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Isotopic and geochemical constraints on the evolution of the Mazury granitoids, NE Poland

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Abstract: The Mazury complex was derived through variable degrees of partial melting from a single essentially homogeneous source that evolved independently by low degrees of differentiation along a 200 km long structure. The Mazury granitoids belong to the ferro-potassic alkali-calcic suite of rocks and are comparable with other AMCG suites from Fennoscandia, *e.g*. Rogaland, southern Norway. The most acidic varieties of the granitoids approach the classic rapakivi granites in their petrogenetic characteristics; they have elevated contents of incompatible elements and REE and, hence, have *A*-type affinities. The granitoids are assigned to the 'post -collisional granite' field. The overall evolution from mafic to acidic rocks is characterized by well -defined trends representing a liquid line of descent. Fractional crystallization with or without assimilation and hybridization can account for their evolution.

Key words: Mesoproterozoic, AMCG suite, Sr, Nd isotopes, geochemical modelling, Mazury complex

INTRODUCTION

The Mesoproterozoic Mazury complex is a part of crystalline East European craton in NE Poland. This structure is composed of granitoid rocks of variable chemical and mineralogical composition which reflect their origin and geochemical evolution and, from their source to their level of emplacement, interaction to varying degrees with continental crust (Bagiński *et al*. 2001, 2001b). The rocks in question have been interpreted as within-plate and anorogenic (*A*-type) multiple intrusions that were emplaced at shallow levels of about 5-7 km depth (Lorenc, Wiszniewska 1999, Wiszniewska *et al.* 2000). Their mineral compositions show that they represent a wide range of rocks from leucogranite, quartz monzonite, monzonite to granodiorite and monzodiorite (Bagiński *et al*. 2001, Skridlaite *et al.* 2003).

The aim of this paper is to present geochemical, petrological and isotope data for the main types of felsic and intermediate rocks in the Mazury complex and to discuss their possible origin and source material using isotope Sr/Nd ratios and existing models of interpretation (Longhi *et al.* 1999, Duchesne *et al.* 1999).

GEOLOGICAL SETTING

The Precambrian crystalline basement of the Polish part of the East European craton is concealed beneath an unmetamorphosed Phanerozoic sedimentary cover of variable thickness. As the crystalline basement dips gently to the SW (Fig.1), the thickness of the cover ranges from 0.6 km in NE of Poland to about 6.5 km along the Trans-European suture zone (TESZ). The recognition of deep basement structures is only possible through interpretation of geophysical data and from direct petrological studies of drill cores from *ca*. 250 deep boreholes, distributed unevenly throughout the area – an area characterised by particularly strong magnetic anomalies.

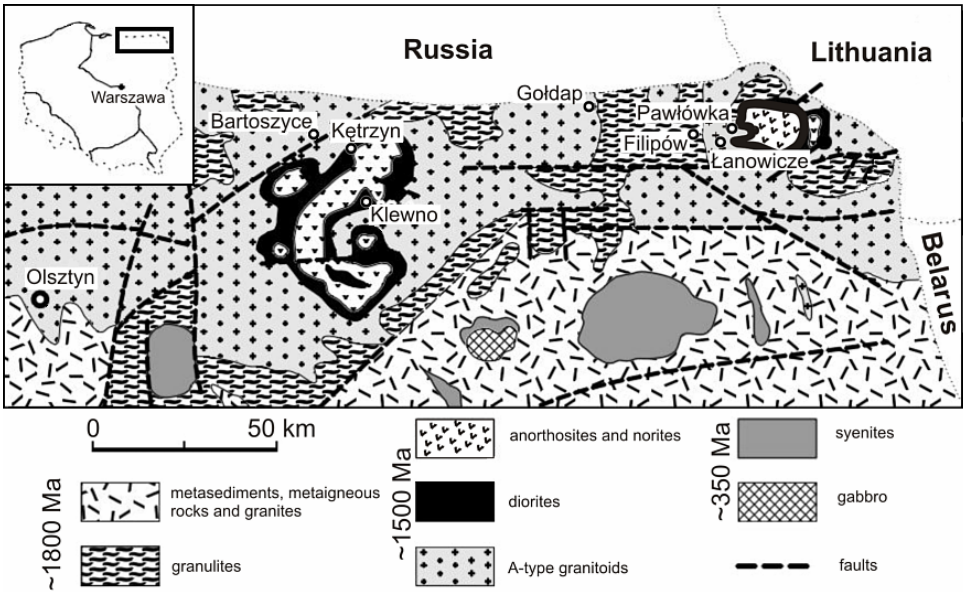


Fig. 1. Geological sketch map of the Mazury complex, NE Poland (*after* Kubicki and Ryka, 1982, modified by Wiszniewska *et al.*, 2000) with borehole localities.

The Polish part of the EEC consists of several tectono-structural and lithological units which reveal the complex Precambrian evolution of the region. Granitic rocks are important components of the rock complexes that form the crystalline basement of NE Poland. In the extreme NE, the Mazury complex composed of Mesoproterozoic granitoid massifs of A-type affinity and with related anorthosite-mangerite-charnockite intrusions (AMCG suite) is associated with a distinct E-W geophysical lineament.

Three anorthosite massifs, Kętrzyn, Suwałki and Sejny, have been recognized within the 200 km long and 40 km wide zone of felsic magmatic rocks of the Mazury complex. The Suwałki anorthosite massif (SAM) is the best documented of the intrusions because of the presence of titanomagnetite with vanadium ore deposits which were extensively drilled (about 100 boreholes) during 1960-1988 (Wiszniewska 2002, Wiszniewska *et al.* 2002). Based on positive gravity and magnetic anomalies, and petrological and geochemical studies of felsic and intermediate rocks from deep drillings around the anorthosite massifs (Bagiński *et al.* 2001, Skridlaite *et al.* 2003), the E-W trending magmatic belt can be linked to deep crustal discontinuities or shear zones.

METHODS

Major and trace elements in 80 samples from 7 cores from boreholes at Bartoszyce, Gołdap, Kętrzyn, Klewno, Pawłówka, Filipów and Łanowicze were analysed by a Philips PW 2400 Rtg spectrometer at the Central Laboratory of the Polish Geological Institute.

Major elements were analysed using standard X-ray fluorescence (XRF) fusion techniques. REE and some ultra-trace elements were analysed by the ICM-MS with a VG elemental PQ 2 Plus spectrometer at the University of Liège (Belgium), following the method described by Vander Auwera *et al.* (1998). The results are presented in Tables 1 and 2.

Electron microprobe analyses (EPMA) of the main rock-forming minerals were carried out on selected thin sections by use of a Cameca SX-100 electron probe microanalyzer at the Inter-Institute Analytical Laboratory for Minerals and Synthetic Substances, Faculty of Geology, Warsaw University. The machine is equipped with 3 wavelength-dispersive spectrometers. Operating conditions were typical for main element measurements: acceleration voltage 20 kV, beam current 10-20 nA and beam spot diameter 2 μm. Natural and artificial substances were used as standards and a PAP program (Pouchou and Pichoir 1991) for corrections.

Sm, Sr and Nd contents and whole-rock isotopic ratios were measured by use use of a VG ISOMASS 54E mass spectrometer in the Laboratoire Magmas et Volcans, Clermont-Ferrand. A CAMECA TSN 206 was used to measure Rb contents. $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$ and $^{143}Nd/^{144}Nd$ ratios to $^{146}Nd/^{144}Nd = 0.7219$. Uncertainties for $^{147}Sm/^{144}Nd$ and $^{87}Rb/^{86}Sr$ ratios are 0.5% and 2%, respectively. Nd ratios were normalized to a La Jolla standard value of 0.511860. T_{DM} ages were calculated with use of the present depleted mantle values of $^{143}Nd/^{144}Nd = 0.51315$ ($\varepsilon_o = +10$) and $^{147}Sm/^{144}Nd = 0.2137$, following a radiogenic linear growth for the mantle with $\varepsilon_{Nd} = 0$ at 4.54 Ga.

Fig. 2 (*left*). Quartz monzonite from Bartoszyce borehole. the rock is coarse grained with large feldspars. Borehole Bartoszyce 1, depth 2125 m.
Fig. 3 (*right*). Quartz diorite from Klewno. Medium to fine-grained, gray rock with small black biotite spots. Borehole Klewno 5, depth 1797.5 m.

PETROLOGICAL CHARACTERISTICS

Bartoszyce

The main rock types in core material from the Bartoszyce borehole are quartz monzonite (Fig. 2) with subordinate quartz monzodiorite, granodiorite and quartz syenite. They are composed of K-feldspar, plagioclase (An_{33-30}), quartz, biotite, hornblende, occasional clinopyroxene, apatite, zircon and opaque minerals. The quartz monzonite is characterized by a coarse to medium-grained texture with large K-feldspar phenocrysts (<3 cm) and plagioclase. K-feldspar usually contains xenomorphic inclusions of quartz.

Myrmekite is widespread. Kinked polysynthetic plagioclase lamellae reflect minor deformation. Incipient alteration is indicated by minor sericitization of plagioclase and amphibolitization of pyroxene (Pl. 1D).

Klewno

Monzodiorite and quartz diorite predominate in the Klewno core (Fig. 3). The rocks are medium- to coarse-grained, massive, porphyritic and, in some cases, ophitic. Plagioclase (An_{39-37}) and biotite are the main components. Perthitic K-feldspar usually forms large (<3 cm) crystals. Anhedral grains of quartz may show undulating extinction. These are typical as small xenomorphic inclusions in plagioclase megacrysts. Clinopyroxene and hornblende after clinopyroxene also occur. Accessory minerals include numerous needles of apatite (Pl. 1B), sphene, opaques and minor zircon and monazite. Myrmekite and biotite-quartz symplectite are also notable. Pyroxene is commonly altered to amphibole. Minor deformation is clear in banded and kinked plagioclase lamellae.

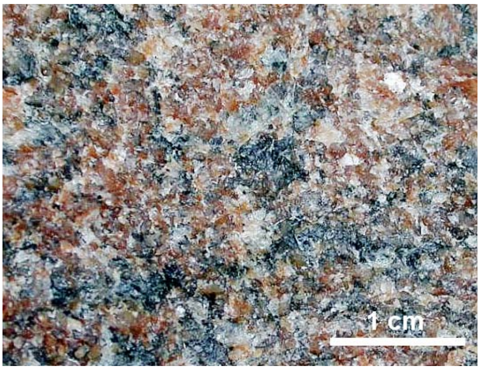
Fig. 5 (*left*). Coarse-grained, porphyritic quartz monzodiorite with large (<5 cm) pink K-feldspars, black biotite and hornblende. Borehole Kętrzyn 1, depth 1535 m.
Fig. 6 (*right*). Coarse grained, porphyritic granodiorite with large K-feldspars. Borehole Gołdap 2, depth 1638 m.

Kętrzyn

Quartz monzodiorite and minor monzodiorite are the most abundant rocks in the Kętrzyn borehole. The coarse and medium-grained rocks are, in some cases, porphyritic with large plagioclase and K-feldspar phenocrysts. The main rock-forming minerals are plagioclase (An_{28-34}) and K-feldspar with minor biotite (Pl. 1A), quartz and hornblende and some small relics of heavily amphibolized pyroxene. Accessory phases include sphene, apatite, zircon, opaques and minor allanite. Zones of deformation and mylonitization occur.

Gołdap

The Gołdap porphyritic quartz monzonite, quartz syenite and minor granites are medium and coarse-grained rocks, with long (3-5 cm) K-feldspar and plagioclase (An_{29-26}) megacrysts. The groundmass comprises plagioclase, K-feldspar, quartz, biotite, minor hornblende, numerous sphene grains (Pl. 1C), apatite, zircon and opaque minerals. Small pyroxene relics are heavily amphibolized. Myrmekites and quartz-biotite symplectites also occur. Changes in plagioclase, K-feldspar and the quartz content mark the passage from granite to quartz monzonite and quartz syenite. Alteration is reflected in some sericitization of plagioclase and the presence of minor prehnite and calcite. Some twinned plagioclases are weakly strained.



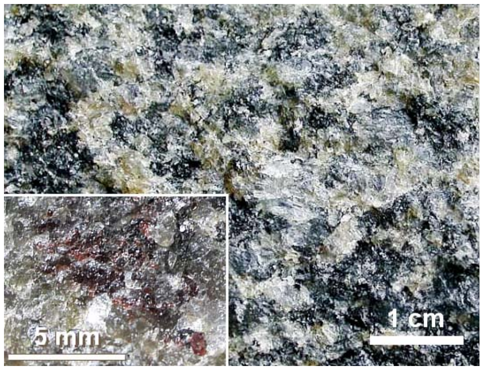


Fig. 7 (*left*). Fine-grained, reddish granodiorite predominantly consisting of feldspars and quartz. Borehole Olsztyn 6, depth 2796.5 m.
Fig.8 (*right*). Gray-greenish medium-grained charnockite with small patches of reddish garnet clusters (*see* insert lower left). Borehole Łanowicze 22, depth 1475.4 m.

Olsztyn

The Olsztyn leucogranite is a medium-grained rock characterized by abundant, oriented anhedral quartz crystals. Drill core material represents heavily altered granite (charnockite?) and granodiorite (Fig. 7). Albitization was the main process of alteration, thus the real formal position of these rocks is now alkaline granite. The rock is composed of quartz, microcline (Pl. 2C), albitized plagioclase and minor biotite often altered to chlorite. There are some evidences indicating the possibility of pyroxene presence in the rock before low temperature alteration, but products of alteration do no yield sufficient information on the parent mineral, and the the habit of the altered phase is only evidence. Myrmekite textures are rare. Apatite and zircon with minor sphene and monazite are the accessory minerals.

Pawłówka

The Pawłówka rocks are granodiorites consisting of quartz, plagioclase (An_{41}-normative), K-feldspar, biotite, minor hornblende (Pl. 2A), clinopyroxene, apatite, zircon, opaque minerals and rare sphene usually associated with hornblende. Large crystals (<5cm) of plagioclase and K-feldspar are typical. Sericitization and chloritization are conspicuous.

Filipów

Quartz monzonite and minor quartz monzodiorite occur in this core. The rocks comprise plagioclase (An_{42}-normative), quartz, K-feldspar, biotite, clinopyroxene, hornblende, sphene, apatite, minor zircon and opaque minerals (Pl. 2B). Large (<5 cm) phenocrysts of plagioclase and K-feldspar are typical. The rock is commonly deformed and partly mylonitized.

Łanowicze

The Łanowicze core is the longest (>600 m) among the studied ones. It consists of several rock types. Charnockite, the main type, is a medium-grained rock displaying a weak biotite fabric (Fig 8). The main constituents are quartz, plagioclase (with typical antiperthitic texures), K-feldspar, biotite, hypersthene (Pl. 2D) and accessory apatite, zircon, magnetite, ilmenite and monazite. In a meta-charnockite variety, garnet appears with hypersthene (Fig. 8, *see* the insert) that breaks to a bowlingite-like substance. Granodiorites and granites are similar to the more common charnockites in composition and texture except for the lack of hypersthene and different proportions of feldspars. Minor leucogranites, granodioritic in composition, are usually albitized with some biotite typically altered to chlorite. Small bodies of metamorphosed gneissic rocks are associated the charnockites, granodiorites and granites.

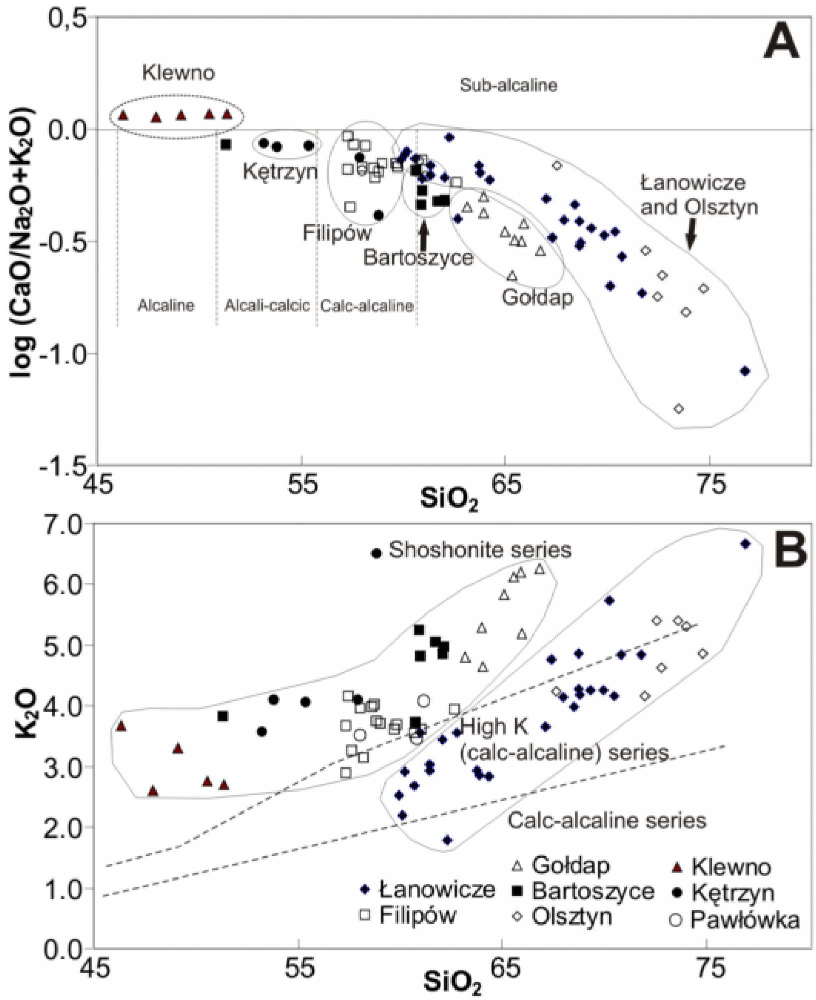


Fig. 9. Selected geochemical characteristics for the granitic rocks from the Mazury complex. **A**. Peacock index *after* Brown (1981). Note the isolated position of samples from Łanowicze and Olsztyn. **B**. K_2O *vs*. SiO_2. (dividers *after* Rickwood 1989).

GEOCHEMICAL FEATURES

The rocks represent a wide range of petrological varieties from felsic to intermediate, *e.g.*, quartz monzonite (Bartoszyce, Gołdap), leucogranite (Olsztyn), quartz monzodiorite (Kętrzyn, Filipów), granodiorite (Gołdap, Pawłówka) and diorite (Klewno). Chemically, they form a continuous series with SiO_2 contents ranging from 46 to 76% (Table 1 in Appendix). The more differentiated rocks, with SiO_2 ranging from 60 to 76%, occur in the Łanowicze drill-core, whereas the other cores contain less differentiated rocks. On the Peacock diagram (Fig. 9A) as revised by Brown (1981), the rocks from different boreholes straddle the limit between alkaline and subalkaline affinity, except for those from Łanowicze, Olsztyn and Gołdap which are subalkaline and those from Pawłówka with Filipów which lie in between. The rocks are close to the border between the calc -alkaline and alkali-calcic series. The Rickwood (1989) K_2O-SiO_2 diagram (Fig. 9B) shows the rocks from Łanowicze and Olsztyn to be high-potassium calc-alkaline, whereas the remainder plot as shoshonites. None has an agpaitic index >0.87 (Fig. 10) except for one albitized sample from Łanowicze, according to the criteria given by Liégeois and Black (1987).

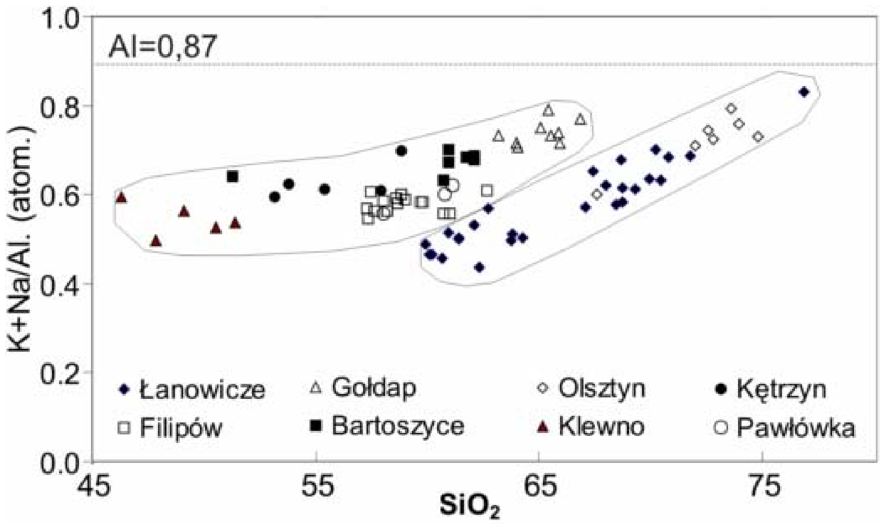


Fig. 10. The plot agpaitic index (Na+K)/Al (atom %) *vs.* SiO_2 for the granitic rocks from the Mazury complex.; the limit at AI=0.87 (minimum value for alkaline metaluminous granitoids) is *after* Liégeois and Black (1987).

Major elements

On the Harker diagrams for major elements (Figs. 11A-H), the rocks plot along a roughly defined jotunitic line of descent (Vander Auwera *et al.* 1998, Duchesne, Wilmart 1997) close to the C-type granite trend (Kilpatrick, Ellis 1992). The mafic members of the suite are rich in TiO_2, total Fe oxides and P_2O_5 (4%, 18% and 3% respectively), as is typical of jotunites (Fe-Ti-P rich monzodiorites). Total Fe oxides, MgO, CaO and TiO_2 positively correlate with SiO_2. The ratio Fe/Mg in most massifs of the Mazury complex is lower than the values in the evolved jotunites of Norway (Duchesne, Wilmart 1997, Vander Auwera *et al.* 1998).

Trace elements

Trace-element Harker diagrams (Fig. 12) do not show single differentiation trends. The most striking variation is observed on the Sr *vs.* SiO_2 diagram (Fig. 12C). Each massif is characterized by a distinct, nearly constant Sr content. The V, Co and Ni contents show systematic decreases with SiO_2 (Figs. 12A, E and G) over the region sampled by the various drill-cores and within each core. This is most certainly due to a constant subtraction of mafic minerals during fractional crystallization or to mixing with a leucogranitic melt.

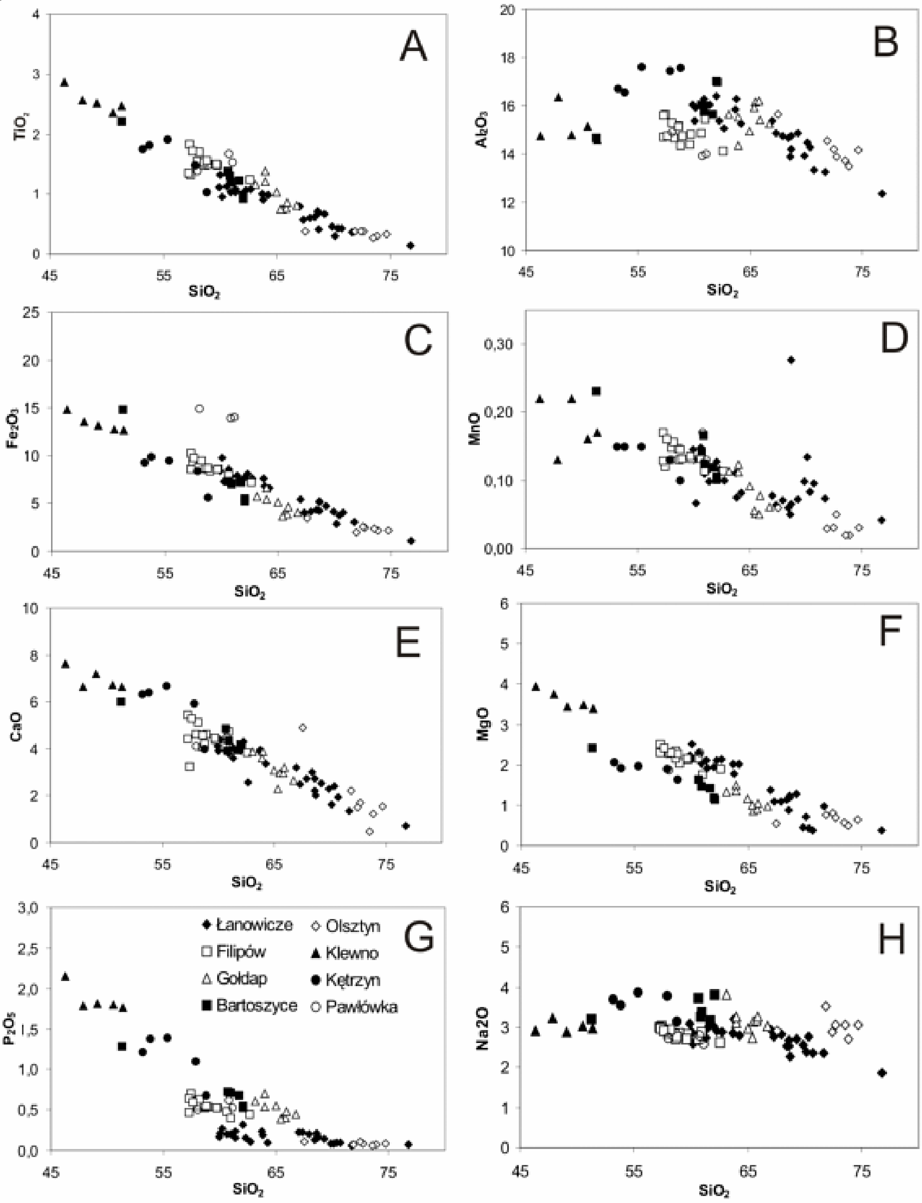


Fig. 11. Major-element Harker-type diagrams (A-H) for 80 samples from deep boreholes in the Mazury complex.

Rare earth elements

Each massif is characterized by similar REE and trace element spidergrams (Fig. 13) and trace elements distributions (Fig. 14) which could corroborate their cogenetic origin as previously assumed by Lorenc and Wiszniewska (1999). Each group of the rocks has, however, its own characteristic when consideration is given to REE amounts and ORG-normalized spidergrams (Fig. 13B). In addition, the limited variation in both REE amounts and on the spider diagrams for each massif, confirm that fractional crystallization played a subordinate differentiation role in each investigated sample set (except for Łanowicze). Variably pronounced Nb and Zr anomalies characterize all the massifs. The Nb anomaly is usually interpreted as reflecting crustal input or fractionation of a Nb-rich mineral. The negative Zr anomaly probably reflects zircon fractionation. As all these features are present in all massifs, it is proposed that they did not originate from any internal or late fractionation; rather they were features of the parental magma.

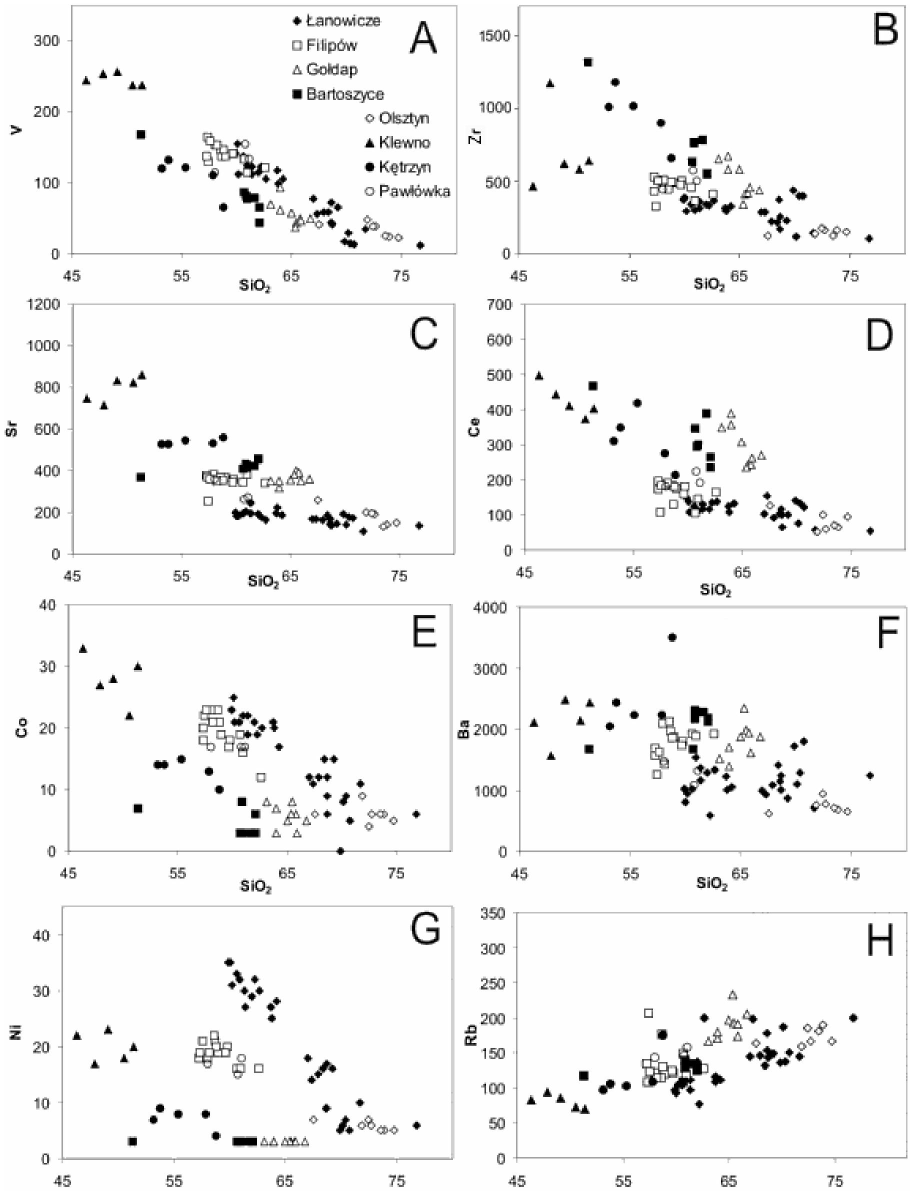


Fig.12. Trace-element Harker-type diagrams (A-H) for 40 samples from deep boreholes in the Mazury complex.

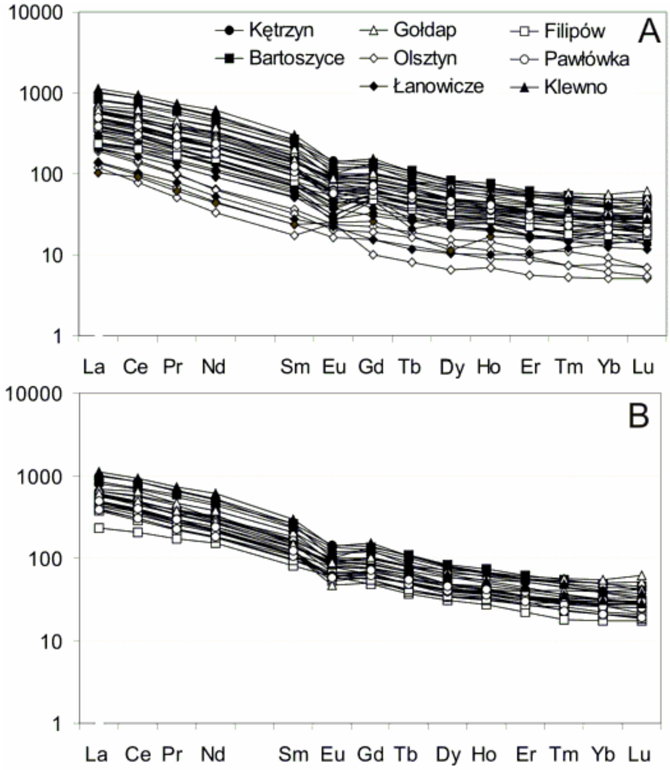


Figure 13. Spider diagrams for rocks from the Mazury complex normalised to MORB (**A**) and ORG (**B**).

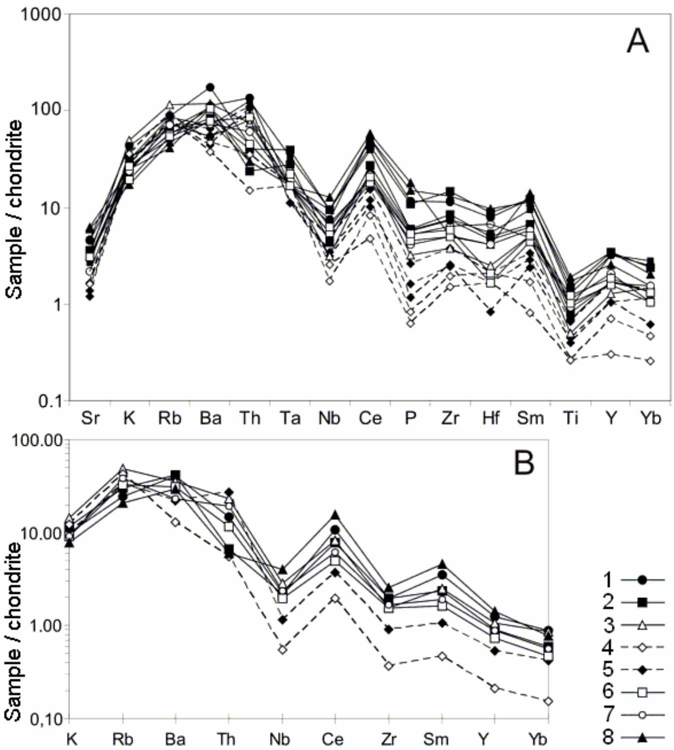


Fig. 14. Chondrite-normalized REE distributions, average values. **A**. Spidergrams for all drill cores examined. **B**. Same as A but with spidergrams for rocks from Łanowicze and Olsztyn removed. Note the almost identical and coherent shape of the remainder. Symbol explanations: 1 – Kętrzyn, 2 – Bartoszyce, 3 – Gołdap, 4 – Olsztyn, 5 – Łanowicze, 6 – Filipów, 7 – Pawłówka, 8 – Klewno.
Pl. 1.

ISOTOPE CHARACTERISTICS

Nd and Sr isotope data, together with the Nd model age valuess, $\varepsilon_{Nd\ (T\ =\ 1.5\ Ga)}$ and initial $^{87}Sr/^{86}Sr$ at 1.5 Ga are presented in Tables 3 and 4 (*see* Appendix) and Fig. 15. At 1.5 Ga, the age of the granitic rocks their emplacement, they all were characterized by negative Σ_{Nd} values (–3.3 to–6.8) and a very wide range of the $^{87}Sr/^{86}Sr$ ratios (0.702 to 0.723). T_{DM} ages range from 2.04 to 2.42 Ga. The Mazury rocks all plot far from the mantle array (Fig. 15); clearly none were directly derived from depleted mantle. The Kętrzyn, Klewno, Bartoszyce and Gołdap rocks could have derived from an enriched mantle. Such a direct origin is not likely in the case of rocks from, *e.g.*, Olsztyn and Łanowicze, with high initial $^{87}Sr/^{86}Sr$ ratios. It is possible that all of the granitic rocks derived from depleted mantle but suffered different degrees of crustal contamination. Finally, remelting at 1.5 Ga of a juvenile mafic crust extracted at 2.0-2.2 Ga from the mantle could also explain the negative Σ_{Nd} values and the low $^{87}Sr/^{86}Sr$ values of some rocks.

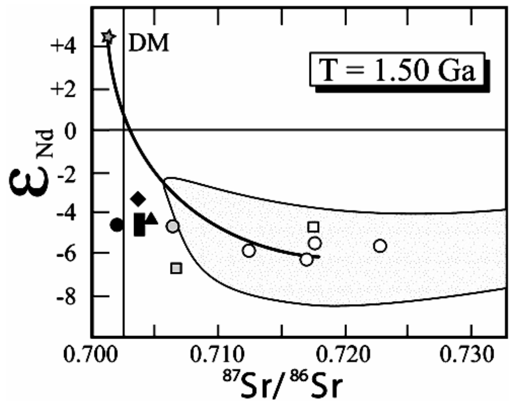


Fig.15. Diagram Σ_{Nd} *versus* $^{87}Sr/^{86}Sr$ at 1.5 Ga for the Mazury granites. Black triangle – Kętrzyn, black diamond – Klewno, black square – Bartoszyce, black circle – Gołdap, grey circle – Filipów, grey square – Pawłówka, open square – Olsztyn and open circle – Łanowicze. The grey star (DM) is the composition of the depleted mantle. The grey field is that of Proterozoic granites and sediments from the Bothnian basin and central Sweden (Claesson, Lundqvist 1995). The heavy dark line is the calculated mixing line between the depleted mantle pole and an average Proterozoic crustal pole.

Granite groups

On a basis of isotope measurements two groups of granites can be distinguished:

Group 1 – the granitic rocks from Kętrzyn, Klewno, Bartoszyce and Gołdap. The group is characterised by $\Sigma_{Nd\ (T=1.5\ Ga)}$ ranging from –3.3 to –4.9 and $^{87}Sr/^{86}Sr$ (at 1.5 Ga) from 0.702 to 0.704 (ε_{Sr} <25). The group is isotopically homogeneous.

Group 2 – the rocks from Olsztyn and Łanowicze. This group is characterised by $\Sigma_{Nd\ (T=1.5\ Ga)}$ ranging from –4.5 to –6.4 and $^{87}Sr/^{86}Sr$ (at 1.5 Ga) from 0.712 to 0.723 (ε_{Sr} >130). This group is more heterogeneous than group 1.

The Filipów and Pawłówka granitic rocks, with $\Sigma_{Nd\ (T=1.5\ Ga)}$ ranging from –4.6 to –6.4 and $^{87}Sr/^{86}Sr$ (at 1.5 Ga) about 0.706 (ε_{Sr} ~55), occupy an intermediate position between the groups 1 and 2. The contrasting compositions of the two groups suggest differences in petrogenesis. The isotopic characteristics of group 2 suggest a potential role for crustal contamination or even a crustal source.

The two groups characterized above are also clearly discriminated by the ε_{Nd} values and SiO_2 contents (Fig. 18). On the ε_{Nd} versus SiO_2 plot, ε_{Nd} values of the group 1 rocks are almost constant without any correlation with SiO_2; group 2 rocks have relatively lower ε_{Nd} values which also show no correlation with SiO_2. The ε_{Sr} values of the group 1 show

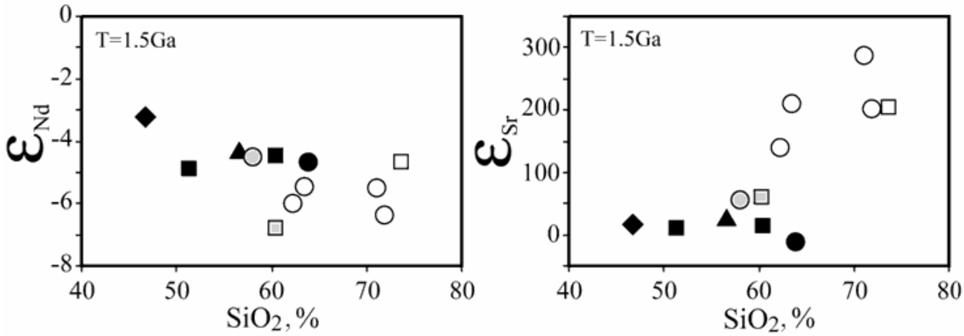


Fig. 16. The values of ε_{Nd} and ε_{Sr} *versus* SiO_2; symbols as in Fig. 15.

no correlation with SiO_2 whereas in the group 2 the ε_{Sr} values are higher and positively correlated with SiO_2. This last correlation strongly favours:
1) a significant crustal component in the group 2 magmas
2) contamination of group 2 magma by crust rich in radiogenic Sr.
In contrast, the lack of correlations with SiO_2 in the group 1 suggests limited crustal contamination or its absence. However, this might also reflect the fact that the group 1 granites could have experienced similar degrees of contamination; the data are not scattered in Fig. 15 where it is also clear that the Filipów and Pawłówka granites plot between the group 1 and group 2.

From Fig. 15 it is clear that each granitic body has interacted to different degree with the continental crust. The Proterozoic crust of the Baltic shield could have been the contaminant in the case of the group 2 rocks – in fact the group 2 granites would be mainly of crustal origin. Major (Table 1 in Appendix) and trace elements (Table 2 in Appendix) indicate that the mantle directly or indirectly played a prominent role in Mazury granite genesis. In this case, Proterozoic granites and sediments from the Bothnian basin and central Sweden would not have been appropriate contaminants but rather a crust with, at 1.5 Ga, ε_{Nd} ranging between –7 and –10 and $^{87}Sr/^{86}Sr$ significantly higher than 0.730. A possibility applicable to group 1 granites, is that they derived from the remelting at 1.5 Ga of a juvenile mafic crust extracted from the mantle at 2.0-2.3 Ga as indicated by the T_{DM} age. This could account for the negative ε_{Nd} values and the low $^{87}Sr/^{86}Sr$ values of some massifs.

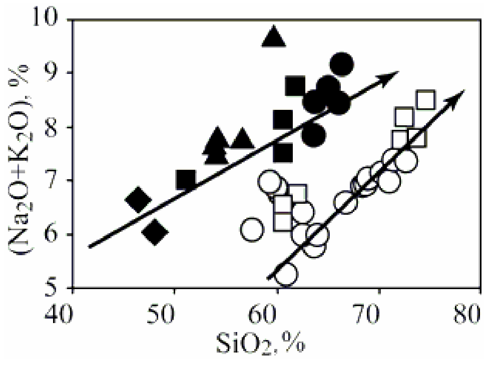


Fig. 17. Alkalis (Na_2O+K_2O) *versus* the SiO_2 contents in the Mazury complex rocks. Symbols as in Fig. 15.

Different positive correlations of alkalis and silica characterize the granites of the groups 1 and 2 on Fig. 17. Here too, the Filipów and Pawłówka rocks occupy an intermediate position. The well-defined trends start from different compositions (SiO_2 ~48% for the group 1 and ~60% for the group 2) and converge towards a single high SiO_2 composition. If the different starting compositions reflect different degrees of crustal contamination, this took place in the source and not during later differentiation and emplacement.

The plots on Fig. 18 clearly discriminate between the group 1 and 2 rocks – perfectly so in the Cr *vs*. SiO_2 plot. The intermediate position of the Filipów and Pawłówka granites is well shown in the Ni *vs*. SiO_2 diagram.

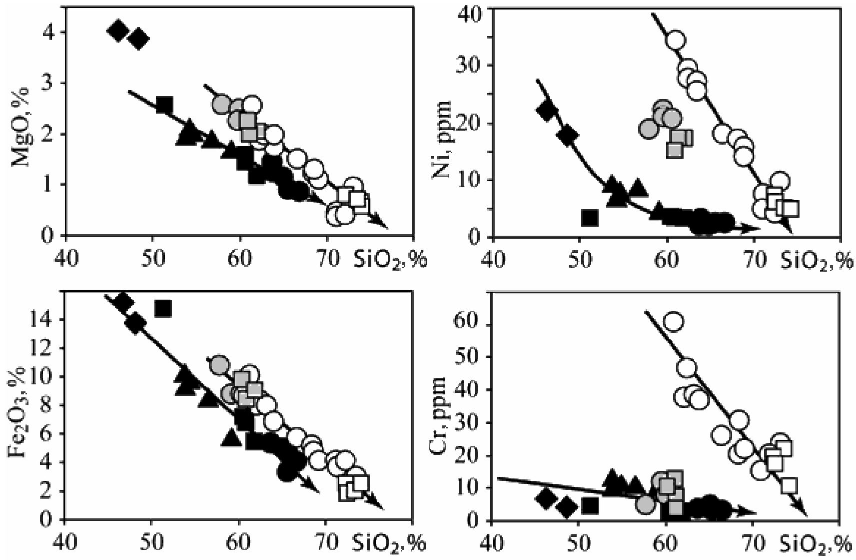


Fig. 18. Contents of MgO, Fe_2O_3, Ni and Cr *versus* the SiO_2 content in the Mazury complex rocks. Symbols as in Fig. 15.

The Mazury granites do not plot in the mantle area of Fig. 15 but have negative epsilon Nd and positive epsilon Sr values, reflecting the crustal role in their genesis. Some of the Mazury rock samples fall within the grey field on Fig. 15 suggesting that some may be the products of melting of Lower Proterozoic crust but the others must be mantle-derived but strongly contaminated or be the result of the mixing of mantle and crustal magmas.

CONCLUSIONS

The rapakivi-type granites of the Mazury complex belong to the ferro-potassic alkali -calcic series. They range widely in mineralogical composition from felsic to more mafic varieties, *e.g*. monzonites, quartz monzonites, quartz monzodiorites to granodiorites and diorites.

The Mazury granitoids are geochemically classified as anorogenic A-type granitoids and are assigned to the post-collisional group mostly on the transition between the within -plate granites and volcanic-arc granites (*see* Pearce *et al*. 1984).

The rocks plot along a well-defined liquid line of crystallization (similar to the **jotunitic line of descent** *sensu* Duchesne and Wilmart 1997), indicating derivation involving variable degrees of partial melting of a single, homogeneous protolith of monotonous mineralogy as is evidenced by uniform REE and small negative Eu anomalies.

The evolution in time of the parental magma batches, and varying degrees of contamination by country rocks, resulted in the different rocks of the rapakivi massifs.

The granites are characterized by negative ε_{Nd} (–3.3 to –6.8) and a very wide range in $^{87}Sr/^{86}Sr$ (0.702 to 0.723) at 1.5 Ga.

Two discrete granitoid groups occur in the Mazury complex. They reflect differences in chemical composition and origin. The group 1 originated from remelting at 1.5 Ga juvenile mafic crust extracted from the mantle. The group 2, in contrast, originated by crustal contamination or a crustal source.

The Filipów and Pawłówka granites are intermediate between the groups 1 and 2.

Different starting compositions reflect different degrees of crustal involvement in the source rather than during later differentiation or emplacement.

Some of the Mazury granite rocks are the products of melting of Lower Proterozoic crust but others must be mantle derived with crustal contamination or the result of the mixing of mantle and crustal magmas.

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APPENDIX

Table 1. Chemical composition of the Mazury complex rocks, wt.%

Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
Łanowicze 1	63,78	0,91	16,28	6,81	0,08	1,78	3,88	3,19	2,86	0,19
Łanowicze 2	71,69	0,37	13,26	3,04	0,07	0,97	1,34	2,35	4,85	0,06
Łanowicze 9	63,71	1,01	15,85	7,57	0,11	2,02	3,97	2,86	2,94	0,23
Łanowicze 11	61,37	1,03	16,03	7,67	0,12	1,92	4,05	2,96	2,94	0,23
Łanowicze 15	62,02	0,99	16,40	7,66	0,13	1,95	3,92	3,03	3,45	0,32
Łanowicze 17	69,24	0,67	14,85	4,70	0,07	1,27	2,53	2,72	4,25	0,14
Łanowicze 19	67,91	0,60	14,75	4,18	0,07	1,10	2,73	2,83	4,14	0,19
Łanowicze 22	67,00	0,79	15,36	5,47	0,08	1,38	3,22	2,93	3,66	0,23
Łanowicze 24	69,86	0,46	13,94	4,14	0,10	0,46	2,30	2,57	4,26	0,08
Łanowicze 25	70,71	0,43	13,35	4,06	0,10	0,39	1,94	2,37	4,85	0,09
Łanowicze 26	70,36	0,43	14,29	3,79	0,08	0,42	2,40	2,76	4,16	0,09
Łanowicze 27	68,66	0,68	14,74	5,10	0,07	1,23	2,72	2,69	4,27	0,18
Filipów 1	58,64	1,49	15,17	8,60	0,13	2,34	4,09	2,72	4,02	0,52
Filipów 5	59,74	1,48	14,83	8,64	0,13	2,14	4,40	2,82	3,69	0,53
Filipów 8	58,57	1,53	15,14	8,71	0,15	2,16	4,59	2,83	3,99	0,54
Filipów 13	57,29	1,84	14,71	10,25	0,17	2,52	5,47	2,97	2,89	0,64
Gołdap 2	65,36	0,75	15,92	3,62	0,06	0,99	2,28	2,75	7,45	0,39
Gołdap 3	63,96	1,38	14,37	6,59	0,12	1,50	3,88	3,11	4,65	0,70
Gołdap 4	63,94	1,21	15,51	5,45	0,11	1,34	3,61	3,26	5,29	0,54
Gołdap 5	65,89	0,86	15,40	4,65	0,08	1,04	3,21	3,27	5,20	0,48
Gołdap 6	66,75	0,81	15,26	4,10	0,06	0,98	2,66	3,03	6,27	0,44
Gołdap 7	64,98	1,04	14,96	5,09	0,09	1,17	3,08	2,97	5,84	0,55
Bartoszyce 4	60,66	1,37	16,05	7,31	0,14	1,63	4,87	3,72	3,74	0,73
Bartoszyce 5	60,91	1,21	16,01	7,12	0,13	1,48	4,35	3,37	4,82	0,71
Bartoszyce 6	51,29	2,22	14,65	14,82	0,23	2,42	6,01	3,19	3,83	1,29
Bartoszyce 7	62,06	0,99	16,97	5,55	0,10	1,15	4,18	3,82	4,98	0,55
Olsztyn 1	71,88	0,39	14,53	1,94	0,03	0,76	2,20	3,53	4,16	0,08
Olsztyn 4	72,45	0,39	14,21	2,58	0,03	0,81	1,49	2,88	5,41	0,10
Olsztyn 5	74,71	0,33	14,15	2,16	0,03	0,65	1,55	3,07	4,86	0,08
Olsztyn 7	73,51	0,27	13,71	2,37	0,02	0,56	0,48	3,06	5,41	0,06
Klewno 2	46,30	2,87	14,74	14,86	0,22	3,93	7,63	2,90	3,68	2,15
Klewno 3	47,87	2,57	16,34	13,53	0,13	3,75	6,63	3,24	2,60	1,79
Kętrzyn 1	58,80	1,03	17,56	5,59	0,10	1,64	4,00	3,16	6,52	0,68
Kętrzyn 3	55,35	1,91	17,60	9,50	0,15	1,97	6,69	3,87	4,07	1,39
Kętrzyn 4	57,86	1,48	17,47	8,42	0,13	1,90	5,92	3,78	4,10	1,10
Kętrzyn 5	53,17	1,75	16,72	9,24	0,15	2,07	6,31	3,69	3,57	1,21
Kętrzyn 6	53,78	1,81	16,56	9,89	0,15	1,92	6,42	3,56	4,11	1,38
Pawłówka 17	61,09	1,53	14,00	8,84	0,13	2,02	4,12	2,60	4,08	0,53
Pawłówka 144	60,75	1,68	13,94	10,02	0,17	2,29	4,51	2,80	3,47	0,62
Pawłówka 85	58,00	1,39	14,91	8,01	0,13	1,87	4,10	2,73	3,52	0,50

Table 2. Trace elements in the Mazury complex rocks, ppm

Sample	Ba	Ce	Co	Cr	Cu	Mo	Nb	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr
Łanowicze 1	1009	109	20	37	33	<2	13	25	23	115	223	23	<3	99	40	82	290
Łanowicze 2	717	58	11	24	13	<2	9	10	31	145	111	10	<3	35	15	46	141
Łanowicze 9	1231	124	21	39	25	<2	13	27	21	109	194	24	<3	118	34	101	314
Łanowicze 11	1371	116	19	47	27	<2	13	27	24	97	245	22	<3	112	35	109	310
Łanowicze 15	1292	117	21	38	54	<2	17	29	23	138	193	22	<3	115	49	109	336
Łanowicze 17	871	100	15	32	21	<2	12	16	25	149	145	21	<3	65	31	64	230
Łanowicze 19	1080	93	12	22	22	2	11	15	26	146	165	18	<3	59	31	61	220
Łanowicze 22	995	103	12	26	25	<2	14	18	24	145	169	21	<3	78	34	79	286
Łanowicze 24	1720	141	<3	15	91	<2	9	5	27	136	193	22	<3	17	30	91	436
Łanowicze 25	1802	122	5	21	40	<2	6	5	34	151	174	15	<3	14	32	97	400
Łanowicze 26	1287	133	9	14	32	<2	5	7	29	137	177	22	<3	15	33	57	396
Łanowicze 27	1244	100	12	21	19	<2	12	17	26	154	169	21	<3	72	27	76	252
Filipów 1	1968	129	23	8	29	<2	19	21	12	177	356	9	3	138	37	149	497
Filipów 5	1795	181	18	10	28	<2	17	20	25	121	359	13	<3	142	45	139	500
Filipów 8	2121	183	21	10	23	<2	19	22	27	114	369	9	<3	147	47	142	444
Filipów 13	1560	198	20	<3	30	<2	22	19	22	108	367	17	3	164	56	169	525
Gołdap 2	2344	236	6	3	10	3	11	3	39	233	383	15	3	37	38	74	336
Gołdap 3	1394	388	7	3	10	4	33	3	34	170	320	25	3	93	97	130	671
Gołdap 4	1701	358	3	3	10	3	31	3	33	180	351	22	3	61	76	111	578
Gołdap 5	1606	262	3	3	10	3	15	3	36	173	348	15	3	47	44	93	457
Gołdap 6	1883	269	5	3	10	4	20	3	35	205	359	14	5	50	33	74	439
Gołdap 7	1874	307	5	3	10	3	26	3	36	196	353	19	3	57	56	96	578
Bartoszyce 4	1679	347	3	3	10	3	20	3	29	108	409	5	6	87	52	147	632
Bartoszyce 5	2164	300	3	3	10	3	15	3	33	129	433	5	5	78	51	140	763
Bartoszyce 6	1673	467	7	3	10	3	33	3	24	117	370	8	7	168	102	240	1316
Bartoszyce 7	2193	265	6	3	10	3	15	3	35	130	457	4	6	66	35	113	552
Olsztyn1	753	51	9	18	10	2	9	6	28	159	199	3	3	48	9	38	134
Olsztyn 4	953	99	4	19	5	2	6	7	24	185	194	7	3	39	21	50	173
Olsztyn 5	652	95	5	23	5	2	7	5	26	166	151	9	3	23	17	34	147
Olsztyn 7	707	71	6	12	6	2	6	5	21	181	134	8	3	25	16	27	123
Klewno 2	2110	497	33	6	68	2	45	22	19	82	745	6	3	244	102	299	462
Klewno 3	1567	444	27	3	27	2	33	17	20	94	712	6	3	254	76	256	1171
Kętrzyn 1	3509	214	10	3	5	2	16	4	26	175	561	9	3	66	52	128	659
Kętrzyn 3	2235	419	15	3	11	2	26	8	20	102	546	27	4	122	96	172	1017
Kętrzyn 4	2228	276	13	3	7	2	18	8	20	109	530	11	3	111	69	170	902
Kętrzyn 5	2042	311	14	3	14	2	24	7	20	97	528	12	3	120	85	184	1010
Kętrzyn 6	2431	350	14	3	13	2	26	9	18	105	529	15	3	132	95	182	1181
Pawłówka 17	1322	192	17	3	22	2	22	18	30	157	274	23	4	134	52	122	504
Pawłówka 144	1083	225	17	12	21	2	24	15	31	146	262	16	3	155	62	173	572
Pawłówka 85	1467	180	17	6	19	2	19	17	30	143	359	12	3	115	50	136	444

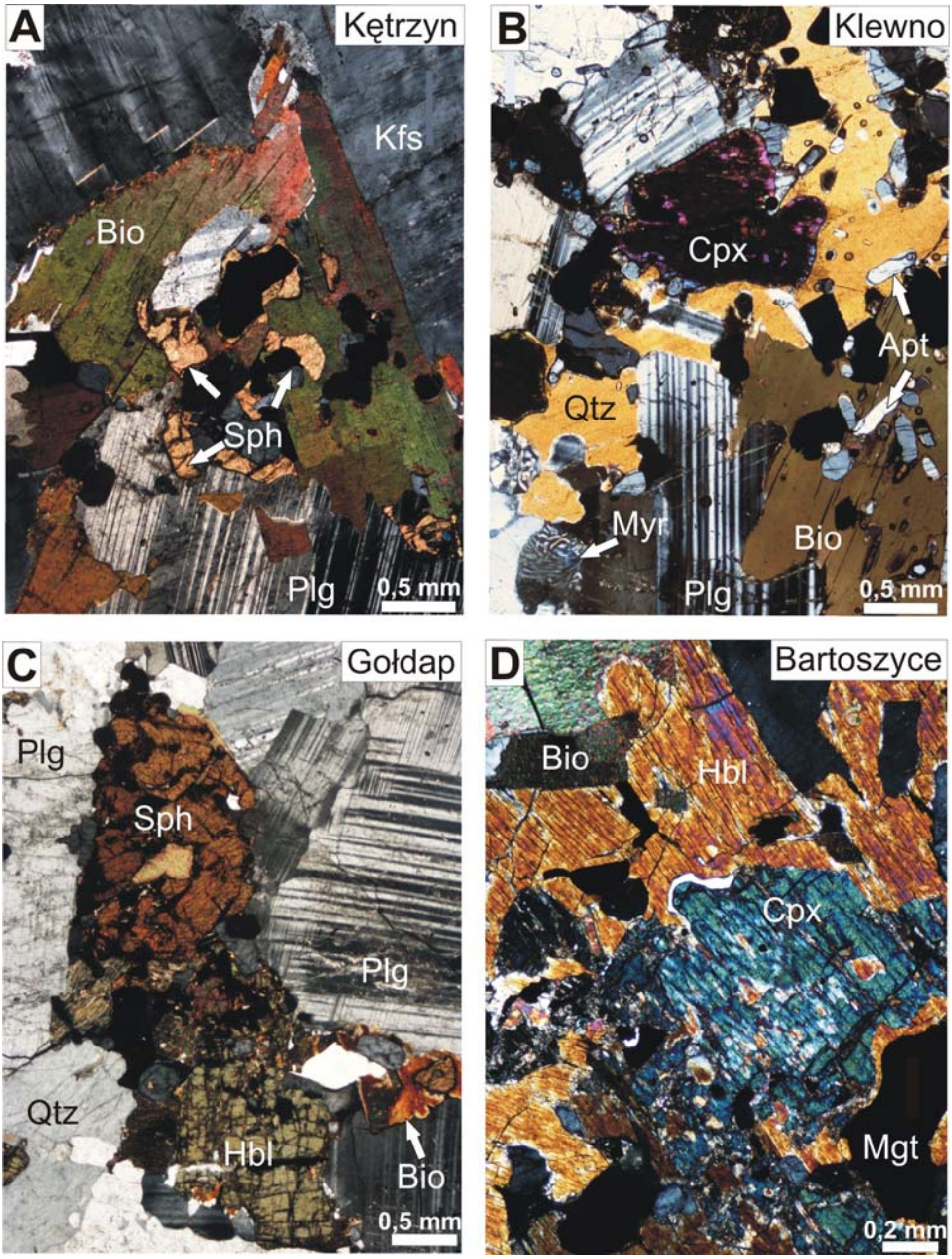
Table 3. Representative Sm-Nd isotope data of the Mazury granites

	Sample name	Sm ppm	Nd ppm	$^{143}Nd/^{144}Nd$	$^{147}Sm/^{144}Nd$	$\varepsilon_{Nd\ (0)}$	$\varepsilon_{Nd\ (1.5\ Ga)}$	T_{DM} (Ga)
Group 1	Kętrzyn 29	25.1	143.7	0.511515	0.105718	-21.91	-4.43	2,16
	Klewno 2	45.57	282.4	0.511492	0.097597	-22.35	-3.31	2,04
	Bartoszyce 4	23.8	137	0.511507	0.105085	-22.06	-4.46	2,16
	Bartoszyce 6	40.5	219	0.511552	0.111865	-21.18	-4.89	2,24
	Gołdap 3	31.1	174	0.511525	0.108117	-21.71	-4.69	2,20
Inter-mediate	Filipów 13	16.67	96.2	0.511499	0.104780	-22.22	-4.56	2,17
	Pawłówka 144	16.1	84.0	0.511493	0.115906	-22.34	-6.82	2,42
Group 2	Olsztyn 5	4.9	29.9	0.511444	0.099171	-23.29	-4.55	2,13
	Łanowicze 9	12.05	71.4	0.511424	0.102149	-23.68	-5.52	2,22
	Łanowicze 11	10.7	61.2	0.511436	0.105775	-23.45	-5.98	2,28
	Łanowicze 24	12.4	69.6	0.51148	0.107778	-22.59	-5.51	2,26
	Łanowicze 25	10.5	58.9	0.511435	0.107850	-23.47	-6.40	2,32

Table 4. Representative Rb-Sr isotope data of the Mazury granites

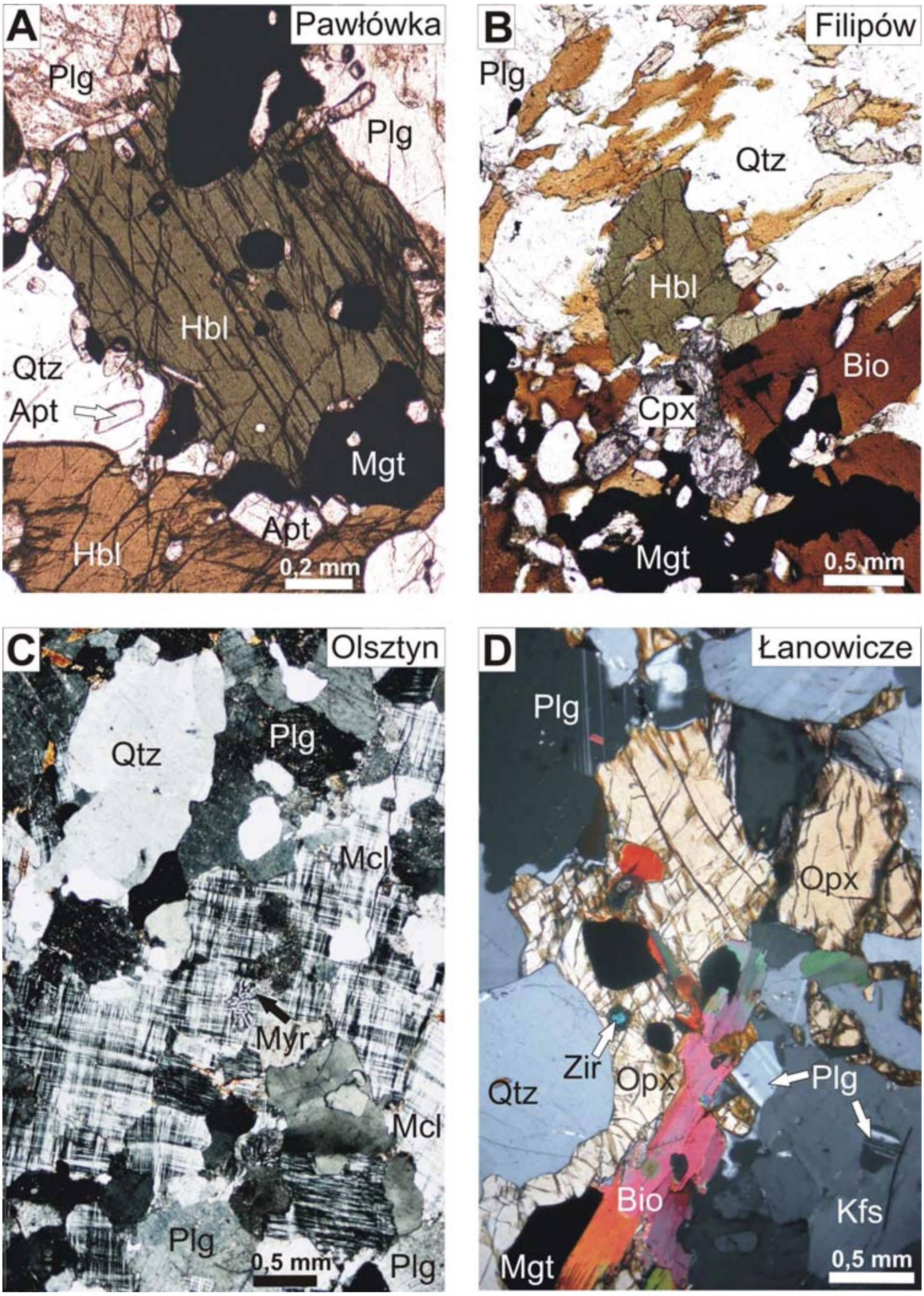
	Sample name	Rb ppm	Sr ppm	$^{87}Sr/^{86}Sr$	$87Rb/^{86}Sr$	$\varepsilon_{Sr\ (0)}$	$\varepsilon_{Sr\ (1.5\ Ga)}$	$(^{87}Sr/^{86}Sr)_0$
Group 1	Kętrzyn 29	109	530	0.717335	0.5949	182	25	0,7045
	Klewno 2	82	745	0.710496	0.3184	85	13	0,7036
	Bartoszyce 4	108	409	0.720319	0.7638	225	16	0,7039
	Bartoszyce 6	117	370	0.723441	0.9147	269	14	0,7037
	Gołdap 3	170	320	0.735106	1.5366	434	-10	0,7020
Inter-mediate	Filipów 13	108	367	0.724976	0.8512	291	56	0,7066
	Pawłówka 144	146	262	0.741254	1.6119	522	54	0,7065
Group 2	Olsztyn 5	166	151	0.785773	3.1798	1154	207	0,7173
	Łanowicze 9	109	194	0.752534	1.6252	682	211	0,7176
	Łanowicze 11	97	245	0.737179	1.1452	464	139	0,7125
	Łanowicze 24	136	193	0.766795	2.0382	884	287	0,7229
	Łanowicze 25	151	174	0.770852	2.5102	942	200	0,7168

Plate 1



A. Quartz monzodiorite; ×N. Kętrzyn 3, depth 1541.5 m. **B.** Quartz monzodiorite with altered clinopyroxene;×N. Klewno 1, depth 1782 m. **C.** Granodiorite; ×N. Gołdap 7, depth 1657 m. **D.** Mafic cluster composed of clinopyroxene partly replaced by hornblende, magnetite and biotite, in quartz monzonite; ×N. Bartoszyce 6, depth. 2142 m. Plg – plagioclase, Kfs – K-feldspar, Mcl – microcline, Qtz – quartz, Bio – biotite, Cpx – clinopyroxene, Opx – orthopyroxene, Hbl – hornblende, Apt – apatite, Sph – sphene, Zir – zircon, Mgt – magnetite, Myr – myrmekite.

Plate 2



A. Granodiorite, hornblende-rich part; PPL. Pawłówka 144, depth 1879 m. **B.** Quartz monzodiorite with clinopyroxene relics partially replaced by hornblende; PPL. Filipów 4, depth 1203 m. **C.** Leucogranite; ×N. Olsztyn 1, depth. 2764 m. **D.** Charnockite, hypersthene is slightly altered; ×N. Łanowicze 24, depth. 1487 m. For explanations of the abbreviations – *see* Pl. 1.