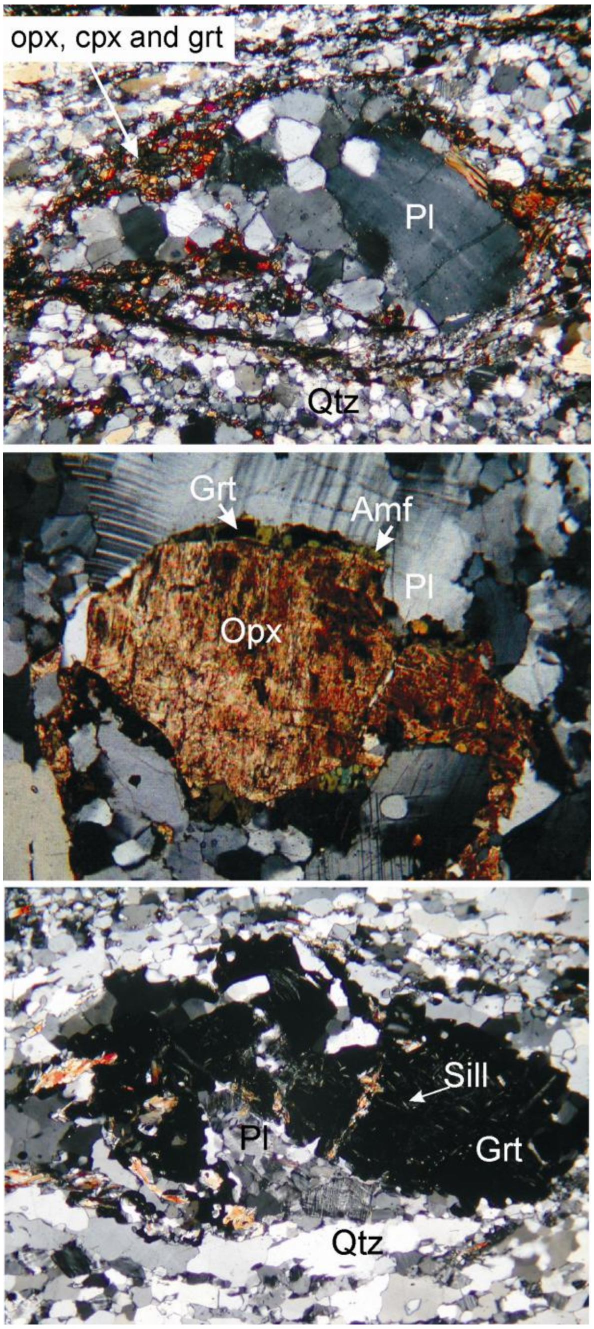


Fig. 4. Microphotographs showing the development of mylonitic mineral assemblages: A) Magmatic plagioclase is recrystallized to fine-grained recrystallized grains of equal shape in the association with metamorphic orthopyroxene and clinopyroxene in the charnockitoid ultramylonite from the Girkaliai-3 drill core. B) Magmatic hypersthene is mantled by new small garnet and amphibole grains in the Tryškiai-73 charnockitoid; C) Garnet with sillimanite in the metapelitic ultramylonite from the Girkaliai–2 drill core. Cross-polarized light (CPL). Width of view of pictures is 2.5 mm.

From the present investigation it is evident that the TDZ charnockitoids vary in P-T metamorphic conditions: 1) Weakly deformed charnockitoids with subsolidus association of Grt+Bt+Pl (An_{30-50})+Qtz+ Mag+Ilm+Sp were crystallized at 800°C and 7-8 kbar; 2) Mesomylonitic and ultramylonitic charnockitoids were formed under conditions of granulite-to upper amphibolite facies at 680-750°C and 4-6 kbar. Similar P-T values 680-720°C and 5-6 kbar characterize the metapelitic ultramylonites with mylonitic mineral association of Grt+Bt+Pl+Kfs+Sill+Sp.

Tentatively, the obtained results (Table 1) indicate that P-T conditions were different for the weakly deformed and mylonitized rocks. Mylonitization occurred along with decreasing temperature and pressure in the middle crust at the depths of 15-18 km while the charnockitoids were crystallized in the lower crust, ca. 30 km deep. This implies that the mylonitization took place during uplift and the formation of shear zones. Some differences of P-T parameters within the TDZ can have been caused by faster exhumation of some blocks and more intensive erosion.

Table 1. Results of PT-calculations for the TDZ rocks

Sample/depth of drill core, m	Rock type	Methods	T, °C large grain	T, °C small grain	P, kbar large grain	P, kbar small grain
Vydmantai-2/2164	Weakly deformed charnockite	Gt-Bt (T)* GBPQ (P)**	800			7-8
Girkaliai-2/2376	Charnockitic mesomylonite	Gt-Bt (T) GBPQ (P)	680–750		4-6	
Tryškiai-73/1641	Charnockitic mesomylonite	Gt-Bt (T) GBPQ (P)	570	<500	4.2	2.5-3
Girkaliai-3/2081	Charnockitic ultramylonite	Gt-Bt (T) GBPQ (P)	680-750	650	4	2.8
Girkaliai-2/2355	Metapelitic ultramylonite	Gt-Bt (T) GBPQ (P)		680-720		5-6

*The uncertainty of the Gt-Bt (Garnet-Biotite) geothermometer by Ferry and Spear is ±50°C. **The uncertainty of the GBPQ (Garnet-Biotite-Plagioclase-Quartz) geobarometer by Hodges and Spear is ±1 kbar.

3. 1. 3. SHRIMP U/Pb ages of zircons of the Telšiai deformation zone

Six samples of different types of rocks (GRK-2, GRK-3, GNC6-1, GNC6-2, MK-1, MK-2) with various intensity of deformation were collected for the present geochronological study. The studied rocks were subdivided into two groups: *charnockitoids* (MK-1, MK-2, GNC6-2, GRK-3) and *granites* (GNC6-1 and GRK-2). They have been dated by U/Pb zircon method using SHRIMP facilities.

3.1.3.1. Description of zircon from the charnockitoid samples and U/Pb age results

Within this study, four charnockitoid samples (MK-2, MK-1, GNC6-2, GRK-3) with different intensity of deformation (a weakly deformed rock, mesomylonite and ultramylonite) have been dated (Fig.6 and 2 Table).

Samples MK-1 and MK-2. These weakly deformed charnockitoids contain rounded prismatic zircons. In CL and BSE images, the zircon grains have core-and-rim textures. The zircon grains display distinct cores with oscillatory or sector zoning, surrounded by a thin light rim in BSE images. The internal alteration of zircon as numerous inclusions and cracks penetrating grains is observed in BSE images (Fig.5. A and B). The alteration is more intensive in sample MK-1 where dark CL bands separate the core of the zircon from the rim. In BSE images, the rim is larger in this more altered zircon grains and have always high U content.

Totally, 17 spots were analyzed from MK-1 and 26 spots from MK-2. One analysis of the MK-2 zircon shows an unusually high U concentration and was rejected from the data base. The Th/U ratios are lower in the MK-2 rims then in those of MK-1. The obtained $^{207}Pb/^{206}Pb$ average age of 1814±20 and 1841±13 Ma for the magmatic zircon cores from MK-1 and MK–2 samples is interpreted as the time of emplacement and crystallization of the charnockitoid magma. Two zircons grains from MK-1 and one zircon grain from MK-2 show older ages of 2101, 1929 and 2058, respectively. We interpret them as ages of xenocrysts assimilated from the host rocks. The rims of zircon from MK-1 and MK-2 give the recrystallization $^{207}Pb/^{206}Pb$ age at 1733±15 Ma and 1680±9 Ma, respectively. Probably, the growth of the rims was promoted by the presence of aqueous fluids.

Sample GNC6-2 is augen mesomylonite of charnockitoid composition, collected from the Genciai-6 drill core. This sample contains rounded-ovoid and prismatic zircon grains. The internal parts show oscillatory zoning in both CL and BSE images. The CL-dark cores are surrounded by a CL-light rim (Fig.5. D). Microcracks are abundant in all crystals. Zircon grains were analyzed in 15 spots. The $^{207}Pb/^{206}Pb$ average age of the zircon cores is 1846±12 Ma. The obtained magmatic age of this rock is similar to the weakly defomed MK-2 and in a good agreement with the overall magmatic ages of charnockitoids in the study area. The rims of zircon have $^{207}Pb/^{206}Pb$ average age of 1679±17 Ma.

Sample GRK-3 is ultramylonite (with ribbon structure) of charnockitoid composition. Sample GRK-3 came from the drill core Girkaliai-3, which is situated near the village Girkaliai of about 3 km to the east from the Baltic Sea shore. This ultramylonite contains rounded prismatic shape zircon with oscillatory zoning in CL image (Fig.5. E). They are of similar morphology as in samples GNC6-2 and MK-1. Numerous cracks are visible in BSE images. Totaly, 16 spots were analyzed. The $^{207}Pb/^{206}Pb$ average age of the most concordant analyses is of 1828±16 Ma and exhibits magmatic crystallyzation age of the charnockitoid magma. The zircon rims have $^{207}Pb/^{206}Pb$ average age of 1712±18 Ma which is close to ages of the zircon rims from sample MK-1, MK-2 and GNC6-2.

3.1.3.2. Description of zircon from the granitic samples and U/Pb age results

Sample GRK-2. The granite sample was recovered from a deep drill hole, Girkaliai-2, which is situated 3 km to the east of the Baltic Sea, within the TDZ. In the drill core, the analyzed granite forms a 10-cm wide dyke intruding the charnockitic rocks. Two groups of zircon grains have been recognized in the granite. Zircons of major group are prismatic in shape and show concentric and oscillatory zoning characteristic of magmatic growth (Fig.5. F). Their U/Pb ratios are 1.34-2.84, and the U contents are 57-348 ppm. A $^{206}Pb/^{238}U$ age of 349.1±5.7 Ma (MSWD=3.2) was obtained from 12 spots. The second group of zircons yielded concordant $^{207}Pb/^{206}Pb$ ages of 2643, 2186, 2081, 1887, 1852, 1724, 1663, and 1476 Ma. These grains represent xenocrysts entrapped from various country rocks during the granite emplacement.

Sample GNC6-1. The GNC6-1 mesomylonitic coarse grained red granite forms about 2 m wide dykes parallel to steeply-dipping foliation in the charnockitic mylonites. The GNC6-1 granite contains rounded prismatic zircons. In BSE images, zircon grains show alteration, forming dark domains (Fig.5. C). Zircons have many radial cracks.

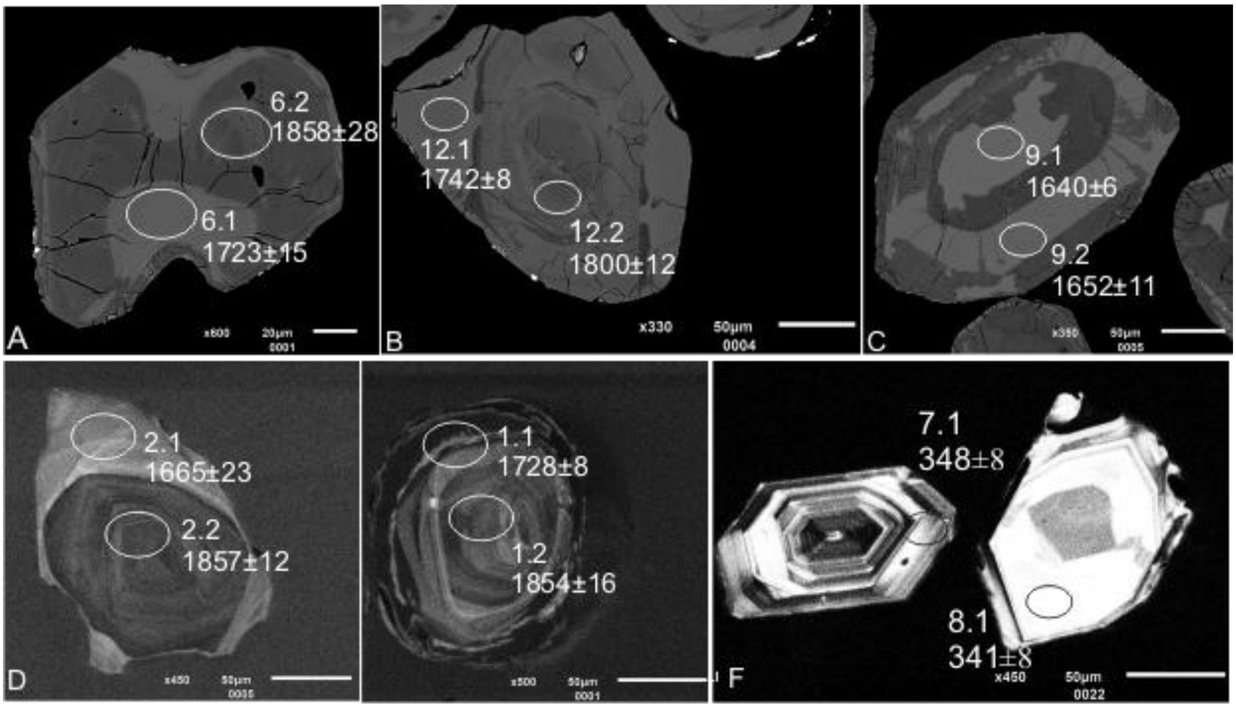


Fig. 5. A, B and C back-scatter electron (BSE) and cathodoluminescence (CL) images D, E and F images of zircon grains from MK-1, MK-2, GNC6-1, GNC6-2, GRK-3 and GRK-2, respectively. Circles depict SHRIMP analytical spots, spots number and age.

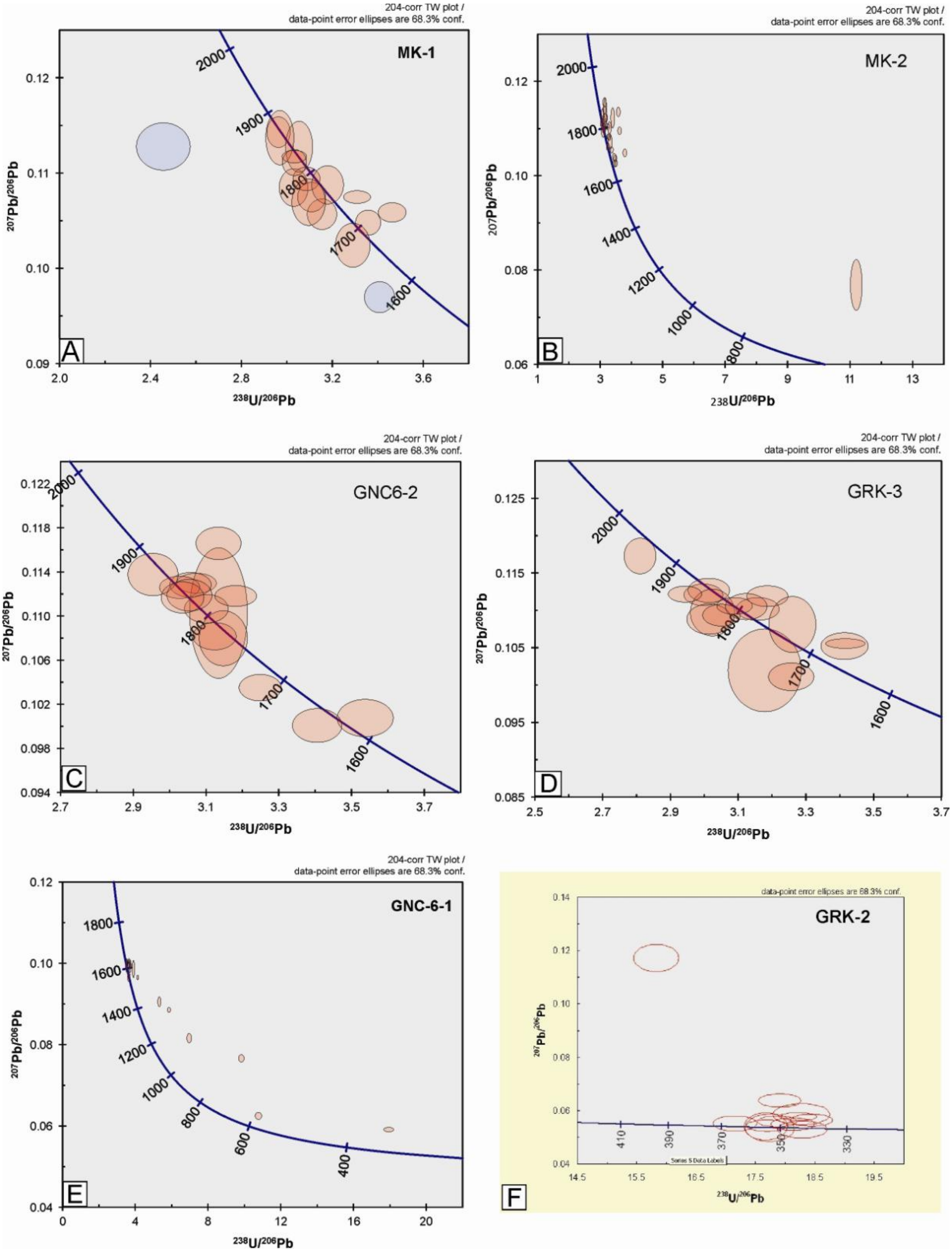


Fig. 6. Tera-Wasserburg concordia diagrams for the TDZ rocks. A) Weakly deformed charnockitoid Mikoliškės-1 (MK-1); B) Weakly deformed charnockitoid Mikoliškės-1 (MK-2); C) Mesomylonite of charnockitic composition Genčiai-6 (GNC6-2); D) Ultramylonite with extremely extended quartz and feldspar of charnockitic composition Girkaliai-3 (GRK-3); E) Mesomylonite of granitic composition Genčiai-6 (GNC6-1); and F) Weakly deformed granite Girkaliai-2 (GRK-2). Error ellipses are drawn at 1σ.

Characteristically they start at the centre of core and develop radially outward to the rim that is probably because of metamictization (Hoskin and Schaltegger 2003). Totally, 17 spots wereanalyzed. Five analyses of dark cores of zircon grains which have a high U content (>2202 ppm) are omitted from the plot. Seven analyses of the rims are concordant, and one core analysis is close to concordia line. The $^{207}Pb/^{206}Pb$ average age is 1622±12 Ma which is the crystallization age of this granitic dyke.

Summary. The obtained zircon datings show that the studied rocks of the TDZ belong to the family of charnockitoids 1846±12 and 1814±20 Ma old, composing large Kuršiai (Curonian) batholith (Motuza et al., 2008) in the WLGD.

Deformation did not affect much the magmatic inherited zircon, but caused its metamictic alteration during the emplacement of the granitic dykes at ca. 1622 Ma. Since these granites and their host charnockitoids were jointly mylonitized, this age constrains the initiation of the TDZ and close to the time of the 1580 Ma Riga AMCG intrusion and to the 1602-1595 Ma Breven dolerites in Sweden (Söderlund, 2006). A tectonothermal event caused the growth of 1733-1679 Ma zircon rims could be a far-field thermal effect of the Gothian orogeny in the present-day southwest. The alkaline intrusions of ca. 350 Ma, well presented in Poland, provided melting of the Mesoproterozoic crust and the coeval granitic dyking in the TDZ.

3.2. THE DRŪKŠIAI-POLOTSK DEFORMATION ZONE

3.2.1. Petrographical - microstructural characteristics of rocks in the Drūkšiai-Polotsk deformation zone

There are only 8 drill cores characterizing the composition of the DPDZ rocks. According to their protholith, the rocks of all these drill cores are subdivided into two major groups: *granitoids* (protomylonite, mesomylonite and ultramylonite) and *mafic rocks* (weakly deformed rocks).

Granitoids: protomylonite, mesomylonite and ultramylonite

Coarse granitic protomylonites with a well pronounced foliation were found in the Novikai-1 (Fig.7. A) and Kazimirovo-6 drill cores. They consist of microcline (30-60%), plagioclase (10-30%), quartz (10-15%), biotite (10-12%), ±amphibole. Accessory minerals are magnetite, zircon, apatite, and monazite. Muscovite occurs as secondary mineral in the matrix. In thin sections, mylonitic foliation is not well seen because of coarseness of feldspars which are fragmented. Some microcline crystals are extended

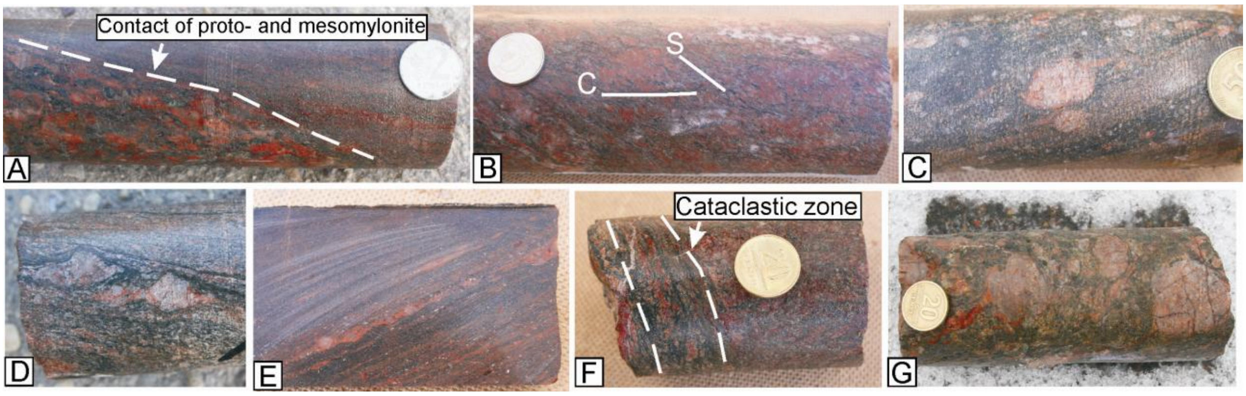


Fig. 7. Photographs of various mylonites from the DPDZ: A) The contact of the granitic protomylonite with the mesomylonite in the Novikai-1 drill core; B) Mesomylonite with S-C structure from the Šaškai-2 drill core; C) and D) Augen mylonites from the Tverečius-336 and Šaškai-2 drill cores, respectively; E) Epidote-rich ultramylonite from Tverečius-336; F) The thin cataclastic zone in the Visaginas drill core; G) The brecciated mylonite in the Tverečius-336 drill core. The diameter of drill core is 7.8 mm.

and about 4.5 cm long. Quartz with undulose extinction occurs as extended bends reaching about 8 mm or boudinaged. Platy brown biotite is about 4 mm long. Amphibole forms large separate crystals, some are boudinaged (Fig.8. B). It is partly replaced by

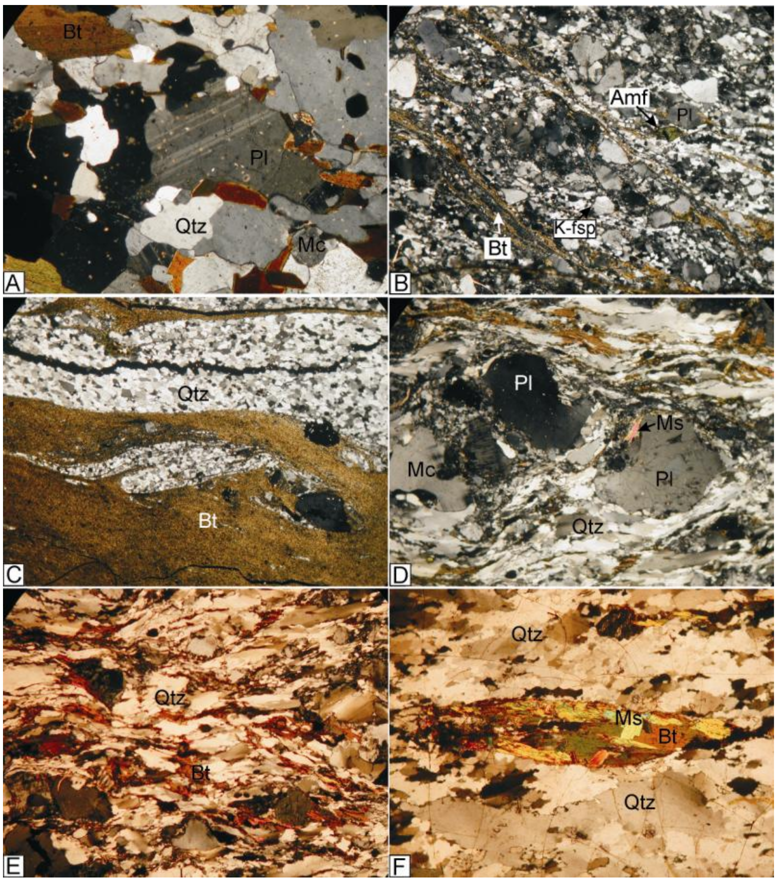


Fig. 8. Deformation microtextures in the DPDZ granitic rocks: A) Protomylonite from the Novikai-1 drill core; B) In S-C mylonite, plagioclase and horblende have deformed plastically into elongate lenses surrounded by fine-grained matrix with polygonal texture (Šaškai-2); C) The strongly recrystallized biotite and quartz grains to fine-grained matrix in the S-C mylonite of granitic composition. The quartz vein is folded (Šaškai-2); D) In S-C mylonite, plagioclase porphyroclasts with undulose extinction. A mantle of dynamically recrystallized quartz surround the porphyroclasts (Schedai-3); E) C‘- type shear band cleavage (from upper left to lower right) transecting the main foliation in a S-C mesomylonite. The shear sense is dextral in thin section (Schedai-3); F) A typical fabric of dynamic recrystallization of quartz in mesomylonite. In the centre, biotite is partly replaced by muscovite (Schedai-3). Microphotograph width is 4 mm. Cross-polarized light (CPL).

biotite. Both deformed amphibole and biotite are oriented along foliation. Fine-grained matrix consisting of microcline, biotite, quartz, plagioclase, muscovite and rare myrmekite places between large grains. Zircon grains are common in the large altered plagioclase. However, it appears between quartz and biotite or within biotite in medium grained parts of the rock. Zircon was dated by U/Pb isotope method.

The mesomylonites of granitic composition (Šaškai-2, Novikai-1, Stankovičiai-4 Schedai-3 and Visaginas-5 drill cores, Fig.7. A, B, D) differ from the granitic protomylonites by more intensively deformed minerals, especially quartz and feldspars. In mesomylonite, thin cataclasite zones are also present (Fig.7. F). Quartz often shows ribbon structures but with irregular boundaries (Fig.8. D). These indicate a dominant dynamic recrystallization. Even quartz was folded as seen on Fig.8. C.

The mylonitic foliation is well marked by quartz, feldspar, biotite and muscovite (Fig.8. F). The characteristic feature is S-C structure (Fig.7. B). S-surfaces are composing of the feldspar augen and C-surfaces are horisontal and consist of recrystallized feldspar, quartz and biotite. They wrap around feldspar (Fig.8. B and D). In thin section, the small C'shear bands are observed. It is oblique to the older foliation and shows dextral shear sence (Fig.8. E).

The mesomylonite of granodioritic composition (Fig.7. C and Fig.9.) in the drill core Tverečius-336 consists of andesine (30-40%), K-feldspar

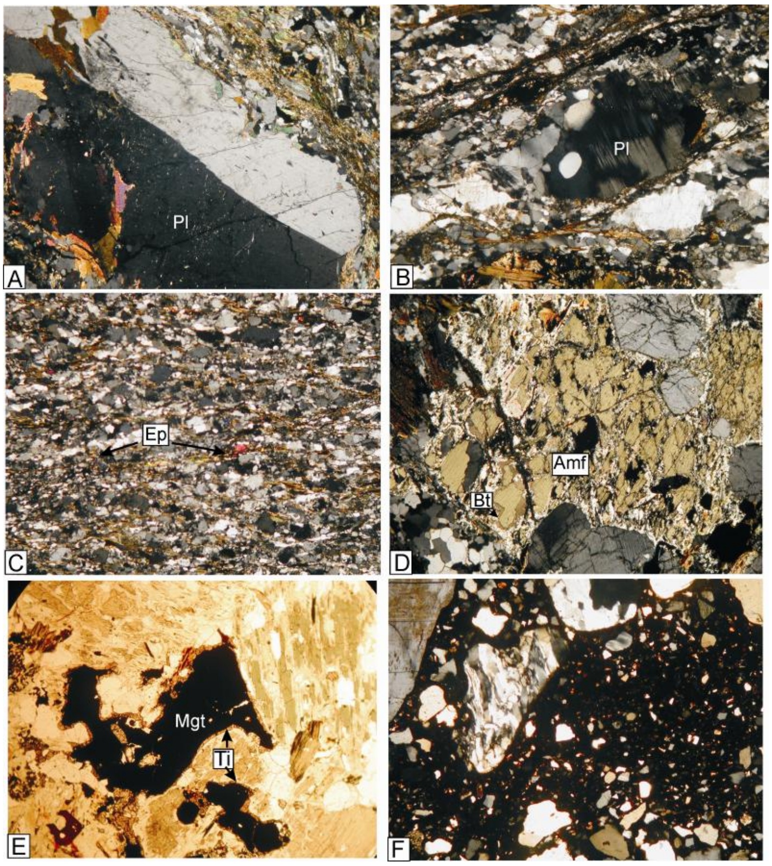


Fig. 9. Deformation microtextures in the DPDZ rocks from the granodiorite Tverečius-336: A) Plagioclase porphyroclast with simple twining; B) Strongly deformed plagioclase with deformation twinning occurs along mylonitic foliation; C) Amphibole partly replaced around its rim by biotite; D) Titanite occurs as mantle around opaque minerals; E) Ultramylonite consisting of K-feldspar, quartz and epidote; F) Pseudotachylite composed by a brown glassy matrix with minor inclusions of quartz. Microphotograph width is 4 mm. Cross-polarized light (CPL).

(10-15%), quartz (10-20%), biotite (10-15%), and amphibole (±7%). Accessory minerals are titanite, magnetite and apatite. Secondary epidote occurs along foliation. Some plagioclase porphyroclasts are euhedral with simple twining (Fig.9. A). Plagioclase is mostly fractured or splitted into several individual grains, which are separated by a fine-grained recrystallized matrix. The porphyroclasts show evidence of much less plastic deformation, extensive fracturing and fragmentation. The mylonitic foliation, which is defined by biotite, quartz, titanite and epidote, is deflected around of the porphyroclasts (Fig.9. B). Biotite is deformed plastically into elongated lenses and also recrystallized to fine-grained aggregates along foliation. Quartz and amphibole form polygonal grain aggregates. Amphibole is partly replaced by biotite as rims and along fractures (Fig.9. D). Some quartz grains are thin, finely recrystallized ribbons. The brown titanite occurs as euhedral crystals up to 0.2 mm size, subhedral grains and as mantle around opaque minerals (Fig.9. E), while light brown titanite is located along the folation in this sample. It is abundant in separate zones, but not throughout the whole rock. It has a preferred orientation parallel to the foliation and was formed during retrogression from amphibolite-to greenschist facies and coeval mylonitization. This titanite and zircon have been dated by U/Pbisotope methods. Pseudotachylite is also present (Fig.9. F).

The ultramylonite within the augen mylonite in the Tverečius 336 drill core (Fig.7. E) consists of K-feldspar, quartz and epidote (Fig.9. C). They depict a well-developed foliation. The ultramylonite can be younger than the augen mylonite, formed due to increasing partitioning of deformation into narrow zones and increased strain rates when the rocks were exhumed to increasingly brittle regime. However, it can have also formed coevally with the augen mylonite due to rheological differences between different rock composition, penetrating fluid or as a result of strain softening in the weaknes zones (Passchier and Trouw; 2005; Torvela et al., 2008).

Mafic rocks

The weakly deformed mafic rocks, metavolcanic or metadoleritic *amphibolites* (Drukščiai-324, Novikai-1 and Kazimirovo-6 drill cores) and *mafic granulites*, possibly, metagabbroids (Drūkšiai-324) have been recognized in the DPDZ. *Amphibolite* is fine-to medium grained having the assemblage of hornblende, plagioclase, biotite, K-feldspar, quartz, magnetite, ilmenite, titanite, apatite, epidote. The foliation in the amphibolite is almost vertical, dipping along the drill core axis. The foliation is defined by the parallel alignment of hornblende, feldspar and biotite. Texturally, this rock is heteroblastic with dominant large sized (up to ca. 2 mm) hornblende, plagioclase, biotite and Ti-magnetite separated by fine-grained (0.05 mm) thin zones of recrystallization along foliation planes. Amphibole is pleochroic from green to light brown and up to 1.5-2 mm in size. Plagioclase (An_{64-68}) is subhedral with a grain size ranging from about 0.05 mm to over 2 mm. The rock has undergone little retrograde alteration, which has mainly been resulted in partial sericitization of feldspars. In some drill cores, opaque minerals are magnetite mantled by thin reaction rim of titanite. Also small aggregates of apatite are common. Biotite is brown, fine grained subhedral and arranged parallel to amphibole. In places it was strongly destroyed by oxidation process. Quartz underwent plastic deformation, displaying undulose extinction, subgrain and dynamic recrystallization.

Mafic granulite (metagabbro) is also deformed, showing steep foliation along the drill core axis. It consists of plagioclase, quartz, pyroxenes, and amphibole. In the present work, this rock was not analyzed in detail.

Summary. Two ductile deformation phases (D1 and D2) have been identified within the DPDZ. The dynamic recrystallization structures of D1 phase in the granitoids of the northern DPDZ are well preserved. They developed by subgrain rotation and grain boundary migration recrystallisation in lower amphibolite-to greenschist facies. The prevailing S-C structures in the mylonites may indicate an inhomogeneous simple shear (Passchier and Trouw, 2005). Synthetic fractures in the feldspar can be formed at temperature more than 450ºC (Tullis et al., 1985) during the late D1 phase. In the granodioritic augen mylonite from the southern DPDZ, the metamorphic titanite is associated with the D1 deformation fabric. The epidote-rich ultramylonite was formed during the progressive D2 deformation along narrow zones when the rocks were exhumed during the uplift to the upper crust. C'–type fabric of D2 phase that transects the main D1 foliation appeared in granitoids locally. It is interpreted as developed during late stages of mylonitization. Later brittle deformation structures feature phase D3.

3.2.2. SHRIMP U/Pb zircon and TIMS U/Pb titanite geochronology of the Drūkšiai-Polotsk deformation zone

Two samples of the DPDZ granitoids (TV-336 and MVK-1) with various intensity of deformation were collected for the present geochronological study.

3.2.2.1. Zircon description and U/Pb age of the granitoids from the northern part of the DPDZ

In the MVK-1 protomylonite of granitic composition (drill core Novikai-1). The majority of zircons are prismatic and subhedral. Most of zircon cores are mantled by CL-bright rims. Usually the cores and rims of zircon grains show a weak sectorial zoning visible in both BSE and CL-images (Fig.10. A). These images show that the core of zircon grains have a mottled pattern, indicating resorption and metamictization. By 25 spot analyses (Fig.11. A) the zircon cores have $^{207}Pb/^{206}Pb$ average age of 1797±10 while their rim age is 1788±13 Ma. The cores of zircon grains are interpreted to be magmatic, but they are strongly altered (usually, they have a high U content and Th/U ratios is <0.01), could be affected by later magmatic fluids, and not show any magmatic evidence. However, these core have edges with remained oscillatory zoning and is interpreted as showing the end of magma crystallization or a prolonged magmatism. The ages of 1916, 1887 and 1884 Ma are of zircon xenocrysts and similar to those of zircon xenocrysts in the TDZ rocks described above.

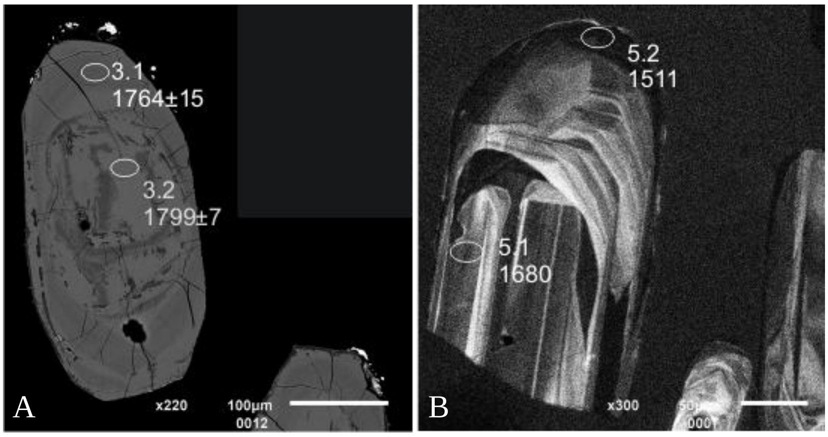
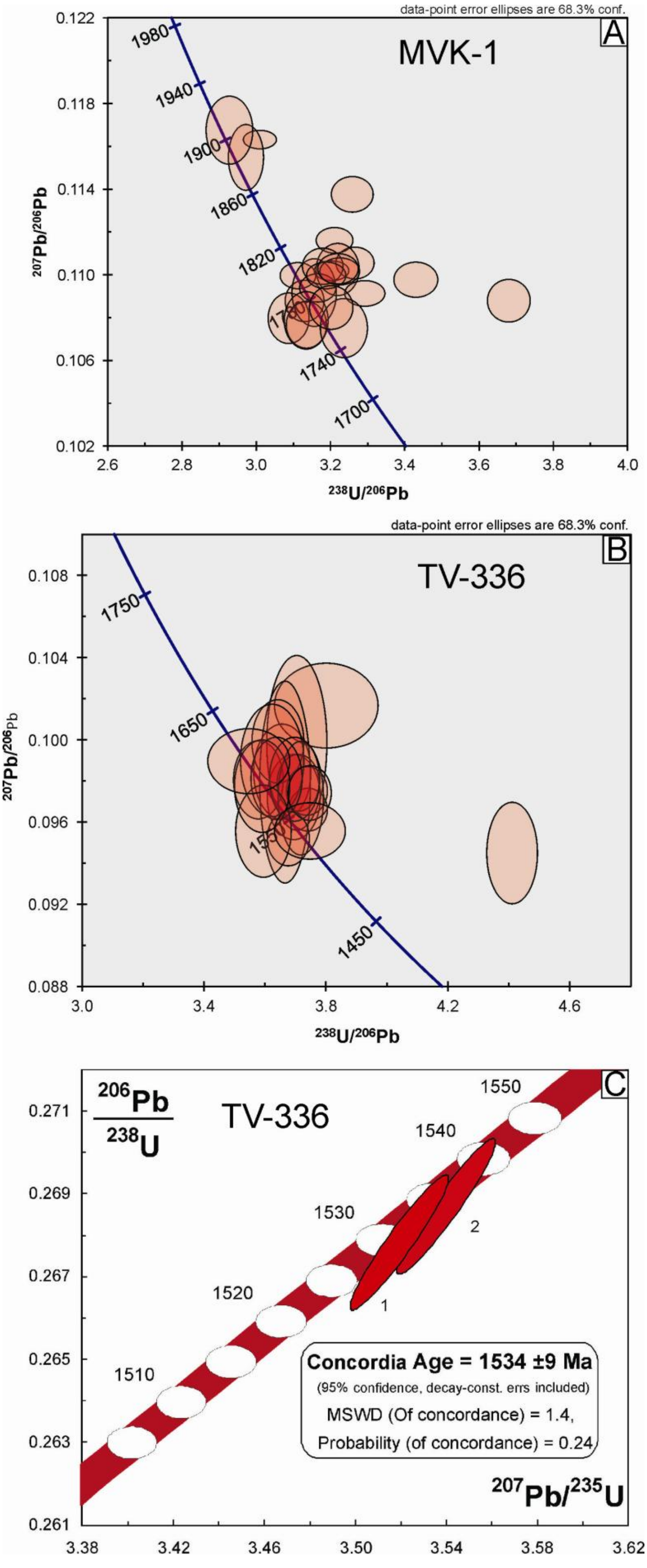


Fig. 10. A) back-scatter electron (BSE) and cathodoluminescence (CL) images B) images of zircon grains from MKV-1 and TV-336, respectively. Circles depict SHRIMP analytical spots, spots number and age.

3.2.2.2. Zircon and titanite description and U/Pb ages of the granitoids from the southern part of the DPDZ

In the TV-336 augen mylonite of granodioritic composition, the majority of zircon grains



are subhedral and transparent. The CL intensities and zoning patterns of zircon are pronounced (Fig.10. B). In CL and BSE images, zircon shows oscillatory zoning. Some crystals have thin CL-dark rim. Totally, 25 spots were analysed. The analyses cluster in four age groups, which might represent different events. An older group with the age of 1758-1680 Ma is interpreted as age of xenocrysts. The $^{207}Pb/^{206}Pb$ average age of magmatic cores with the most concordant analyses and with minimal error is 1580±17 Ma. It is the crystallisation age of the mylonitic granitoid protolith. The group of ages between 1572 and 1528 Ma dates most probably the ductile deformation in the DPDZ and overlaps with 1534±9 Ma TIMS

Fig. 12. A) Tera-Wasserburg concordia diagram of the SHRIMP U-Pb data for zircon from Novikai-1 drill core (n=19); B) Tera-Wasserburg concordia diagram of the SHRIMP U-Pb data for zircon (n=20) from drill core Tverečius-336 (TV-336). C) Concordia diagram displaying the U/Pb TIMS data on titanite from sample TV-336. Error ellipses are drawn at 1σ (A, B) and 2σ (C).

titanite age (Fig.11. B and C). The latter has been applied to the time of the mylonitization (Vejelyte et al., 2010). The ages of zircon overgrowths of 1511, 1494 and 1468 Ma in can be related to hydrothermal reworking.

In summary, the following ages have been obtained: 1580 Ma – the crystallization age of the granodiorite which was mylonitized between 1570 and 1530 Ma, and hydrothermally reworked between 1511 and 1468 Ma.

Table. 2. U-Pb zircon ages of the TDZ and DPDZ rocks

Name of the drill core/sample	Rock	Magmatic age/core, Ma	Metamorphic age/rim, Ma
Mikoliškės-1/MK-1	Weakly deformed charnockitoid	1814±20*	1733±15*
Mikoliškės-1/MK-2	Weakly deformed charnockitoid	1841±13*	1680±9*
Genčiai-6-2/GNC6-2	Charnockitic mesomylonite	1846±12*	1679±17*
Girkaliai3/ GRK-3	Charnockitic mesomylonite	1828±16*	1712±18*
Genčiai6-1/ GRK6-1	Granitic ultramylonite	1622±12*	
Girkaliai2/GRK-2	Weakly deformed granite	349±6	
Novikai-1/MVK-1	Granitic protomylonite	1797±10 and 1788±13(rim)	
Tverečius-336/TV-336	Granodioritic mesomylonite	1580±17	1530±30 and 1468±29
Tverečius-336/TV-336	Granodioritic mesomylonite		1534±9 (titanite)

*age average of the most concordant analyses (concordance < 10%)

4. GENERAL SUMMARY AND CONCLUSIONS

The obtained results on the age of deformation and magmatism within the TDZ allow new considerations of its development and connections with other regional structures both of the covered crystalline basement in Lithuania and in the Baltic Shield.

4.1.Timing of deformation and reactivation stages within the TDZ and regional correlation

Some years ago the Telšiai deformation zone has been considered as a continuation of the Loftahammar-Linköping Deformation Zone (LLDZ) on the Baltic coast in SE Sweden (Motuza, 2004, Vėjelytė and Motuza, 2004, Motuza, Vėjelytė, 2005). The assumption was that the LLDZ can be conjugated with the Nieman (Nemunas) fault in the NW-SE direction. The 1800-1780 Ma LLDZ marks the southwestern boundary of the Berslagen terrane in central Sweden (Beunk and Page, 2001). Recent geochemical and geochronological data suggest the continuation of this terrane boundary into the northwesternmost Lithuania (Skridlaite et al., 2010).

However, now available data point to the superimposed nature of the TDZ. The present study shows that mylonites from the TDZ were formed at the expense of coarse grained charnokitoids and granites of various ages. The magmatic age of the deformed charnockitoids (weakly deformed, mesomylonite and ultramylonite) in the western part of the TDZ, is constrained by 4 new datings between to 1846±12 and 1814 ±20 Ma (Table 2). These coincide with the crystallization age of zircon from the Vydmantai-1 opdalite dated by SIMS method as 1815±20 Ma (Claesson et al., 2001), and the U-Pb (TIMS) zircon age from the Macuičiai-1 charnockite of 1846±12 Ma (Motuza et al., 2008). The zircon age of the TDZ charnockitoids is similar to the 1844±5 Ma garnet-cordierite granite (Kužiai-65 drill core) and the 1837±6 Ma granitic gneiss from the (Graužai-105 drill core) (Motuza et al., 2008). The cores of monazite from the Šiupariai-3 opdalite preserve ages of ca. 1850 Ma (Skridlaite et al., 2007).

In the overall, the 1846-1814 Ma TDZ charnockitoids appear to belong to the same group of high grade magmatic rocks composing large bodies in the WLGD described by Motuza et al., 2011. Some age differences can be due to either multiphase charnockitoid intrusions or different rate of cooling and uplifting. As a whole, this resembles timing and tectonic setting of the TIB-0 magmatism along the SW active margin of the Berslagen terrane in the south-central Sweden (Andersson et al., 2006; Motuza et al., 2008).

The Early Gothian metamorphic events are also recognized in the TDZ area. The zircon metamorphic rims from the charnockitoids grew between 1733±15 and 1679±17 Ma (Table 2). A previous work has also shown that the “major” metamorphism in the WLG occurred not early than ca. 1700 Ma when monazite, zircon and garnet grew. Temperature and pressure of these events were estimated for the Šiupariai-3 (Sp-3), Vydmantai-1 (Vd-1) and Palukne-1 (Pl-1) drill cores. The peak temperature was reached at 800-760° C and at 7 kbar, while retrogression occurred along near-isothermal trend from 500-450° C at 3-4 kbar (Skridlaite et al., 2010).

In the present study, a magmatic phase at the very end of the Paleoproterozoic - the beginning of the Mesoproterozoic has been revealed within the TDZ. The magmatic zircon from the strongly deformed granite dyke cutting the charnockitods in the Genčiai 6 drill core defines the ages of the granitic intrusion as 1622±12 Ma (Tables 2 and 3). This is close to the U/Pb zircon rims age of ca. 1620 Ma from the charnockitoids in the Vydmantai -1 drill core (Claesson et al., 2001). Also, monazite from the same rocks recorded ages of ca. 1630-1590 Ma (Skridlaite et al., 2007, 2010). We presume that ca. 1622 Ma old granite dykes can be related to the emplacement of the 1.58 Ga Riga pluton (Rämö et al., 1996, Kirs et al., 2004) and to the mafic magmatism in central Sweden (Soderlund et al. 2005). The similar age rocks such as of the Lithuanian granite dykes (1622 Ma) characterize the Estonian rapakivi suite, which comprises two larger Marjamaa (1629±7Ma) and Naissaare (1624±10 Ma) and three smaller (Neeme, Ereda and Taebla) K-rich granite stocks in northern Estonia and a quartz monzodioritic (Abja) in the south (Rämö et al., 1996). Totally, there are six rapakivi intrusions suites are present in the Baltic countries. We suggest that the 1.62-1.63 Ga granitic intrusions and dykes in the periphery of the Riga pluton could emplace at an early stage of its emplacement in extensional tectonic setting.

The TDZ cuts and superimposes the investigated charnockitoids and granitoids in the northwesten Lithuania. Deformational fabrics both in the 1622 Ma granite dykes and the host coarse-grained charnockitoids of 1846-1814 Ma age indicate that rocks were deformed and strongly mylonitized at the same time. The charnockitoids and coarse granitic dykes and veins were sheared at the depths of 15–18 km under ductile deformation and conditions from granulite- to amphibolite facies. The mylonitization took place during the uplift from the lower crust where the charnockitoids were crystallized at the depths of ca. 30 km (Motuza and Motuza, 2011; this study). It is characterized by well developed foliation and the typical augen mylonites. The petrographic results and geothermobarometry indicate that dynamic metamorphism and shearing occurred at 680-750° C and 4-6 kbar in the middle crust. According to the age of the sheared granite dykes in the TDZ, the upper age limit to the main ductile deformation along the TDZ is 1622 Ma.

A lower age limit to the TDZ ductile deformation phases is probably 1460 Ma. The Mesoproterozoic reactivation of the TDZ was associated with granitoid intrusions such as Žemaičių Naumestis (Motuza et al., 2006) and Pilsote (Motuza's personal comment) which intruded (ca. 1460 Ma) the charnockitic rocks at ca. 1460 Ma. The shear band cleavage in the TDZ ultramylonites can be formed in response to a compression during this magmatic event.

In the study, information on the isotopic ages is lacking for the pegmatite veins and the pseudotachylites and we can not conclude when they were formed in the TDZ. As compared with other pseudotachylites on a regional scale, they can be of few generations as well as in Finland (Torvela et al., 2008).

The ductile pattern was partly overprinted by later deformation under brittle conditions. Breacciated charnockitoids can be formed in the Precambrian, however, breccia composed of fragments of charnockitoids and Cambrian sedimentary rocks indicate their Phanerozoic age. During the Caledonian orogeny, the TDZ was reactivated, and the Telšiai fault, the important tectonic feature in the Phanerozoic sedimentary cover with offset for more than 200 m, was formed (Stirpeika, 1999, Suveizdis, 2003).

The crystallization of the fine-grained granitic dykes at 350 Ma in the western part of the TDZ proves that the Paleoproterozoic crust in western Lithuania as well as in Poland was affected by the Early Carboniferous magmatism. The Girkaliai granitic dyke has similar age to the 330±12 and 370±12 Ma diabase dykes, in the eastern Baltic offshore (K-Ar method, Birkis, Kanev, 1991) and alkaline-carbonatite intrusions in Poland such as Elk (348±8 Ma, SHRIMP), Pisz (346±5 Ma, SHRIMP) and Tajno (348±15 Ma, TIMS). They characterize intracratonic magmatism related to a stage of Paleozoic rifting in the East European Craton (Demaiffe et al. 2005, Wiszniewska et al. 2010).

Thus, the TDZ demonstrates the long tectonic „life cycles" of the crust evolution. The TDZ was initiated after 1622 Ma along with the intensive deformation through phase D1. D1 phase is characterized by the development of different types of mylonites and probably related to the late Gothian orogeny. The TDZ was reactivated under ductile conditions at ca. 1460 Ma during Danopolonian orogeny (D2 phase), and then at least twice in brittle conditions at the Cambrian and Silurian-Devonian periods. The Early Carboniferous magmatism completed the TDZ evolution.

4.2. Timing of magmatic activity and deformation phases of the Drūkšiai-Polotsk deformation zone

The Proterozoic evolution of the crust in north-eastern Lithuania is still poorly known and has mostly been reconstructed using geochronological data from southern Lithuania, Belarus, Latvia and Poland. In this study, both protoliths and time of rock mylonitization from the the Drūkšiai-Polotsk deformation zone (DPDZ) have been dated for the first time. Two previously unknown magmatic events are now recognized in the DPDZ.

In the northern part of the DPDZ, the granitic protomylonite (drill core Novikai-1) contains magmatic zircons of 1797±10 Ma age (Table 2), which is interpreted as the age of the granite magma emplacement and crystallization. The zircon was affected by later magmatic (?) fluids at 1788±12 Ma. Similar ages in error limits are known for Vydmantai-1 charnockitic rocks from western Lithuania (1813±20 Ma, Claesson et al., 2001) and for the Mazsalaca granodiorite in northern Latvia (1816±5 Ma, Mansfeld, 2001). The Novikai-1 granite includes zircon xenocrysts with the ages of 1916, 1915, 1887 and 1884 Ma, which are close to the age of the 1890 Ma magmatic stage and ca. 1879 Ma migmatization in the Belarus-Podlasie Granulite belt, in Belarus (Taran and Bogdanova, 2003)

Along the southern margin of the DPDZ, the augen mylonite (drill core Tverečius-336) has magmatic zircon of 1580 Ma (Table 2), which reflects the time of crystallization of its granitoid protolith. This magmatic event is close to the Genčiai-6 granites in the TDZ and of the same age as the 1580 Ma Riga age anorthosite-mangerite-rapakivi pluton in Latvia and Estonia (Rämö et al. 1996). These igneous activities reflect an intracontinental extensional setting at 1600-1500 Ma (Korja et al., 1993, Puura and Floden, 1999).

The newly obtained ages indicate that the ductile deformation (phase D1) accompanied the DPDZ faulting at ca. 1530 Ma. This is supported by the 1534±9 Ma U/Pb age of syndeformational titanite from the Tverečius-336 augen mylonite (Vejelyte et al., 2010). The group of zircon grains from this rock with similar ages was most probably formed during this phase of the ductile deformation in the DPDZ. A similar the $^{40}Ar/^{39}Ar$ amphibole age of 1534±11 Ma was obtained from a sheared gabbro in the Vepriai borehole-22 nearby the DPDZ (Skridlaitė et al., 2006). The DPDZ steep shearing, occurring during the retrograde stage of metamorphism, developed in the DPDZ and likely in the whole Polotsk-Kurzeme fault belt. Numerous anorthosite-mangerite-charnockite-granite suites (AMCG) and A-type granitoid intrusions of similar age were emplaced into the crust in Fennoscandia at the same time, such as the Mazury complex in NE Poland (1525-1500 Ma, Dörr, 2002; Wiszniewska et al., 2002) and in South Lithuania (Sundblad et al., 1994), the Salmi AMCG intrusion in Karelia (Amelin et al., 1997), and several intrusions in Central Sweden (Andersson et al., 2002). Characteristically, they are accommodated mostly within E-W faulting zones caused by regional extension of the crust between ca. 1.55 and 1.50 Ga.

Phase D2 of deformation occurred in the in the DPDZ between 1511 and 1468 Ma when zircon rims grew in the Tverečius-336 augen mylonite. This phase is less expressed than D1 and characterized by locally formed ultramylonites and mylonite with C'–type fabric. The D2 phase in the DPDZ occurred at similar ages of the D2 phase in the TDZ and 1460-1450 Ma granitoid intrusions, which are also located close to E-W trending deformation zones in western Lithuania such as Žemaičių Naumestis (Motuza et al., 2006), Pilsotės (Motuza's person. comment) and Gėluva (Skridlaite et al., 2007). In the Lazdijai area (southern Lithuania) the cooling $^{40}Ar/^{39}Ar$ amphibole age from the gabbro intrusions is 1427-1473 Ma (Skridlaite et al., 2006) and from an ampibolite ca. 1470-1490 Ma (Bogdanova et al. 2001). The detailed $^{40}Ar/^{39}Ar$ geochronological studies in the Oskarshamn area, southern Sweden (Soderlund, P. et al., 2008) have confirmed the superimposition of two tectonic events 1.51-1.47 and 1.43-1.42 Ga. The ductile pattern has partly overprinted by later brittle deformation when pseudotachylites and breccias were formed. The possible time of their formation can be Late Proterozoic or/and Phanerozoic.

Thus, the major ductile deformation in the DPDZ and the formation of its different mylonites occurred after the 1580 Ma magmatism. The phase D1 of ductile deformation is 1534 Ma old while the ductile or transitional, from ductile to brittle deformation of phase D2 took place between 1511 and 1468 Ma along with the uplift and intense fluid activity which produced epidote-rich ultramylonites. The brittle deformation (D3) completed the tectonic history of the DPDZ in late Proterozoic or Phanerozoic time.

4.3. Comparison of the TDZ and DPDZ evolutions

The results of the present study allow to compare the TDZ and DPDZ evolutions (Tables 2 and 3). In the TDZ, deformation ductile phase (D1) occurred after the emplacement of the granitic dykes at 1622 Ma and at 1534 Ma in the DPDZ. Phase D2 is nearly similar in both the TDZ and DPDZ and reflects a compression between ca. 1500 and 1450 Ma.

In the TDZ, the brittle phase (D3) caused the formation of breccias. Breccias can be formed in the DPDZ at a close time as well. The D4 phase is recorded only in the TDZ and related to fault formation in the sedimentary core during Silurian-Devonian time.

Both, the TDZ and DPDZ, belonging to the wide Polotsk-Kurzeme fault belt in the western part of the East European Craton, represent the Mesoproterozoic E-W-trending ductile shear systems in the western and eastern Lithuania and characterize their deformational history.

Table 3. Major magmatic and deformational events of the development of the TDZ and DPDZ

Deformation zones	**Magmatic age, Ma**	**Phase D1, age, Ma**	**Phase D2 age, Ma**	**Phase D3 age, Ma**	**Phse D4, age, Ma**	**Magmatic age, Ma**
TDZ	1622 granitic dykes	<1622 ductile deformation	~1460 ductile deformation	500 brittle deformation	443-360 brittle deformation	350 granitic dyke
DPDZ	1580 granodiorite	1534 ductile deformation	1511-1468 ductile-brittle deformation	brittle deformation Late Proterozoic - Phanerozoic		

CONCLUSIONS

1. According to the present petrographic-microstructural study, two phases of ductile deformation (D1 and D2) have been recognized in the TDZ. During mylonitization coarse grained charnockitoids, granites and metapelites were deformed at high grade metamorphic conditions from granulite to amphibolite facies. During D1 phase within the TDZ syndeformational microstructures were formed by subgrain rotation and grain boundary migration recrystallization, whereas postdeformational microstructures characterize a recovery stage. Phase D2 characterizes a ductile compressive phase in the

TDZ. This caused local crenulation cleavage in the ultramylonites. The ductile pattern was partly overprinted by later deformation under brittle conditions (D3 and D4) in the uppermost crust when breccias and pseudotachylites were formed.

2. The major ductile shearing (phase D1) in the TDZ produced the mylonites at 680–750°C and 4–6 kbar in the crust at the depths of 15-18 km. Some differences of P-T parameters within the TDZ can have been because of faster exhumation of some blocks and more intensive erosion.

3. The crystallization age of the charnockitoids located in the TDZ is between 1846 and 1814 Ma as constrained by U/Pb ion probe analyses on zircons from a weakly deformed charnockitoid, its mesomylonite and ultramylonite. The zircon's rims grew at 1733-1679 Ma and reflect a tectonothermal event during the Gothian orogeny. At ca. 1622 Ma granitic dykes intruded the 1846-1814 Ma charnockitoids. This can has been related to the adjacent 1.58 Ga Riga pluton and probably indicates an early stage of its formation and melting of the crust.

4. Since both charnockitoids and granitic dykes deformed in the same degree during the major D1 phase the TDZ was initiated not earlier than the emplacement of the 1622 Ma granitic dykes. Reactivation of the TDZ occurred in relation with the 1460 Ma granitoid intrusions.

5. The western part of the TDZ also was reactivated at 350 Ma and affected by the previously unknown Early Carboniferous magmatism.

6. Two ductile deformation phases (D1 and D2) have been identified within the DPDZ. The dynamic recrystallization structures of phase D1 in the granitoids of the northern DPDZ are well preserved. They were developed by subgrain rotation and grain boundary migration recrystallization in lower amphibolite- to greenschist facies. In the granodioritic augen mylonite the metamorphic titanite is associated with the D1 deformation fabric. The epidote-rich ultramylonite was formed during the progressive D2 deformation along narrow zones when the rocks were exhumed during the uplift. C'–type fabric of D2 phase appeared in granitoids locally and developed during late stages of mylonitization. During the DPDZ reactivation in the brittle regime, breccias and pseudotachylites were produced.

7. Two new stages of magmatism have been recognized by U/Pb zircon geochronological studies within the DPDZ. The Novikai granitoid at the northern margin of the DPDZ was emplaced between 1797±10 and 1788±13Ma. The crystallization age of the Tverečius granitoid, located at the southern margin of the DPDZ, is 1580±17 Ma old. The zircon's overgrowths and TIMS titanite ages obtained for this mylonitized granitoid demonstrate that the DPDZ shearing occurred at 1534±9 Ma. Zircon was hydrothermally reworked between 1511 and 1468 Ma.

8. Generally, both the TDZ and DPDZ were developed in the Mesoproterozoic between 1622 and 1534 Ma, but reactivated at ca. 1460 Ma and later in the Phanerozoic within the large Polotsk-Kurzeme fault belt.

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2008 Lithuanian Science Award for the publication “Breathing of Earth planet”.

2007 The Lithuanian-American engineer Edmundas Čapas’ award for the Young scientists’ publications in the journal “Mokslas ir gyvenimas” (Science and Life).

2005 The first place of High school student’s research papers for the work “A comparative analysis of the Telšiai and Drūkšiai-Polotsk shear zones".

Geologic Work Experience:

2008 September – until now: Lecturer of courses: Formation of mineral deposits, Cryology, Economic geology, Geology and Quaternary geology field works at the Dept. of Hydrogeology and Engineering Geology, Vilnius University, Lithuania.

September 2006 – September 2008 Lecturer of courses: Structural Geology and Geology and Quaternary field works at the Dept. Geology and Mineralogy, at Vilnius University, Lithuania.

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2. July 2007: Field trip on magmatic rocks petrology and structural geology on Bornholm, Denmark (Prof. Svetlana Bogdanova, Lund University).

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4. December 2006: Field trip on regional geology on the Canary Islands. (Prof. Anders Lindh, Lund University).

5. July 2006: Field trip of magmatic and metamorphic petrology in South and Central Sweden (Prof. Svetlana Bogdanova, Lund University and Prof. Gediminas Motuza, Vilnius University).

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2006 and 2008 "Major Weakness Zones in the Lithosphere of Western Baltica" as part of Visby Programme supported by the Swedish Institute, Sweden and Lithuanian State Science and Studies Foundation.

TELŠIŲ IR DRŪKŠIŲ-POLOCKO DEFORMACIJOS ZONOS: PETROGRAFIJA ir U/Pb GEOCHRONOLOGIJA

REZIUME

Telšių (TDZ) ir Drūkšių-Polocko deformacijos zonos (DPDZ) kristaliniame pamate yra svarbios plastinės šlyties sistemos, priklausančios Kurzemės-Polocko lūžių juostai, esančiai vakariniame Rytų Europos kratono pakraštyje. Skirtingai nei šalia esančios uolienos, deformacijos zonose slūgso labiau pakitusios uolienos. Uolienos pasikeitimo pobūdis priklauso nuo tektoninėje zonoje vyraujančių plastinės ar trapiosios deformacijos sąlygų. Deformacijos mechanizmą zonos viduje daugiausiai lemia uolienos mineralinė sudėtis, grūdelių dydžiai ir fizikiniai procesai. Dažnai plastinės deformacijos vyrauja prie aukštesnių metamorfizmo sąlygų, o trapiosios – prie žemesnių.

Taikant petrografinį, mikrostruktūrinį ir izotopinės geochronologijos metodus kristalinių uolienų tyrimams, šiame darbe išaiškinti dar prekambre vykę magmatizmo, deformacijų ir metamorfizmo procesai bei stadijos tirtose lūžių zonose, kurios kelis kartus reaktyvavosi (atsinaujino) proterozojuje ir fanerozojuje. Tokie tektoniniai judesiai galėjo įtakoti geoterminės energijos, naftos ir dujų susidarymą ir jų paplitymą. Deformuotų uolienų išsiaiškinimas lūžių zonose svarbus ir praktiniu ir moksliniu požiūriu. Jų palyginimas su panašiomis deformacijos zonomis Baltijos skyde Švedijoje bei Baltarusijoje gali padėti atskleisti regiono aplink Baltijos jūrą, esančio Rytų Europos kratone, evoliuciją.

Pagrindinis šio darbo objektas yra Telšių ir Drūkšių-Polocko deformacijos zonų kristalinio pamato uolienos.

Pagrindinis darbo tikslas – nustatyti Telšių ir Drūkšių-Polocko deformacijos zonų uolienų vystymosi istoriją remiantis petrografiniais, mikrostruktūriniais, geotermobarometriniais ir U/Pb geochronologiniais duomenimis.

Darbo uždaviniai: petrografiškai-mikrostruktūriškai apibudinti Telšių ir Drūkšių-Polocko deformacijos zonų uolienas ir atlikti jų klasifikaciją; charakterizuoti uolienų mikrostruktūras bei nustatyti magmatizmo, metamorfizmo ir deformacijos stadijas tirtose deformacijos zonose; apskaičiuoti uolienų slėgio ir temperatūros sąlygas Telšių

deformacijos zonoje; gauti magmatizmo, metamorfizmo ir deformacijos amžius iš Telšių ir Drūkšių-Polocko deformacijos zonų uolienų.

Mokslinis naujumas: pirmą kartą atlikta petrografinė-mikrostruktūrinė uolienų klasifikacija Telšių ir Drūkšių-Polocko deformacijos zonose; pirmą kartą U/Pb geochronologiniu metodu jautrios aukštos rezoliucijos joniniu mikrozondu ir terminiu joniniu masės spekrometru atitinkamai pagal cirkoną ir titanitą nustatyti nauji magmatizmo ir deformacijos amžiai Telšių ir Drūkšių-Polocko deformacijos zonose; pirmą kartą Vakarų Lietuvoje surasti ankstyvojo karbono laikotarpio granitai datavus cirkoną U/Pb metodu jautrios aukštos rezoliucijos joniniu mikrozondu (SHRIMP).

Atlikus petrografinius, mineralų cheminės analizės, geotermobarometrijos ir geochronologinius tyrimus Telšių ir Drūkšių Polocko deformacijos zonose gautos šios išvados:

1. Remiantis petrologiniais ir mikrostruktūriniais tyrimais dvi plastinės deformacijos fazės (D1 ir D2) nustatytos Telšių deformacijos zonoje. Milonitizacijos metu stambiagrūdžiai čarnokitoidai, granitoidai bei pelitai buvo milonitizuoti granulitinės ir amfibolitinės facijų sąlygomis. Fazės D1 sindeformacinės mikrostruktūros susidarė dėl subgrūdų rotacijos ir grūdų ribų migracijos perkristalizacijos, o postdeformacinės – jau streso atsistatymo metu. Fazei D2 charakteringa plastinė deformacija kompresinėmis sąlygomis, kurios metu krenuliacinis klivažas susidarė ultramilonite. Vėliau, plastinės deformacijos struktūros vietomis buvo paveiktos trapiosios deformacijos (D3 ir D4) procesų viršutinėje plutoje, todėl susidarė brekčijos ir pseudotachylitai.

2. Pagrindinės plastinės deformacijos (D1) metu Telšių deformacijos zonoje milonitai susidarė esant 680–750ºC temperatūrai ir 4-6 kbar slėgiui 15-18 km plutos gylyje. Slėgio-temperatūros parametrų skirtumai TDZ galėjo atsirasti dėl kai kurių blokų greitesnio kilymo ir intensyvesnės erozijos.

3. Sipnai deformuotų čarnokitoidų, jų protomilonitų, mezomilonitų ir ultramilonitų, esančių TDZ, kristalizacijos amžius yra tarp 1846-1814 mln. metų, gautas datavus cirkonus U/Pb metodu pagal SHRIMP technologiją. Šių cirkonų apaugimai augo prieš 1733-1679 mln. m. ir susiję su tektonoterminiu įvykiu Gotiškosios orogenezės metu. Prieš 1620 mln. m. granitinės daikos įsiterpė į 1846-1814 mln. laikotarpio čarnokitoidus.

Šis magmatizmo etapas yra susijęs su šalia esančiu Rigos plutonu ir rodo jo ankstyvosios stadijos formavimąsi bei lydymąsi plutoje.

4. Kartu čarnokitoidai ir granitinės daikos buvo vienodo laipsnio deformacijos paveiktos D1 fazės metu, todėl Telšių deformacijos zona pradėjo formuotis ne anksčiau kaip prieš 1622 mln. metų. TDZ reaktyvacija vyko prieš 1460 mln.m. ir susijusi su granitinėmis intruzijomis.

5. Vakarinėje TDZ dalyje dar įvyko reaktyvacija prieš 350 mln. m., kai buvo paveikta anksčiau nežinomo ankstyvojo karbono magmatizmo.

6. Dvi plastinės deformacijos (D1 ir D2) buvo nustatytos Drūkšių-Polocko deformacijos zonoje. Dinaminės perkristalizacijos struktūros gerai išliko granitoiduose fazės D1 metu. Jos susidarė dėl subgrūdų rotacijos ir grūdų ribų migracijos perkristalizacijos amfibolitinės- ir žaliųjų skalūnų facijų sąlygomis. Grandioritiniame akiniame milonite titanitas susidarė fazės D1 metu. Epidotinis ultramilonitas charakteringas D2 fazei, kuris susidarė siauromis juostomis dalyvaujant fluidams. C‘-tipo šlyties juostelės aptiktos granitoiduose formavosi vėlyvosios milonitizacijos stadijoje. DPDZ reaktyvuojantis trapiosios deformacijos sąlygomis susiformavo brekčijos ir pseudotachilitai.

7. Dvi naujos magmatizmo stadijos remiantis U/Pb geochronologiniais tyrimais nustatytos Drūkšių-Polocko deformacijos zonoje. Novikų granitoidai šiauriniame DPDZ pakraštyje įsiskverbė į plutą tarp 1797±10 ir 1788±13 mln. metų, o pietiniame DPDZ pakraštyje Tverečiaus granitoidai intrudavo prieš 1580±17 mln. metų. Cirkono apaugimų ir titanito datavimai U/Pb metodu su joniniais mikrozodais rodo, kad uolienos buvo milonitizuotos prieš 1534±9 mln. m. Be to tie patys cirkonai buvo hidrotermiškai paveikti prieš 1511 ir 1468 mln. metų.

8. TDZ ir DPDZ, esančios Polocko-Kurzemės lūžių juostoje, formavosi mezoproterozojaus laikotarpiu tarp 1620 ir 1530 mln. m., o reaktyvavo prieš 1460 mln. metų ir vėliau – fanerozojuje.