Geological Quarterly, 2011, **55** (1): 63–70

Charnockitic rocks in the crystalline basement of Western Lithuania: implications on their origin and correlation with the Askersund suite in SE Sweden

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Motuza G. and Motuza V. (2011) – Charnockitic rocks in the crystalline basement of Western Lithuania: implications on their origin and correlation with the Askersund suite in SE Sweden. Geol. Quart., **55** (1): 63–70. Warszawa.

The polyphase Kuršiai batholith of charnockitic rocks, extending over some 10 000 km^2 with a few smaller plutons, has been revealed in the West Lithuanian Granulite Domain. Plutons intruded between 1850 and 1815 Ma, and are composed of intermediate and acid varieties of charnockitic rocks. They are ferroan, calc-alkalic to alkali-calcic, predominantly peraluminous, and reveal both S- and A-type granite characteristics. Based on petrochemical data charnockitic magma was generated in the continental crust more then 30 km-thick, that formed in a subduction-related collisional tectonic environment. Magmatism took place in the later orogenesis period, transitional from syn-kinematic collisional to post-kinematic extensional phases. Magma generation was presumably triggered by intrusions of basalt magma in the crust. The rock composition was determined by the interaction of basaltic magmas with anatectic melt of Al-rich metasedimentary rocks, involving mechanisms of assimilation and hybridization. The close geochemical affinity of the Kuršiai suite in Western Lithuania to the coeval Askersund plutonic suite in southeastern Sweden implies a similar tectonic environment and processes of the formation of continental crust and suggests possibilities of wider correlation between these regions.

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Key words: Charnockitic rocks, West Lithuanian Granulite Domain, Kuršiai pluton, Askersund suite.

INTRODUCTION

Lithuania is situated near the western margin of the East European Craton (EEC) within the Svecofennian Domain covered by Phanerozoic platformal strata and separated from the Fennoscandian Shield by the Baltic Sea. The crystalline crust has been investigated using drilling and geophysical methods.

Plutons of charnockitic and coeval granitic rocks have been revealed in the basement of Western Lithuania, marking an extensive magmatic event in the history of EEC formation (Fig. 1). The Kuršiai batholith, which encompasses an area of approximately 140 × 80 km in Western Lithuania and offshore under the Baltic Sea, is one of the largest known charnockitic bodies in the western part of the EEC. Charnockitic rocks of this pluton have been obtained from 86 boreholes (Fig. 1). A few smaller charnockitic plutons – Sidabravas, Ariogala and Kybartai – are each characterized by cores from a single borehole. Together with the Kuršiai batholith they are referred to as the Kuršiai suite. U-Pb zircon dating places the ages of the charnockitic rocks at between 1850 and 1815 Ma (Claesson *et al*., 2001; Motuza *et al*., 2008). Along with the charnockitic rocks, large granitic plutons have been revealed. The granitic rocks have similar geochemical characteristics to the charnockites. The U-Pb zircon age of garnet- and cordierite-bearing granite from the Kužiai-65 borehole is 1844 ±12 Ma and gneissic granite from the Graužai-105 borehole is 1832 ±4.9 Ma i.e. within the time span of the Kuršiai suite (Motuza *et al*., 2008).

The general structural, mineralogical and geochemical parameters of the charnockitic and granitic rocks, and the original chemical analyses and dating results, are published and available on the web (Motuza *et al*., 2008).

This paper is devoted to a more detailed petrological characterization of the charnockitic rocks, the implications for their formation, and a proposed correlation with the Askersund suite in southeastern Sweden.

The Askersund suite in SE Sweden is located geographically close to Western Lithuania (Fig. 1). That suite embraces a number of plutons composed of granitic rocks, subordinated monzodiorite, quartz monzonite and gabbro (e.g., Wikström and Andersson, 2004). In the granite of the Graversfors intrusion and the quartz monzonite of the Tiveden area both clino- and orthopyroxenes are present, thus representing

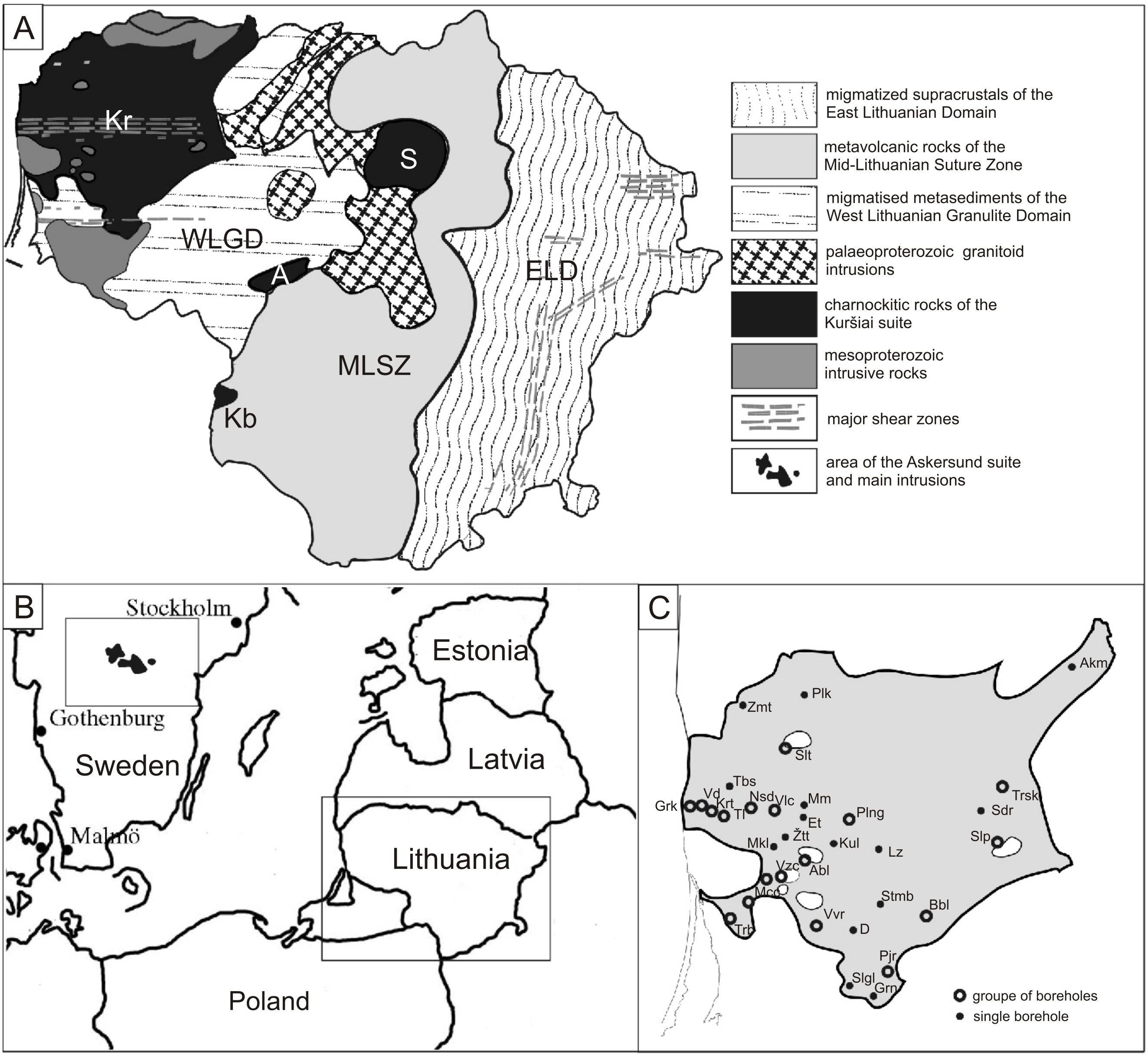

Fig. 1A – geological sketch of the crystalline basement of Western Lithuania; B – geographical position of the research area, Askersund suite plutons marked in black; C – location of boreholes and their groups in the Kuršiai batholith

ELD – East Lithuanian Domain, MLSZ – Mid-Lithuanian Suture Zone, WLGD – West Lithuanian Granulite Domain; plutons of charnockitic rocks: A – Ariogala; Kb – Kybartai; Kr – Kuršiai; S – Sidabravas; boreholes: Abl – Ablinga, Akm – Akmenė, Bbl – Baubliai, D – Darius, Et – Eitučiai, Grk – Girkaliai, Grn – Goraininiai, Krt – Kretinga, Kul – Kuliai, Lz – Laužai, Mcc – Macuičiai, Mkl – Mykoliškis, Mm – Mamiai, Nsd – Nausodis, Pjr – Pajūris, Plk – Paluknė, Plng – Plungė, Sdr – Syderiai, Slp – Šlapgiriai, Slt – Salantai, Slgl – Šilgaliai, Stmb – Stumbrės, Tbs – Tūbausiai, Tl – Toliai, Trb – Traubai, Trsk – Tryškiai, Vd – Vydmantai, Vlc – Vėlaičiai, Vvr - Veivirėžnai, Vzc – Vėžaičiai, Zmt – Žemytė, Žtt – Žutautai

acharnockitic association. Plutons of the Askersund suite are located in the southern part of the Transscandinavian Igneous Belt (TIB), along the border with the Svecofennian province, but are older compared to the major part of the TIB in this area (1.81–1.76 Ga), partly deformed and referred to as “TIB-0” (Ahl *et al*., 2001; Wikström and Andersson, 2004). The U-Pb in zircon ages of the Askersund suite fall in the age range 1.86–1.83 Ga (e.g., Persson and Wikström, 1993; Wikström, 1996; Andersson, 1997*a*; Andersson *et al*., 2006; Andersen *et al*., 2009).

GEOLOGICAL SETTING OF THE CHARNOCKITIC ROCKS IN WESTERN LITHUANIA

The extent of the charnockitic and coeval granitic plutons studied is limited to the West Lithuanian Granulite Domain (WLGD), which is a particular lithospheric block with a composition and structure distinct from the adjacent domains (Fig. 1). The crust in the WLGD is 40–45 km-thick while its lower crust is thin (~10 km). In the adjacent East Lithuanian

Domain the crust is 50–55 km-thick and more variable both in terms of thickness and composition (Giese, 1998; Eurobridge Seismic Working Group, 2001; Bogdanova *et al*., 2006). Both domains are separated by the Mid-Lithuanian Suture Zone, regarded as a subduction-related collisional zone formed at 1845–1830 Ma (Motuza, 2005).

The WLGD is a high-grade terrain characterized by temperatures of peak metamorphism of up to T = 850^{o}C, and corresponding pressures of up to 8 kbar (Skridlaitė and Motuza, 2001). Presuming an average crustal density of 2800 kg/m^3, a lithostatic pressure of 8 kbar corresponds to a depth of *ca*. 29 km.

Supracrustal rocks are preserved as highly migmatized relics. They are represented by metapelitic paragneisses with garnet and sillimanite, pyroxene-bearing calcium-rich paragneisses and felsic biotite paragneisses grading into quartzites. The supracrustals are interpreted as primary greywackes, in places with an admixture of pyroclastic material, and arkosic sandstones (Motuza and Staškus, 2009). Mafic metavolcanics are not known on the subsurface of the crystalline crust in the WLGD. The possible age of sedimentation is limited by an interval 2.1–1.85 Ga set by the youngest age of the detrital zircon (2.1–2.145 Ga) and the oldest crystallization age of charnockitic rocks (1.846 ±12 Ga; Claesson *et al*., 2001; Skridlaitė *et al*., 2007; Motuza *et al*., 2008).

PETROGRAPHIC FEATURES OF THE WLGD CHARNOCKITIC ROCKS

The Kuršiai batholith is almost entirely composed of charnockitic rocks except for a few minor bodies of granite and local enclaves of migmatized supracrustals. The classification of charnockitic rocks follows that of Le Maitre (2002). The principal varieties of charnockitic rocks in Kuršiai pluton are: opdalite, mangerite, charnockite, enderbite. The Sidabravas pluton is represented by mangerite, and the Ariogala and Kybartai plutons by charnockite.

Typical rock-forming minerals are plagioclase (An 40-55), K-feldspar, quartz, orthopyroxene (ferroenstatite to magnesian ferrosalite), biotite, clinopyroxene (ferrodiopside), and garnet (almandine). Common accessory minerals are magnetite, ilmenite, hercynite, zircon, monazite, xenotime and fluorapatite. Hornblende appears locally as a secondary mineral, forming replacement rims on clinopyroxene. The bulk content of mafic minerals is up to 20–25%.

The igneous texture is well-preserved in the charnockitic rocks. They are medium-grained (1–5 mm) to coarse-grained (5–10 mm), often porphyritic, formed by K-feldspar and plagioclase phenocrysts up to 20–30 mm in diameter. Plagioclase is often euhedral or hypidiomorphic with simple twins and oscillatory zoning. Orthopyroxene appears mainly in separate grains, in places overgrown by clinopyroxene, indicating an earlier crystallization of the orthopyroxene (Motuza *et al*., 2008). The rock structure is predominantly massive, but in shear zones the rocks are strongly deformed up to mylonites.

GEOCHEMICAL CHARACTERISTICS OF THE WLGD CHARNOCKITIC ROCKS AND THE ASKERSUND SUITE

47 analyses of the Kuršiai suite rocks were compiled from Motuza *et al*. (2008) and compared with TIB rocks of the Askersund suite compiled from Andersson (1997*b*). The SiO_2 content in the WLGD charnockitic rocks varies from 53 to 73%, while the average is 63%, indicating a predominance of intermediate varieties.

All charnockitic rocks of the Kuršiai pluton have features of S-type granite based on parameters proposed by Chappell and White (2001). In particular, the Aluminum Saturation Index (Al_2O_3/K_2O+Na_2O+CaO) varies between 1.2 and 2.1, thus most of rocks are peraluminous, but on the Shand ASI diagram (Maniar and Piccoli, 1989) almost 20% of the samples fall within the metaluminous field (Fig. 2). At the same time, most of Kuršiai charnockitic rocks reveal an A-type affinity (Motuza *et al*., 2008).

Following the geochemical classification of granitic rocks proposed by Frost *et al*. (2001), the Kuršiai charnockitic rocks are ferroan in terms of the Fe-number, alkali-calcic or calc-alkalic in terms of their modified alkali-lime index, a high-K or shoshonitic, except for the enderbites which are medium-potassic (Fig. 3).

Generally most of the S-type granitoids are magnesian and invariably peraluminous, while the A-type granitoids typically are ferroan, metaluminous, alkalic or alkali-calcic (Frost *et al*., 2001). The WLGD charnockitic rocks demonstrate an affinity to both S- and A-type granitoids being at the same time ferroan, peraluminous and calc-alkalic.

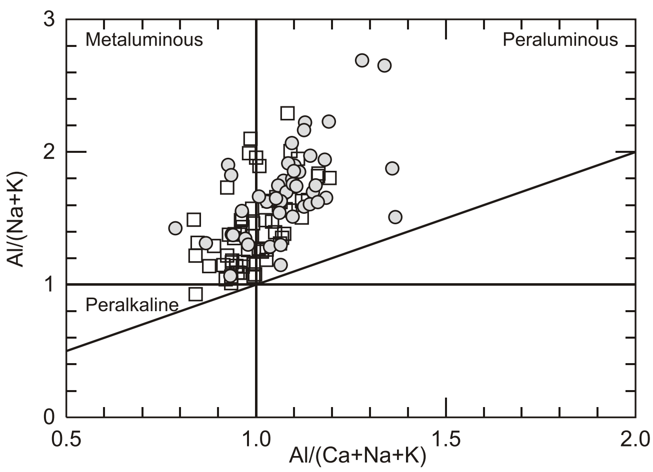

Fig. 2. Aluminum Saturation Index diagram (Maniar and Piccoli, 1989) for the charnockitic rocks of the Kuršiai suite (full circles; Motuza *et a*l., 2008) and the Askersund suite (open squares; Andersson, 1997*b*)

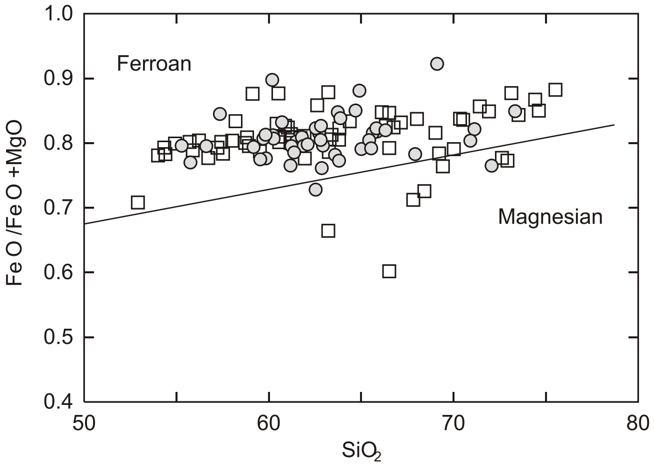

Fig. 3. FeO/FeO+MgO *vs*. SiO_2 diagram distinguishing ferroan and magnesian plutons by Frost *et al*. (2001)

Explanations and references as in Figure 2

CONSIDERATION OF MAGMA SOURCE AND TECTONIC SETTING

Models of magma generations produce the charnockitic rocks suggest various sources, but mainly a combined mantle and crustal source. According to Frost and Frost (2008) and Rajesh (2007) intrusion of basic magma from the mantle into the lower crust and its subsequent interaction with the crustal material (in terms of assimilation-fractional crystallization models) are the principal mechanisms of magma generation. Patiño Douce (1999), Frost *et al*. (2001), Rajesh and Santosh (2004) emphasize the contribution of reduced tholeitic or mildly alkalic basaltic magma to the generation of iron-enriched melts, producing ferroan granitic and charnockitic rocks while peraluminous potassic magmas are originated by melting and assimilation of pelitic or semipelitic rocks. Patiño Douce (1999) experimentally demonstrated that the best explanation for the origin of charnockitic rocks is an interaction between basaltic magmas and Al-rich metasedimentary rocks at relatively shallow depths (15–20 km), where the former acts as the source of both matter and heat. The geochemical and mineralogical composition of the Kuršiai rocks fit these petrogenetic scenarios (Fig. 4). The affinity of the Kuršiai rocks to the S-type granites (*sensu* Chappell and White, 2001) suggests that both a tholeiitic magma and supracrustals (metagreywackes and metapelites) were involved in the melt generation.

In spite of the fact that basic rocks are rare on the subsurface of the WLGD, evidence for the possible involvement of basaltic magma is provided by basic enclaves rarely appearing within the charnockitic rocks as a few metres-thick intervals within drillcores. These rocks consist of clino- and orthopyroxene and plagioclase, are fine-grained and granoblastic, locally with a relic porphyritic texture defined by the presence of 1–2 mm plagioclase phenocrysts. Some basic enclaves (borehole Grk-4) contain phenocrysts of feldspar up to 10–15 mm in size, macroscopically similar to those in the surrounding rocks, a feature indicating mingling of magmas. The involvement of Al-rich metasedimentary rocks in the magma generation of the mostly peraluminous Kuršiai suite is supported by the fact that the suite is hosted by migmatized metasedimentary sequences and contains such enclaves. Moreover, inherited detrital cores of Paleoproterozoic age (2.15–2.45 Ga) have been revealed in zircons from the charnockitic rocks, indicating input from metasediments (Claesson *et al*., 2001).

The crystallization temperature of the Kuršiai and Askersund rocks was roughly evaluated using experimental diagrams by Green and Pearson (1986) and Harrison and Watson (1984) respectively (Fig. 5). The isotherms show Fe-Ti oxide and apatite saturation at a pressure of 7.5 kbar. On the TiO_2 *vs*. SiO_2 plot the majority of points are grouped along the 900–950°C isotherms, while on the P_2O_5 *vs*. SiO_2 plot they are grouped predominantly between the 800–900°C isotherms, which is close to the typical emplacement temperature (900–1100°C) of charnockitic plutons (Frost and Frost, 2008). Detrital cores in zircons suggest that the assimilation took place at a magma temperatures not exceeding 850°C, because at higher temperature zircons might have dissolved (Watson, 1996). This pressure (7.5 kbar) and estimated temperature correspond to parameters for the peak metamorphism in the WLGD (8 kbar and 850°C), indicating the generation of the magma at a crustal level of around 30 km or slightly deeper. At the same time it provides evidence for the existence of a thick (>30 km) crust before 1.85 Ga – the time indicated by the oldest age of the charnockitic rocks.

On the Y-Nb-Ga and Rb/Nb *vs*. Y/Nb diagrams (Fig. 6) the charnockitic rocks of the WLGD reveal an affinity to A_2-type granites. Rocks of the A_2 group may be emplaced in a variety of tectonic settings, including postcollisional, but it is essential that their “magmas were generated from crust that had been through a cycle of subduction zone or continent-continent collision magmatism” (Eby, 1992, p. 643).

It has been noted that the geochemical composition of granitic magmas primarily reflect the composition and tectonic setting of their source rocks (Eby, 1992; Frost *et al*., 2001). Nevertheless certain tectonic implications are possible. Thus conditions for the generation of ferroan, relatively anhydrous magmas are common in extensional environment (Frost *et al*., 2001).

CORRELATION OF THE KURŠIAI AND ASKERSUND SUITES

Looking for possible correlatives, the Kuršiai suite has been compared with the Askersund suite in southeastern Sweden. The diagrams (Figs. 2–6) demonstrate certain similarities of both suites in composition, and possibly also in origin. Content and proportions of both major and trace elements vary within the same limits and form overlapping areas on the diagrams. One difference is that the Kuršiai suite has a higher abundance of peraluminous rocks and a systematically lower content of Na_2O. On the Y-Nb-3Ga ternary plot and Y/Nb *vs*. Rb/Nb plot both the Kuršiai and Askersund suites fall in the same A_2 field, implying the generation of magmas by melting of the crustal material, which had undergone subduction (Eby, 1992).

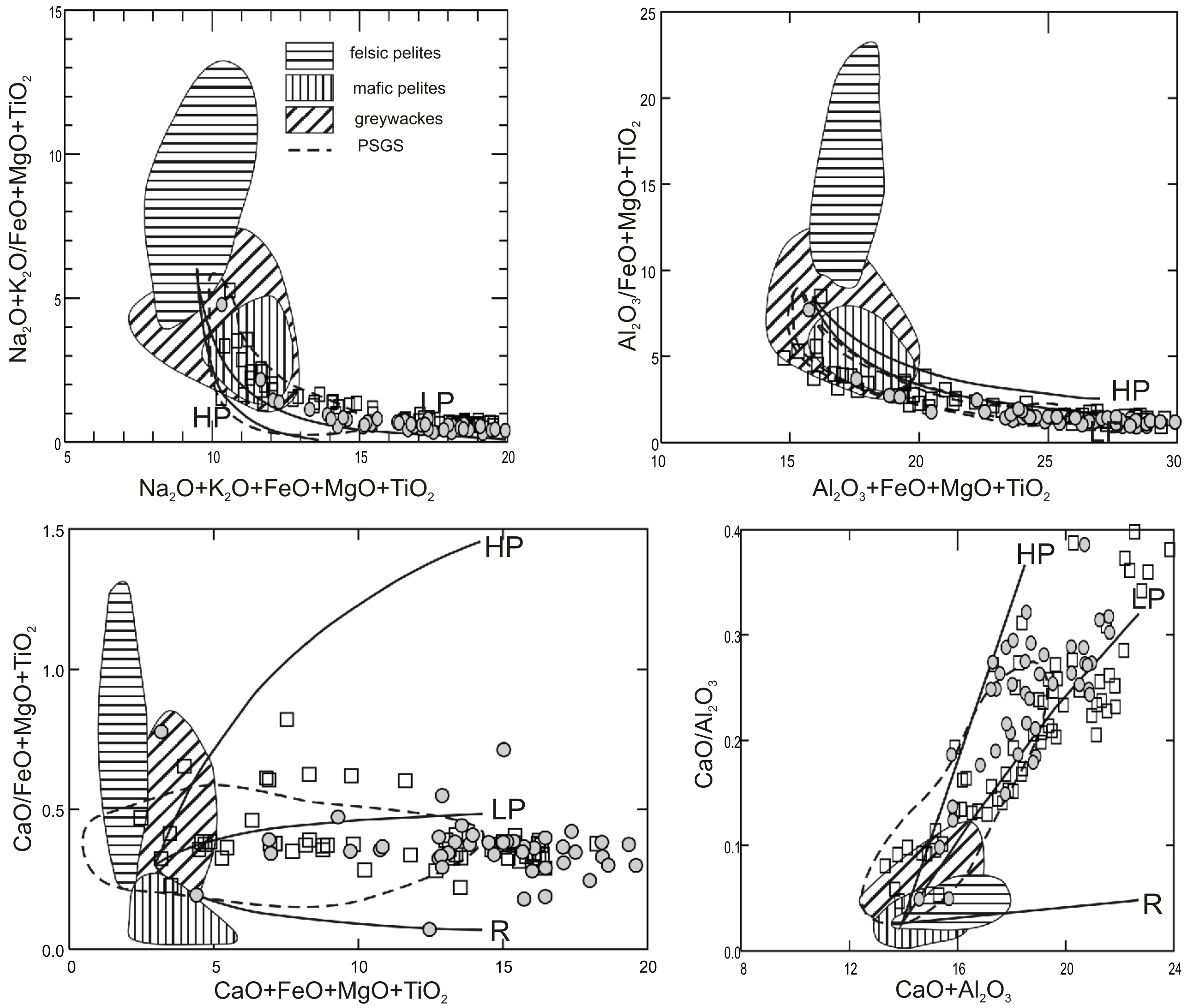

Fig. 4. The position of the Kuršiai and Askersund suites on experimental diagrams of magma composition, generated by the interaction between basalt melt and melt from various supracrustals (Patiño Douce, 1999)

HP – at high pressure (>10 kbar); LP – at low pressure (5–6 kbar); PSGS – Peraluminous S-type Granite Suite; R – magma composition that would result from melt-restite mixing in a pelitic system with addition of basaltic components; explanations and references as in Figure 2

The formation of the Askersund suite has been explained as due to melting of the pre-existing calc-alkaline crust, provoked by mafic underplating in a continental arc involving a mixing of granitic and gabbroic magmas to produce the intermediate rocks, and marks the shift from a collisional to the post-collisional extensional regime (Andersson, 1991, 1997*b*; Andersson and Wikström, 2004; Andersen *et al*., 2009).

Based on the geochemical data presented in the previous sections a similar model might be applied for the formation of the Kuršiai suite. The higher content of alumina and lower content of sodium in the Kuršiai suite might be caused by a different composition of the supracrustals, in particular a higher abundance of metapelitic rocks which influenced the composition of the Kuršiai magmas.

CONCLUSIONS

The Kuršiai plutonic suite, embracing the polyphase Kuršiai batholith and smaller plutons intruded between 1.850 and 1.815 Ga, has been revealed in the WLGD, Western Lithuania. It is composed of intermediate and acid varieties of charnockitic rocks. They are ferroan, calc-alkalic to alkali-calcic, predominantly peraluminous, and have both S- and A-type granite characteristics.

Charnockitic magma in the WLGD was generated in continental crust, more than 30 km-thick, formed in a subduction-related tectonic environment before 1850 Ma.

Magma generation presumably was triggered by intrusions of basaltic magma into the crust provoking its melting. The

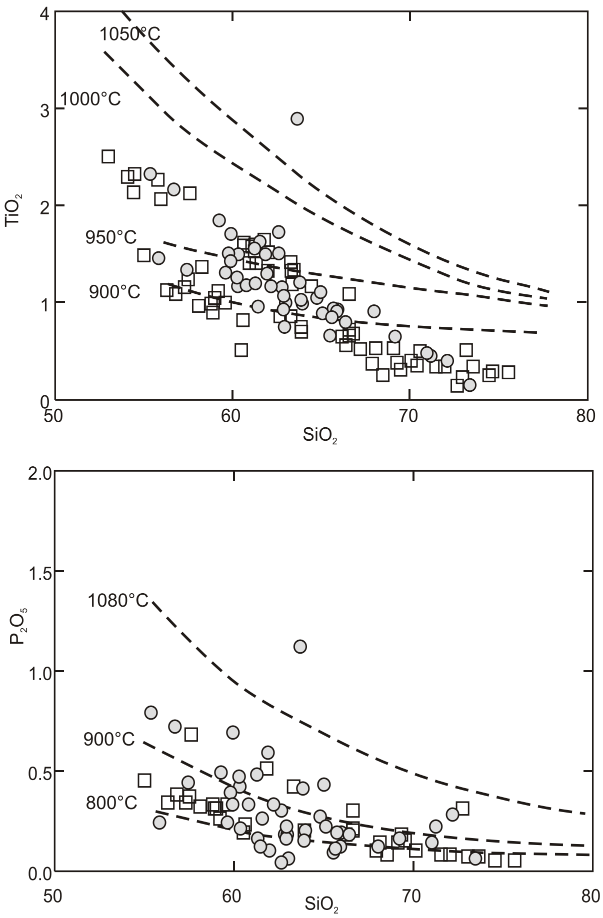

Fig. 5. The estimation of crystallization temperature of the Kuršiai charnockitic rocks using the experimental diagrams TiO_2 *vs*. SiO_2 of Green and Pearson (1986) and P_2O_5 *vs*. SiO_2 of Harrison and Watson (1984)

The isotherms show Fe-Ti oxide and apatite saturation temperatures at 7.5 kbar (Rajesh, 2007); explanations and references as in Figure 2

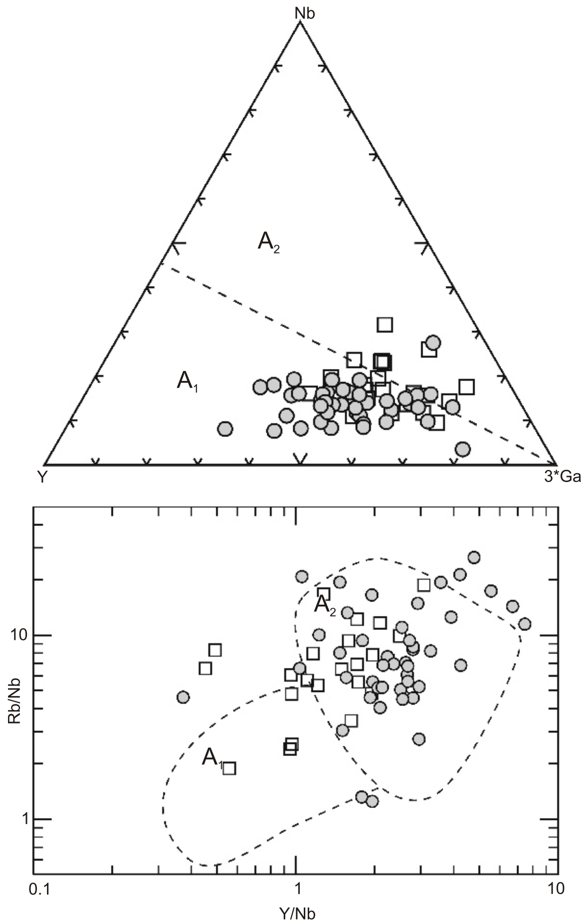

Fig. 6. The tectonic setting of the charnockitic magmatism in Western Lithuania and in SE Sweden using Y-Nb-Ga and Rb/Nb *vs*. Y/Nb diagrams (Eby, 1992)

A_1 – granitoids related to plumes, hotspots, or rift zones located in anorogenic settings; A_2 – granitoids derived from magmas generated in the crust formed in subduction zones; symbols and references as in Figure 2

composition of the charnockitic rocks was determined by the interaction of basaltic magmas with anatectic melt of Al-rich metasedimentary rocks, involving mechanisms of assimilation and hybridization.

Magmatism took place in late orogenesis, transitional from syn-kinematic collisional, to post-kinematic extensional phases.

The close geochemical affinity between the Kuršiai suite in Western Lithuania and the coeval Askersund plutonic suite in southeastern Sweden suggests a similar tectonic environment and processes of the continental crust formation, and a wider correlation between these regions.

Acknowledgments. This work was supported by the Lithuanian Science and Studies Foundation, the Swedish institute's VISBY Programme and the Foundation of Vilnius University. The authors wish to acknowledge all of these institutions for their contribution. The authors are particularly thankful to Dr. U. B. Andersson for analysis of the Askersund suite, constructive comments and discussion, Dr. S. Bogdanova and Dr. E. Krzemińska for valuable remarks and corrections, and Dr. S. Keen for improving the language of the manuscript.

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