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DETRITAL ZIRCON GEOCHRONOLOGY AND PROVENANCE OF THE PROTEROZOIC QUARTZ-RICH METASEDIMENTS OF THE MAZOWSZE DOMAIN: SOURCE AREAS AND REGIONAL CORRELATION

GEOCHRONOLOGIA DETRYTYCZNEGO CYRKONU I PROWENIENCJA PROTEROZOICZNYCH BOGATYCH W KWARC SKAŁ METAOSADOWYCH W DOMENIE MAZOWIECKIEJ: OBSZARY ŹRÓDŁOWE I REGIONALNA KORELACJA

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Abstract. Drilling at Mońki IG 2 and Zabiele IG 1 in the Mazowsze domain has intersected mature quartz-rich metasedimentary rocks belonging to the basement of NE Poland, described so far as a Biebrza complex. The geochemical composition of these rocks is characteristic of a passive margin. The subarkose–quartz arenite underwent low-T metamorphism, but preserved textures typical for the fluvial sediments. The detrital material in range 1.68–2.11 Ga was provided from surrounding late Paleoproterozoic margins of the Fennoscandia and Sarmatia. The maximum depositional age probably did not exceed 1.6 Ga. A previously suggested correlation with Mesoproterozoic molasse-type deposits of the Jotnian formation has not been confirmed. It seems more likely that the sediments formed after Fennoscandia-Sarmatia collision (*i.e.* termination of Svecofennian orogeny) but before denudation of the Mesoproterozoic Mazury AMCG intrusions.

Key words: mature metasandstones, zircon U-Pb age, maximum depositional age, Paleoproterozoic, Late Svecofennian, Fennoscandia, Sarmatia.

Abstrakt. W otworach wiertniczych Mońki IG 2 i Zabiele IG 1 na obszarze domeny mazowieckiej rozpoznano dojrzałe, bogate w kwarc skały metaosadowe. Należą one do podłoża krystalicznego północno-wschodniej Polski i były opisywane dotychczas jako kompleks biebrzański. Skład geochemiczny tych skał jest charakterystyczny dla krawędzi pasywnej. Skały sklasyfikowane jako arenity kwarcowe i subarkozy uległy metamorfizmowi niskotemperaturowemu, zachowując jednak struktury typowe dla osadów rzecznych. Materiał detrytyczny o wieku 1,68–2,11 mld lat pochodził z erozji paleoproterozoicznych skał na krawędziach Fennoskandii i Sarmacji. Maksymalny wiek depozycji materiału okruchowego prawdopodobnie nie przekraczał 1,6 mld lat. Sugerowana wcześniej korelacja z osadami molasowymi mezoproterozoicznej formacji jotnickiej nie została potwierdzona. Bardziej prawdopodobne wydaje się, że osady powstały po kolizji Fennoskandii z Sarmacją (wygasanie orogenezy swekofeńskiej), a przed denudacją mezoproterozoicznych intruzji AMCG obszaru Mazur.

Słowa kluczowe: dojrzałe metapiaskowce, wiek U-Pb cyrkonu, maksymalny wiek depozycji, paleoproterozoik, późnoswekofeński, Fennoskandia, Sarmacja.

INTRODUCTION

During the last decades, the basement of northeastern Poland located on the edge of Fennoscandia close to the Sarmatia margin (Fig. 1), have been an object of investigation on crustal evolution and paleogeography of the East European Craton (EEC) during Paleoproterozoic to Mesoproterozoic time (Bogdanova *et al.*, 2006, 2015 and ref. therein). Recently some of these studies have been focused on detrital zircon analyses, that provide important insights into the provenance

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of detritus (Sultan *et al.*, 2005; Bergman *et al.*, 2008; Williams *et al.*, 2009; Krzemińska *et al.*, 2009). The wide range of information can be extracted from detrital zircon crystals, not only evidence of maximum depositional age of the host sediment, but also including the provenance of detrital material, paleogeography and tectonic setting of the source areas, and possible stratigraphic correlations between units (Cawood *et al.*, 2012; Gehrels, 2014). In consequence the tectonic connection and proximity between multiple terranes over geologic time can be approximated. This type of analytical works have been conducted in Precambrian basement of northeastern Poland, where the rocks are known exclusively from deep drill core samples.

The first reconnaissance study of detrital zircon from metasediments recognized by two deep boreholes (Mońki IG 2 and Jastrzębna IG 1), allows to document the maximum depositional age of arc related sediments remarkably similar to that of Svecofennian metasediments known from exposed areas in Sweden and Finland. The Paleoproterozoic deposition of sediments in NE Poland, that was confirmed by detrital zircon data and from the central parts of the Svecofennian orogen in Sweden and Finland, supports the idea of the Svecofennian marginal basin (Rutland *et al.*, 2004; Williams *et al.*, 2009; Krzemińska *et al.*, 2009; Bogdanova *et al.*, 2015).

The mature quartz-rich metasediments from the top of a Precambrian part of the Mońki IG 2 and Zabiele IG 1 core sections are spatially associated with a large Mesoproterozoic Mazury Complex dominated by rapakivi-type granitoids (Fig. 2). Previously they were considered to be part of a "quasiplatform" group of sediments of EEC (Kubicki *et al.*, 1996). The weakly metamorphosed quartz-rich rocks from Mońki and Zabiele were presumed as a Mesoproterozoic molasse to belong to the Jotnian formation or even Neoproterozoic cover that filled a grabens and depressions related to the "system of the Gothian dislocations" (Kubicki *et al.*, 1996; Ryka, 1998). The Jotnian sediments were usually assigned to the Riphean Stage of the Mesoproterozoic Era. They are younger than the rapakivi granites and older than post-Jotnian diabase dykes that intrude these sediments, thus were deposited approximately from 1600 to 1260 Ma (Paulamäki *et al.*, 2002 and ref. therein). The Jotnian Mesoproterozoic sedimentary rocks lying on the Paleoproterozoic crystalline bedrock are preserved in a few places within the Svecofennian domain in Muhos, Satakunta and at Lappajärvi in Finland and Dalarna and Nordingrå in Sweden. All occurrences of the Jotnian sediments cannot be explained by one single tectonic event or process (Lundmark, Lamminen, 2016), but many of the Jotnian sandstones are spatially closely related to the sites of 1.65–1.5 Ga rapakivi or AMCG magmatism. Here we present the first results of detrital zircon Pb-Pb geochronology and geochemical study of the quartz-rich samples from two drillings (Mońki IG 2 and Zabiele IG 1), that constrain the age of upper level of metasediments and suggest a new chronostratigraphic position of these rocks.

GEOLOGICAL CONTEXT

Over the past two decades a large number of isotope studies in Lithuania, Latvia and Estonia (Claesson *et al.*, 2001; Soesoo *et al.*, 2004) and Poland (Claesson, Ryka, 1999; Krzemińska *et al.*, 2005, 2017) resulted in developing a modern view on geodynamic evolution of East European Craton between Fennoscandian and Ukrainian shields. All isotopic investigations, including U-Pb geochronology, document the Paleoproterozoic age of the crust in this region (Fig. 1; Bogdanova *et al.*, 2015 and ref. therein). In the northern part of NE Poland, where crystalline basement is subdivided into the Mazowsze (MD), Dobrzyń and Pomorze-Blekinge domains, the crust formation were associated with orogenic activity at *c.* 1.84–1.80 Ga in the central part and at 1.79–1.75 Ga in the northwest, completed by anorogenic Mesoproterozoic intrusions of anorthosite-mangerite-charnockite-granite (AMCG) suites of *c.* 1.54–1.49 and 1.48–1.45 Ga (Krzemińska *et al.*, 2017). The AMCG suite with dominated A-type rapakivi granitoids forms a long distinctive belt from the southern Lithuania and Belarus to northeastern Poland including Mazury Complex. The drill core material in MD comprises various lithology, including calc-alkaline granitoids (Wiszniewska *et al.*, 2007), Late Paleoproterozoic mafic to intermediate metavolcanics, and metagreywackes (Krzemińska *et al.*, 2005; Krzemińska, 2010). The bottom part of the drill core from the Łomża IG 2 and Mońki IG 2 boreholes is represented predominantly by orthoamphibolites and orthogneisses which crystallized at 1.80 Ga and 1.82 Ga, respectively. Their well-preserved

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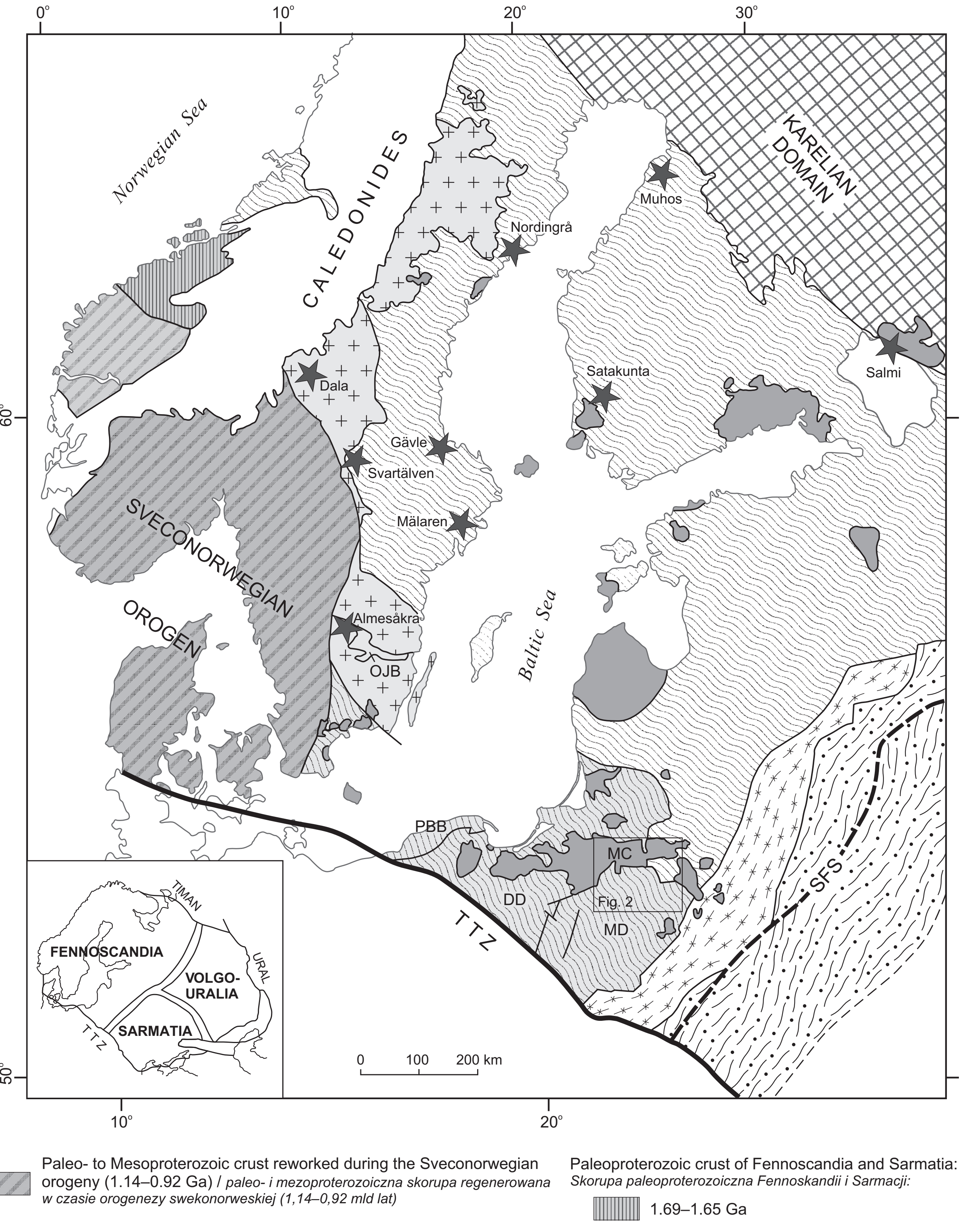
Fig. 1. Crustal age domains within the western part of the East European Craton (modified from Bogdanova *et al.*, 2015). Location of the main occurrences of Jotnian sandstone after Kohonen *et al.* (1993) and Lundmark and Lamminen (2016). Three-segment subdivision of the East European Craton (left-corner inset) according to Gorbatschev and Bogdanova (1993)

SFS – Sarmatia-Fennoscandia suture; TTZ – Teisseyre–Tornquist Zone; MD – Mazowsze domain; DD – Dobrzyń domain; PBB – Pomorze-Blekinge belt; OJB – Oskarshamn-Jönköping belt; MC – Mazury Complex

Wiek głównych domen skorupowych w zachodniej części kratonu wschodnioeuropejskiego (wg Bogdanovej i in., 2015, zmienione). Lokalizacja głównych wystąpień piaskowców jotnickich wg Kohonena i in. (1993) oraz Lundmarka i Lamminena (2016). Podział kratonu wschodnioeuropejskiego na trzy segmenty (lewy narożnik) wg Gorbatscheva i Bogdanovej (1993)

SFS – szew Fennoskandia-Sarmacja; TTZ – strefa Teisseyre'a–Tornquista; MD – domena mazowiecka; DD – domena dobrzyńska; PBB – pasmo Pomorze-Blekinge; OJB – pasmo Oskarshamn-Jönköping; MC – kompleks mazurski



Paleo- to Mesoproterozoic crust reworked during the Sveconorwegian orogeny (1.14–0.92 Ga) / *paleo- i mezoproterozoiczna skorupa regenerowana w czasie orogenezy swekonorweskiej (1,14–0,92 mld lat)*

Jotnian sandstone occurrences
wystąpienia piaskowców jotnickich

AMCG suites and A-type granites (1.65–1.44 Ga)
intruzje AMCG i granity typu A (1,65–1,44 mld lat)

Transscandinavian Igneous Belt (1.81–1.75 Ga)
Transskandynawskie Pasmo Magmowe (1,81–1,75 mld lat)

Paleoproterozoic crust of Fennoscandia and Sarmatia:
Skorupa paleoproterozoiczna Fennoskandii i Sarmacji:

1.69–1.65 Ga

1.85–1.74 Ga

1.95–1.85 Ga

1.90–1.85 Ga

2.0–1.9 Ga

Archean to Paleoproterozoic rocks (3.5–1.88 Ga)
skały archaiczne i poleoproterozoiczne (3,5–1,88 mld lat)

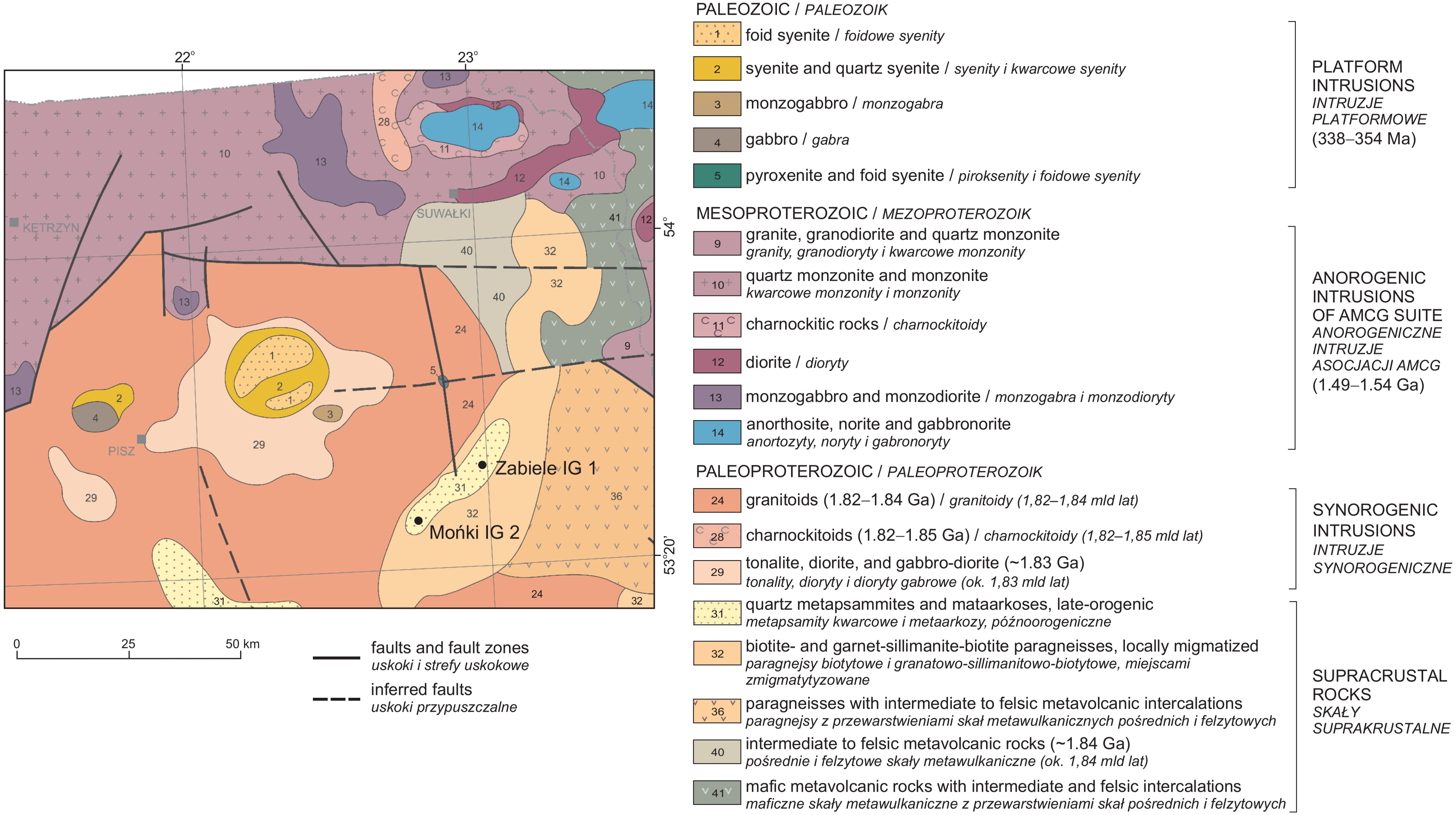


Fig. 2. Geological map of crystalline basement of northern part of the Mazowsze domain and AMCG suite showing an inferred distribution of mature quartz-rich metasedimentary rocks (code 31) with a location of the sampling sites: Mońki IG 2 and Zabiele IG 1 boreholes (adapted from Krzemińska *et al.*, 2017)

Mapa geologiczna podłoża krystalicznego północnej części domeny mazowieckiej i skał intruzyjnych asocjacji AMCG. Pokazano rozprzestrzenienie dojrzałych, bogatych w kwarc skał metaosadowych i lokalizację opróbowanych otworów wiertniczych: Mońki IG 2 i Zabiele IG 1 (na podstawie mapy Krzemińskiej i in., 2017) volcanogenic features and trace element geochemistry point to a subduction signature and island arc tectonic setting. These igneous rocks are accompanied by metasediments with increasing maturity recovered within the Mońki IG 1 and IG 2, Łomża IG 1, and Zabiele IG 1 core sections.

The first detrital zircon geochronology in MD area was conducted on metagraywacke from the Mońki IG 2 drilling, depth 819 m (Williams *et al.*, 2009). The ages of youngest detrital zircon and the metamorphic overgrowths formed after 1.83–1.82 Ga constrain the maximum deposition age (period 1.86–1.82 Ga), similar to that of some sediments from the exposed part of Fennoscandia, *e.g.* from the Västervik area in SE Sweden (Sultan *et al.*, 2005) and Tiirismaa, Pyhäntaka and Luukkola areas in southeastern Finland (Bergman *et al.*, 2008). The geochemical signatures of the arc magmatism at 1.83–1.80 Ga (Krzemińska *et al.*, 2005) and similar characteristics of the accompanied metasedimentary unit provide convincing evidence for the existence of an active continental margin in the area of Fennoscandia which is now overlain by Neoproterozoic to Phanerozoic cover (Williams *et al.*, 2009). This margin was coeval with the juvenile volcanic arc of the Oskarshamn-Jönköping belt formed at 1.83–1.82 Ga and exposed in SE Sweden (Mansfeld *et al.*, 2005).

QUARTZ-RICH SAMPLES

Further investigation of metasediments including detrital zircon and geochemical provenance study were performed on the upper part of sedimentary succession of Mońki IG 2 and Zabiele IG 1 drill sections (Fig. 2), that is represented by weakly metamorphosed quartz-rich rocks (quartzites). These quartzites were previously interpreted as a quasi-platform cover probably Neoproterozoic or Late Mesoproterozoic in age, formed during post-Gothian peneplenisation as a molasse-type deposit (Kubicki *et al.*, 1996) after emplacement of Mesoproterozoic Mazury Complex. Correlation with the Jotnian sediments exposed in the Central Fennoscandia (Baltic Shield) was suggested. This metasedimentary formation composed of a quartz arenites and subarkoses was described as the Biebrza complex (Ryka, 1998) occurred in Mońki IG 2 (N: 53°26'10" and E: 22°44'45") at a depth of 626 to 745.7 m and in Zabiele IG 1 (N: 53°32'42" and E: 22°57'55") at a depth of 557.5 to 619 m. Horizontally bedded or slightly deformed siliciclastic sediments were weakly metamorphosed in the range from zeolite to greenstone facies. All primary features observed are typical for the fluvial sandstone (Fig. 3).

ANALYTICAL METHODS

Chemical analyses of 22 whole-rock samples were performed at the Central Chemical Laboratory of the Polish Geological Institute – NRI, Warsaw. The major element compositions were analysed by X-ray fluorescence (XRF)

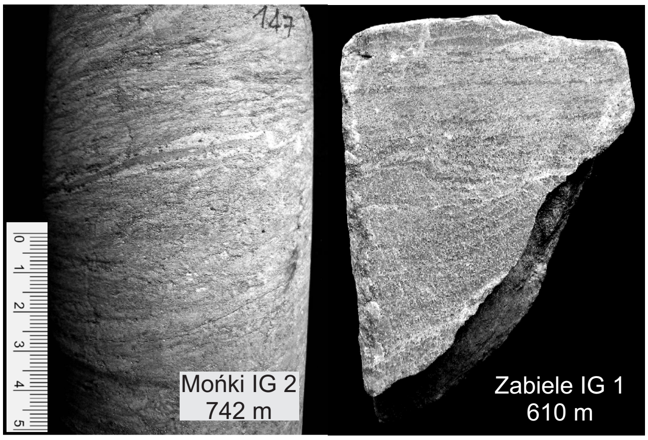


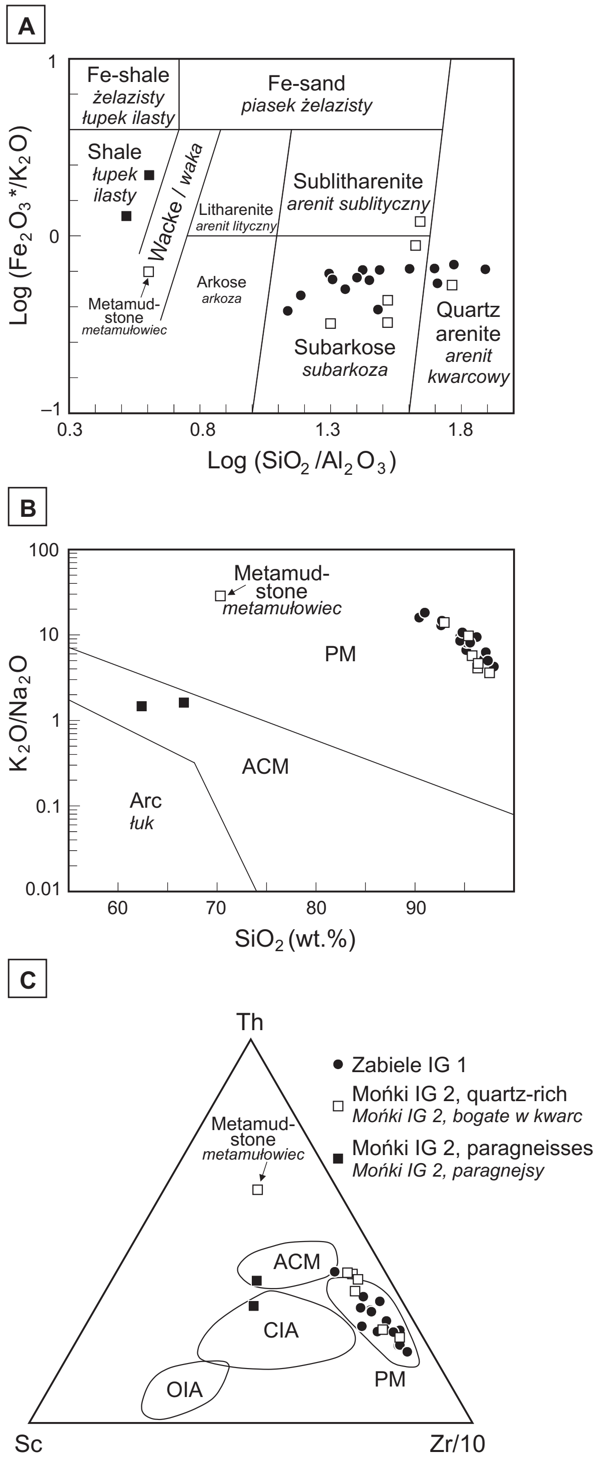
Fig. 3. Typical lithofacies in drill core samples from Mońki IG 2 (depth 742 m) and Zabiele IG 1 (depth 610 m) showing quartz-rich layers alternating with chlorite-sericite rich fine-grained lamellae. Scale in centimetres

Typowa litofacja w próbkach rdzenia wiertniczego z otworów Mońki IG 2 (głęb. 742 m) i Zabiele IG 1 (głęb. 610 m). Warstwy bogate w kwarc przewarstwione drobnoziarnistymi laminami bogatymi w chloryt i serycyt. Skala w cm

on glass beads formed by fusing a sample with lithium metaborate $LiBO_2$, and the Zr concentrations were determined on pressed powder pellets, using a Philips PW2400 sequential spectrometer in both cases. The concentrations of Th and Sc were determined by inductively coupled plasma mass spectrometry (ICP-MS) using a Perkin Elmer ELAN DRC II system. The samples were air-dried and ground, and then were decomposed with multi-acid digestion including hydrofluoric acid. The analytical accuracy and precision were found to be better than 1% for major elements, 5% for Zr and Th, and 10% for Sc, as checked by international standards and analysis of replicate samples.

Three samples for geochronology were processed by standard methods for separating zircon grains, *i.e.* crushing, sieving, heavy liquids as well as a Frantz isodynamic separator and final hand-picking at the University of Wrocław. The zircon concentrates together with chips of the reference zircons Temora-2 and SL13 were mounted in epoxy and polished until quasi-central sections were reached. The U-Pb detrital zircon analyses were conducted by SHRIMP II at the Research School of Earth Sciences, Australian National University in Canberra, according to the procedure and strategy described in more detail by Williams *et al.* (2009). The random selection of grains has been applied during this study of detrital zircon (cf. Fedo *et al.*, 2003) and only grains with strong surface imperfections were avoided. Cathodoluminescence (CL) technique was used to identify distinct zircon domains. The U, Th and Pb isotope ratios were analyzed using Duoplasmatron that produced primary ion beam from a high-purity oxygen. The sputtered secondary ions were extracted at 10 kV collected on a single electron multiplier by cycling the magnet through five scans across the nine mass: $^{196}Zr_2O$, ^{204}Pb, 204.1 as a background, ^{206}Pb,

^{207}Pb, ^{208}Pb, ^{238}U, ^{248}ThO, and ^{254}UO). The measurements were carried out with a mass resolution of approximately 5000 (at 1% peak height). Analyses were conducted using a beam diameter of ~20×24 µm, generating a pit depth of *c.* 4–5µm. The $^{206}Pb/^{238}U$ ratios were calibrated using the Temora-2 with $^{238}U/^{206}Pb$ age 416.78 ±0.33 Ma (Black *et al.*, 2004), but U concentration on standard SL13 (U = 238 ppm, U-Pb 572 Ma; Claoué-Long *et al.*, 1995). The analyses were conducted in a sequence consisting of one analysis of a Temora-2 reference zircon measurement after every fourth unknown sample analysis. Raw data were reduced using the SQUID2 Excel Macro software and the diagrams were generated by Isoplot (Ludwig, 2003).



GEOCHEMISTRY

The metasediments from Mońki and Zabiele contain about 92–97 wt.% and 89–97 wt.% of SiO_2 respectively, thus their high SiO_2/Al_2O_3 ratio indicates high maturity of the sediments. Geochemically, these rocks are classified mainly as subarkose to quartz arenite in contrast to the original shale or wacke composition of previously analyzed paragneisses in the Mońki section from depth 819 to 1020 m (Fig. 4A). The values of Chemical Index of Alteration (CIA) of these mature rocks vary from 69 to 83, indicating moderate to high degree of weathering in the source areas. The K_2O/Na_2O ratio, that specify of the potassium feldspar and mica versus plagioclase content in the rock, allows to determine the tectonic setting of terrigenous sedimentary rocks *i.e.* volcanic arc (Arc), active continental margin (ACM) to passive margin (PM) settings (Roser, Korsch,1986). The K_2O/Na_2O vs. SiO_2 plot for the rocks from Zabiele and Mońki quartz–rich part of the section, along with data from the bottom part of metasedimentary succession (Mońki), document the transition from an active continental margin to passive margin setting (Fig. 4B). This ACM to PM shift can be confirmed using the trace element contents on Sc-Th-Zr diagram (Fig. 4C).

DETRITAL ZIRCON GEOCHRONOLOGY

Isotopic U-Th-Pb data and ages of a single spot SHRIMP analyses of zircon grains from the Mońki (740 m) and Zabiele (610 m) metasandstones are reported in full as Table 1. Final ages quoted in the text are at 2σ error, whereas those (single spot) in the Table 1 are reported at 1σ error. The

Fig. 4. Geochemical classification and tectonic setting discrimination diagrams for Mońki and Zabiele quartz-rich metasedimentary rocks (this study) and paragneisses from Late Paleoproterozoic part of the Mońki section (data from Williams *et al.*, 2009)

A – Log (Fe_2O_3*/K_2O) vs Log (SiO_2/Al_2O_3) after Herron (1988); **B** – K_2O/Na_2O vs SiO_2 after Roser and Korsch (1986); **C** – Sc–Th–Zr/10 diagram after Bhatia and Crook (1986); PM – passive margin; ACM – active continental margin; CIA – continental island arc; OIA – oceanic island arc

Klasyfikacja geochemiczna i diagramy dyskryminacyjne środowiska tektonicznego dla bogatych w kwarc skał metaosadowych z Moniek i Zabieli (niniejsza praca) oraz późnopaleoproterozoicznych paragnejsów z profilu Mońki (dane z pracy Williamsa i in., 2009)

A – Log (Fe_2O_3*/K2O) vs Log (SiO_2/Al_2O_3) wg Herrona (1988); **B** – K_2O/Na_2O vs SiO_2 wg Rosera i Korscha (1986); **C** – Sc–Th–Zr/10 wg Bhatii i Crooka (1986); PM – krawędź pasywna; ACM – aktywna krawędź kontynentalna; CIA – kontynentalny łuk wysp; OIA – oceaniczny łuk wysp

Table 1

U-Th-Pb analytical results for zircons from Mońki and Zabiele metasandstones

Wyniki analityczne U-Th-Pb dla cyrkonu z metapiaskowców w profilach Mońki i Zabiele

Grain.spot	Pb* ppm	U ppm	Th ppm	Th/U	$^{208}Pb^*/^{206}Pb$	±	$^{206}Pb^*/^{238}U$	±	$^{207}Pb^*/^{235}U$	±	$^{207}Pb^*/^{206}Pb$	±	Apparent ages (Ma) 206/238	±	207/235	±	207/206	±	% concordant
Mońki 740																			
Cores																			
M-1.1	56	147	110	0.75	0.2189	0.0035	0.3328	0.0052	5.18	0.12	0.1128	0.0017	1852	25	1849	20	1845	27	100
M-2.1	57	141	97	0.69	0.1981	0.0027	0.3537	0.0033	5.91	0.07	0.1211	0.0009	1952	16	1962	11	1973	13	99
M-3.1	60	149	104	0.70	0.1989	0.0024	0.3510	0.0039	6.09	0.10	0.1259	0.0015	1939	18	1989	15	2041	21	95
M-4.1	56	154	40	0.26	0.0724	0.0017	0.3533	0.0039	5.89	0.09	0.1210	0.0011	1951	19	1961	13	1971	16	99
M-5.1	92	242	257	1.06	0.2396	0.0041	0.3222	0.0043	5.54	0.12	0.1247	0.0020	1801	21	1907	19	2025	29	89
M-6.1	41	102	110	1.08	0.3055	0.0063	0.3291	0.0046	5.08	0.10	0.1121	0.0012	1834	23	1834	16	1833	20	100
M-7.1	83	201	114	0.57	0.1637	0.0018	0.3717	0.0048	6.42	0.12	0.1252	0.0014	2038	23	2035	16	2032	20	100
M-8.1	81	199	85	0.43	0.1182	0.0015	0.3786	0.0069	6.62	0.14	0.1268	0.0012	2070	32	2062	19	2054	17	101
M-9.1	62	143	121	0.84	0.2358	0.0035	0.3676	0.0042	6.30	0.10	0.1243	0.0012	2018	20	2018	14	2018	17	100
M-10.1	38	101	46	0.46	0.1284	0.0039	0.3507	0.0051	5.74	0.12	0.1187	0.0015	1938	24	1937	18	1936	23	100
M-11.1	52	142	110	0.78	0.2212	0.0025	0.3192	0.0045	4.98	0.09	0.1132	0.0011	1786	22	1816	15	1851	17	97
M-12.1	28	72	43	0.59	0.1638	0.0053	0.3553	0.0098	5.79	0.20	0.1182	0.0022	1960	47	1945	31	1930	34	102
M-13.1	70	191	160	0.84	0.2203	0.0032	0.3190	0.0038	4.85	0.08	0.1102	0.0011	1785	19	1793	14	1803	18	99
M-14.1	54	150	41	0.27	0.0773	0.0016	0.3481	0.0066	5.81	0.14	0.1211	0.0016	1926	32	1948	21	1972	23	98
M-15.1	66	180	63	0.35	0.0945	0.0017	0.3538	0.0039	5.84	0.08	0.1198	0.0010	1953	19	1953	13	1953	15	100
M-16.1	61	168	49	0.29	0.0766	0.0017	0.3521	0.0041	5.86	0.11	0.1207	0.0017	1945	19	1955	17	1966	26	99
M-17.1	49	127	61	0.48	0.1390	0.0033	0.3571	0.0077	5.88	0.16	0.1194	0.0018	1969	37	1958	24	1947	27	101
M-18.1	95	400	305	0.76	0.0749	0.0073	0.2335	0.0030	3.63	0.12	0.1128	0.0032	1353	15	1556	26	1845	52	73
M-20.1	48	132	79	0.60	0.1711	0.0031	0.3259	0.0044	5.05	0.09	0.1125	0.0012	1818	21	1828	16	1840	19	99
M-21.1	41	107	95	0.89	0.2585	0.0043	0.3272	0.0046	5.11	0.09	0.1133	0.0011	1825	22	1838	15	1853	17	99
M-22.1	96	262	146	0.56	0.1384	0.0022	0.3377	0.0049	5.57	0.11	0.1196	0.0013	1876	24	1912	17	1951	20	96
M-23.1	117	718	1005	1.40	0.1635	0.0044	0.1469	0.0011	2.48	0.04	0.1223	0.0018	884	6	1265	13	1990	27	44
M-24.1	62	161	78	0.48	0.1400	0.0029	0.3550	0.0036	5.77	0.08	0.1179	0.0009	1958	17	1942	12	1925	14	102
M-25.1	39	101	54	0.54	0.1511	0.0026	0.3557	0.0047	5.96	0.11	0.1216	0.0014	1962	22	1971	16	1980	20	99
M-26.1	100	171	180	1.05	0.2552	0.0034	0.4695	0.0063	11.90	0.20	0.1838	0.0017	2482	28	2596	16	2687	15	92
M-27.1	31	86	61	0.71	0.2012	0.0046	0.3234	0.0055	5.01	0.11	0.1123	0.0012	1806	27	1821	18	1838	20	98
M-28.1	64	189	131	0.69	0.1070	0.0044	0.3186	0.0049	5.24	0.15	0.1193	0.0027	1783	24	1859	25	1945	40	92
M-29.1	43	125	83	0.66	0.1868	0.0041	0.3107	0.0042	4.60	0.09	0.1075	0.0014	1744	21	1750	17	1757	24	99
M-30.1	62	173	45	0.26	0.0721	0.0019	0.3518	0.0054	5.79	0.11	0.1194	0.0011	1943	26	1945	17	1947	17	100
M-31.1	90	227	226	1.00	0.2837	0.0022	0.3298	0.0051	5.28	0.10	0.1161	0.0011	1837	25	1866	17	1898	17	97
M-32.1	83	249	294	1.18	0.2820	0.0036	0.2780	0.0027	4.35	0.07	0.1134	0.0013	1581	14	1703	14	1855	22	85
M-33.1	64	200	166	0.83	0.1604	0.0037	0.2896	0.0042	4.84	0.10	0.1211	0.0017	1640	21	1791	18	1973	26	83
M-34.1	72	187	61	0.33	0.0897	0.0014	0.3661	0.0067	6.41	0.13	0.1269	0.0009	2011	32	2033	18	2056	12	98
M-35.1	46	134	56	0.42	0.1169	0.0023	0.3226	0.0055	4.96	0.11	0.1115	0.0015	1802	27	1813	19	1824	24	99
M-36.1	41	110	87	0.79	0.2226	0.0028	0.3241	0.0043	4.95	0.09	0.1107	0.0013	1810	21	1810	16	1810	21	100
Mońki 742																			
Overgrowths																			
MO-1.1	180	2545	294	0.12	0.3152	0.0262	0.0587	0.0013	0.699	0.101	0.0864	0.0121	368	8	538	62	1346	297	discordant
MO-2.1	86	1165	293	0.25	0.2213	0.0125	0.0652	0.0007	0.867	0.053	0.0966	0.0056	407	4	634	29	1559	114	discordant
MO-3.1	81	257	78	0.30	0.0716	0.0021	0.3105	0.0041	4.739	0.101	0.1107	0.0017	1743	20	1774	18	1811	28	discordant
MO-4.1	95	970	394	0.41	0.2449	0.0128	0.0848	0.0008	1.141	0.060	0.0976	0.0049	525	5	773	29	1578	98	discordant
MO-5.1	40	446	502	1.13	0.3135	0.0225	0.0733	0.0011	1.154	0.097	0.1141	0.0092	456	7	779	47	1866	153	discordant
MO-6.1	102	2423	1054	0.44	0.4308	0.0189	0.0316	0.0005	0.470	0.038	0.1079	0.0083	201	3	391	26	1764	147	discordant

Table 1 cont.

Grain.spot	Pb* ppm	U ppm	Th ppm	Th/U	^{208}Pb*/^{206}Pb	±	^{206}Pb*/^{238}U	±	^{207}Pb*/^{235}U	±	^{207}Pb*/^{206}Pb	±	Apparent ages (Ma) 206/238	±	207/235	±	207/206	±	% concordant
Zabiele 610																			
Cores																			
Z-1.1	86	223	86	0.39	0.1100	0.0013	0.3631	0.0035	6.17	0.08	0.1233	0.0009	1997	16	2001	11	2005	14	100
Z-2.1	67	194	171	0.88	0.1889	0.0041	0.3106	0.0035	4.79	0.11	0.1118	0.0022	1744	17	1783	20	1829	36	95
Z-3.1	52	141	59	0.42	0.1156	0.0021	0.3508	0.0045	5.61	0.11	0.1160	0.0015	1939	22	1918	17	1896	23	102
Z-4.1	58	136	113	0.83	0.2351	0.0025	0.3657	0.0041	6.07	0.12	0.1204	0.0017	2009	20	1986	17	1962	25	102
Z-5.1	41	93	78	0.83	0.2401	0.0029	0.3757	0.0080	6.46	0.16	0.1247	0.0013	2056	38	2040	22	2024	19	102
Z-6.1	58	158	49	0.31	0.0870	0.0020	0.3555	0.0041	5.83	0.09	0.1189	0.0011	1961	20	1950	14	1939	17	101
Z-7.1	74	384	388	1.01	0.1913	0.0040	0.1734	0.0013	2.48	0.05	0.1038	0.0021	1031	7	1267	16	1694	37	61
Z-8.1	100	643	836	1.30	0.1922	0.0058	0.1393	0.0010	1.98	0.05	0.1032	0.0024	841	6	1110	17	1683	43	50
Z-9.1	65	93	85	0.92	0.2438	0.0032	0.5640	0.0125	15.87	0.39	0.2041	0.0017	2883	52	2869	24	2860	14	101
Z-10.1	113	225	165	0.73	0.1514	0.0025	0.4426	0.0048	10.04	0.14	0.1645	0.0011	2362	22	2438	13	2502	12	94
Z-11.1	66	188	128	0.68	0.1913	0.0018	0.3154	0.0030	4.64	0.08	0.1068	0.0014	1767	15	1757	15	1745	25	101
Z-12.1	74	201	73	0.37	0.0934	0.0012	0.3539	0.0048	5.92	0.11	0.1213	0.0013	1953	23	1964	16	1976	19	99
Z-13.1	57	190	87	0.46	0.1038	0.0030	0.2870	0.0031	4.57	0.08	0.1154	0.0015	1626	16	1743	15	1886	23	86
Z-14.1	73	224	211	0.94	0.2038	0.0027	0.2900	0.0029	4.35	0.06	0.1089	0.0010	1642	14	1704	12	1781	17	92
Z-15.1	105	332	182	0.55	0.1204	0.0017	0.2974	0.0032	4.65	0.07	0.1133	0.0009	1678	16	1758	12	1854	14	91
Z-16.1	63	180	64	0.36	0.0983	0.0022	0.3332	0.0049	5.37	0.11	0.1170	0.0013	1854	24	1881	17	1910	21	97
Z-17.1	46	129	82	0.63	0.1780	0.0032	0.3193	0.0036	4.90	0.08	0.1113	0.0010	1786	18	1802	13	1821	17	98
Z-18.1	73	197	114	0.58	0.1606	0.0021	0.3363	0.0038	5.47	0.08	0.1180	0.0009	1869	18	1897	13	1927	14	97
Z-19.1	79	172	194	1.13	0.3164	0.0031	0.3697	0.0044	6.63	0.10	0.1302	0.0011	2028	21	2064	14	2100	15	97
Z-20.1	37	97	52	0.53	0.1517	0.0021	0.3455	0.0073	5.71	0.16	0.1199	0.0019	1913	35	1933	24	1955	28	98
Z-21.1	113	289	176	0.61	0.1742	0.0022	0.3503	0.0031	5.81	0.07	0.1203	0.0009	1936	15	1948	11	1961	13	99
Z-22.1	31	90	32	0.35	0.0989	0.0026	0.3290	0.0054	5.25	0.11	0.1157	0.0014	1834	26	1861	19	1891	22	97
Z-23.1	25	68	54	0.80	0.1508	0.0035	0.3396	0.0075	5.56	0.16	0.1188	0.0017	1885	36	1911	24	1939	26	97
Z-24.1	78	138	61	0.44	0.1171	0.0014	0.5060	0.0070	12.80	0.21	0.1834	0.0013	2640	30	2665	15	2684	12	98
Z-25.1	28	77	38	0.50	0.1358	0.0036	0.3411	0.0070	5.45	0.14	0.1159	0.0014	1892	34	1893	22	1894	22	100
Z-26.1	115	420	492	1.17	0.2020	0.0023	0.2405	0.0018	3.92	0.05	0.1183	0.0010	1389	9	1618	10	1930	15	72
Z-27.1	101	290	95	0.33	0.0887	0.0011	0.3368	0.0043	5.53	0.10	0.1190	0.0014	1871	21	1905	16	1941	21	96
Z-28.1	55	152	63	0.41	0.1179	0.0025	0.3388	0.0037	5.49	0.08	0.1175	0.0009	1881	18	1899	12	1918	14	98
Z-29.1	68	190	92	0.48	0.0979	0.0018	0.3429	0.0051	5.70	0.10	0.1206	0.0010	1901	25	1932	16	1966	15	97
Z-30.1	73	215	88	0.41	0.1140	0.0017	0.3208	0.0054	4.81	0.09	0.1087	0.0008	1794	26	1786	16	1778	13	101
Z-31.1	80	241	134	0.55	0.1562	0.0016	0.3051	0.0031	4.54	0.07	0.1081	0.0010	1716	15	1739	12	1767	16	97
Z-32.1	65	179	56	0.31	0.0877	0.0014	0.3511	0.0048	5.80	0.10	0.1199	0.0011	1940	23	1947	15	1955	16	99
Z-33.1	64	189	119	0.63	0.1582	0.0019	0.3106	0.0029	4.79	0.06	0.1118	0.0009	1744	14	1782	11	1828	15	95
Z-34.1	69	207	115	0.56	0.1563	0.0017	0.3083	0.0028	4.63	0.06	0.1089	0.0010	1732	14	1754	12	1780	17	97
Z-35.1	67	185	52	0.28	0.0797	0.0018	0.3515	0.0038	5.81	0.09	0.1198	0.0011	1942	18	1947	13	1953	17	99
Z-36.1	79	223	68	0.30	0.0841	0.0014	0.3432	0.0046	5.73	0.09	0.1210	0.0009	1902	22	1936	14	1972	13	97
Z-37.1	51	119	59	0.50	0.1325	0.0019	0.3922	0.0050	7.08	0.11	0.1309	0.0011	2133	23	2121	15	2110	15	101
Z-38.1	65	178	54	0.30	0.0846	0.0016	0.3531	0.0044	5.93	0.09	0.1218	0.0009	1949	21	1966	14	1983	14	98
Z-39.1	61	172	81	0.47	0.1001	0.0018	0.3365	0.0052	5.53	0.11	0.1191	0.0012	1870	25	1905	17	1943	19	96
Z-40.1	63	175	132	0.76	0.2241	0.0022	0.3098	0.0034	4.94	0.08	0.1157	0.0013	1740	17	1809	14	1890	21	92

results are plotted on concordia diagrams (Fig. 5) and shown on probability density plots (Fig. 6A, B). A total of 35 and 40 randomly selected cores of detrital zircon grains from both samples were analyzed. Individual zircon grain ages were evaluated using $^{207}Pb/^{206}Pb$ ratios (all grains are older than 1.0 Ga). The Pb-Pb age distributions demonstrate (Fig. 5) that detrital material was derived mainly from Paleoproterozoic sources with ages in the range of 1.76–2.06 Ga in Mońki (740 m) and 1.68–2.11 Ga in Zabiele (610 m), and Archean grains (older than 2.5 Ga) are rare. Within dominated Paleoproterozoic population the ages are grouped in two clusters (Fig. 6A, B): older with the major peak age at 1959 Ma (Zabiele) and 1966 Ma (Mońki), and a minor younger cluster peaked at *c.* 1779 Ma (Zabiele) and 1847 Ma (Mońki). The similar prevailing population peaked at 1969 Ma (Fig. 6C) was previously recognized in Mońki metagreywacke at depth 819 m (Williams *et al.*, 2009). The comparison of all three samples (Fig. 6A–C) shows that most prominent group of detritus are the same with peak at 1.96 Ga, but the younger populations are slightly different from those recognized in Mońki at depth 819 m. The youngest concordant grains were dated at 1816 ±22 Ma (Mońki 819 m), 1757 ±24 Ma (Mońki 740 m), and 1685 ±43 Ma (Zabiele 610 m). Usually, the youngest detritus should define maximum depositional age, but only within orogenic setting. The lack of interlayered volcanics or crosscutting intrusive rocks make impossible precise delimitation of deposition time. The recognizable differences associated with the youngest age group derived from a proximal source, demonstrate a delivery of increasingly younger detritus, according to the stratification from the bottom to the top.

Despite a short distance (<100 km) between quartz-rich succession and AMCG suite as the potential source area, the Mesoproterozoic component was not detected in the clastic material whose deposition has finished before denudation of the AMCG suite with emplacement age of 1.54–1.49 Ga (Fig. 2). Most of the regional studies in central Fennoscandia show, that distribution of Jotnian sediments (Fig. 1) has to be spatially associated with the occurrence of Mesoproterozoic rapakivi granite and their deposition has been continued

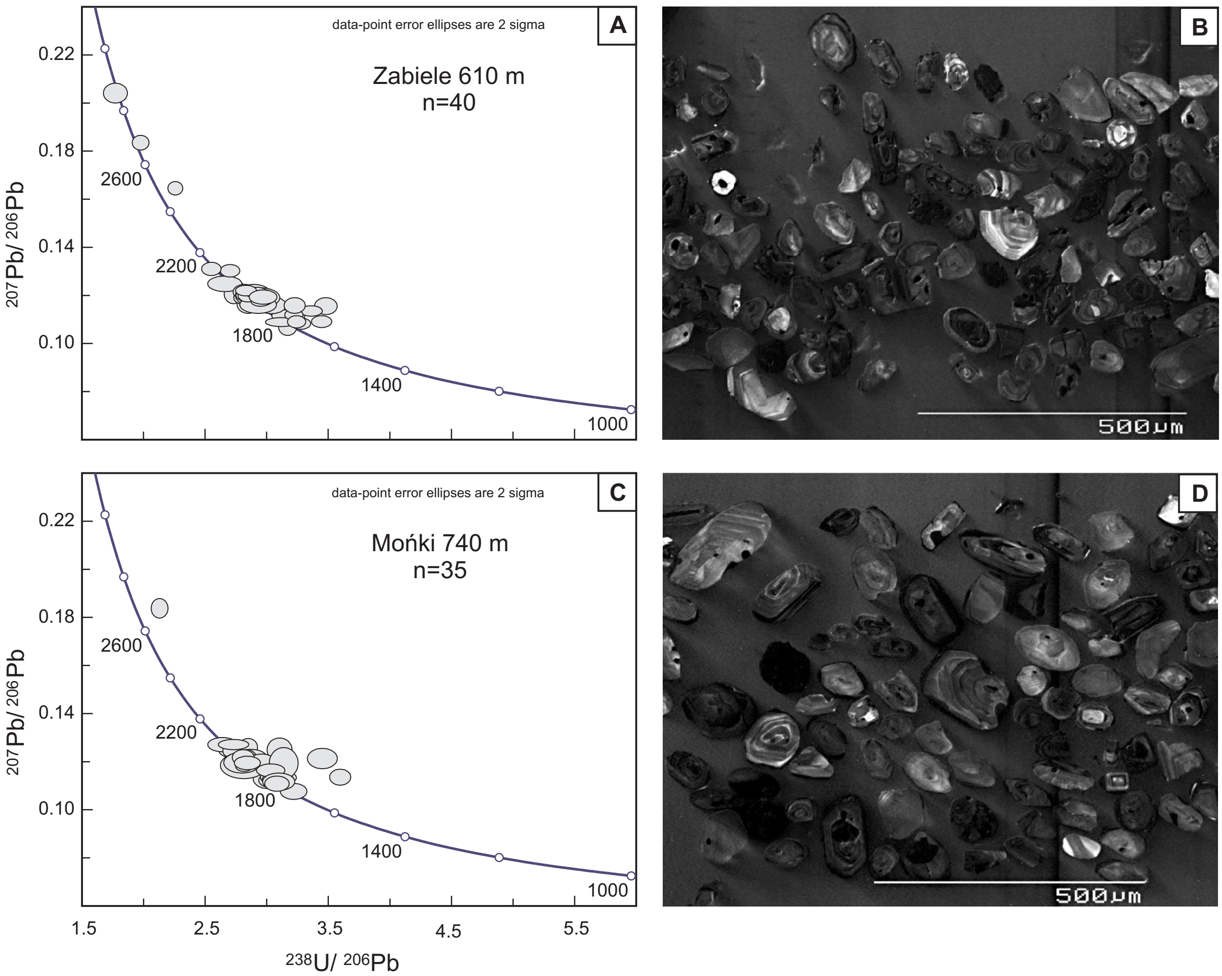


Fig. 5. U-Pb concordia diagrams and CL images showing the results of single-grain detrital zircon analyses from metasedimentary rocks: (A–B) Zabiele IG 1 (depth 610 m); (C–D) Mońki IG 2 (depth 740 m)

Diagramy zgodności wieku U-Pb i obrazy CL detrytycznego cyrkonu ze skał metaosadowych: (**A**–**B**) Zabiele IG 1 (głęb. 610 m); (**C**–**D**) Mońki IG 2 (głęb. 740 m)

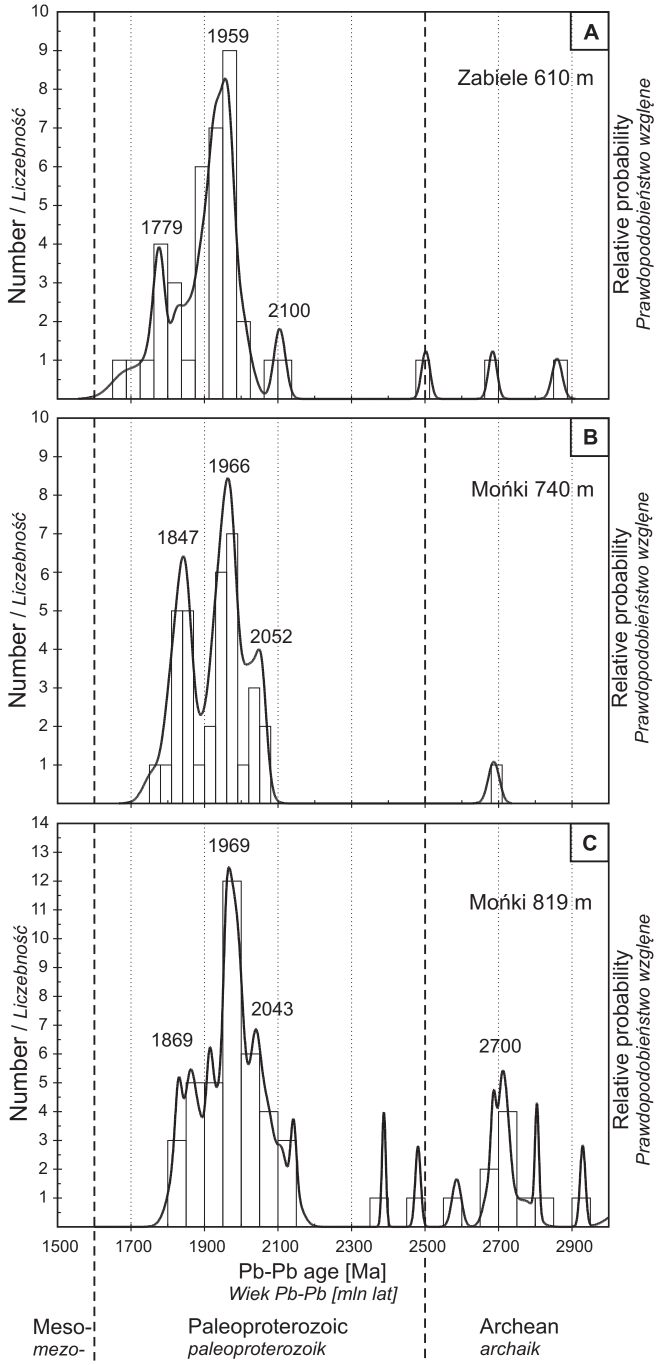


Fig. 6. Relative probability plots of concordant and nearly concordant $^{207}Pb/^{206}Pb$ detrital zircon ages representing the main clusters of detritus from (A) Zabiele IG 1 (depth 610 m) and (B) Mońki IG 2 (depth 740 m) metasediments (this study), and (C) Mońki IG 2 (depth 819 m) paragneisses (data from Williams *et al.*, 2009)

Krzywe względnego prawdopodobieństwa zgodnego i prawie zgodnego wieku $^{207}Pb/^{206}Pb$ detrytycznego cyrkonu reprezentujące główne grupy materiału okruchowego w skałach metaosadowych (**A**) z profilu Zabiele IG 1 (głęb. 610 m) i (**B**) Mońki IG 2 (głęb. 740 m) (niniejsza praca) oraz (**C**) w paragnejsach z profilu Mońki IG 2 (głęb. 819 m) (dane z pracy Williamsa i in., 2009)

long after the 1.55 Ga anorogenic magmatism up to 1.26 Ga (Amantov *et al.*, 1996; Pokki *et al.*, 2013; Lundmark, Lamminen, 2016). The K-Ar datings of the Jotnian sandstone in Finland documented a diagenesis time at approximately 1300 Ma (Kohonen *et al.*, 1993).

Both types of sediments from the Mońki, *i.e.* quartz-rich sandstones (*e.g.* interval 740 and 742 m) and greywacke to shale (*e.g.* depth 819 m) were affected by low-temperature metamorphism, forming subtle low-luminescent overgrowths (Figs. 5 and 7). Only a few zircon rims from these metasedimentary rocks (Mońki sample) were analyzed, giving however an uncertain results (Fig. 7). The analyses which have experienced isotopic disturbance plot off the concordia line. It is a visual record of Pb exchange with the external environment by intra-grain Pb mobility (Pb-loss) and diffusion in metamict zircon. Such problem of open U-Pb system is one of the most important limiting factors in the reliable interpretation of isotope ratios. Sometimes however Pb-loss is caused by geological events, thus discordant ages may provide geochronologically useful information (*e.g.* Gehrels, 2014; Reimink *et al.*, 2016 and ref. therein). As a consequence, a discordia-line with a lower intercept on concordia diagram may be considered as a diagnostic tool to interpret single zircon age data. The lower intercept on concordia diagrams at 1833 ±67 Ma (depth 819 m) and 1813 ±57 (depth 742 m) is probably the combined result of Pb-loss and/or new zircon growth during a low-T metamorphic event. This time of Pb-loss event together with deficiency of grains younger than 1.6 Ga may suggest that the effective deposition time was probably completed before 1600 Ma.

SOURCE AREAS

The seismic and geological data indicate that, about 2.0 billion years ago, the Fennoscandian and Sarmatian lithospheric plates were separated by the Belarus oceanic plate (Garetsky, Karatayev, 2011). The period of about 1.82–1.80 Ga was interfered with the first oblique collision of the Fennoscandia and Sarmatia (Volga–Sarmatia), that was completed before 1.70 Ga (Lubnina *et al.*, 2016). The Mońki and Zabiele sediments deposited north of Fennoscandia–Sarmatia suture during final collision have to contain detritus from the both blocks. It is very likely that westernmost Sarmatia with Andean-type Osnitsk–Mikashevichi igneous belt (OMI) at 2.10–1.96 Ga has become the most significant source of detritus older than 1.96 Ga. The complementary isotope information *e.g.* O and Hf signatures of dated zircon from the Mońki metagreywacke supports this hypothesis. The average $\delta^{18}O_{zrn}$ of 5.95 ±0.26‰ suggests a significant amount of juvenile "mantle-derived material" mixed with crustal slightly elevated oxygen isotope composition (Krzemińska *et al.*, 2016). Moreover the comparison of new $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ zircon data (Wiszniewska *et al.*, 2018) showed a similarity of age and Hf isotope signatures of Mońki detritus versus zircon from felsic juvenile igneous rocks from north-west region of the Sarmatia (Shumlyanskyy *et al.*, 2015).

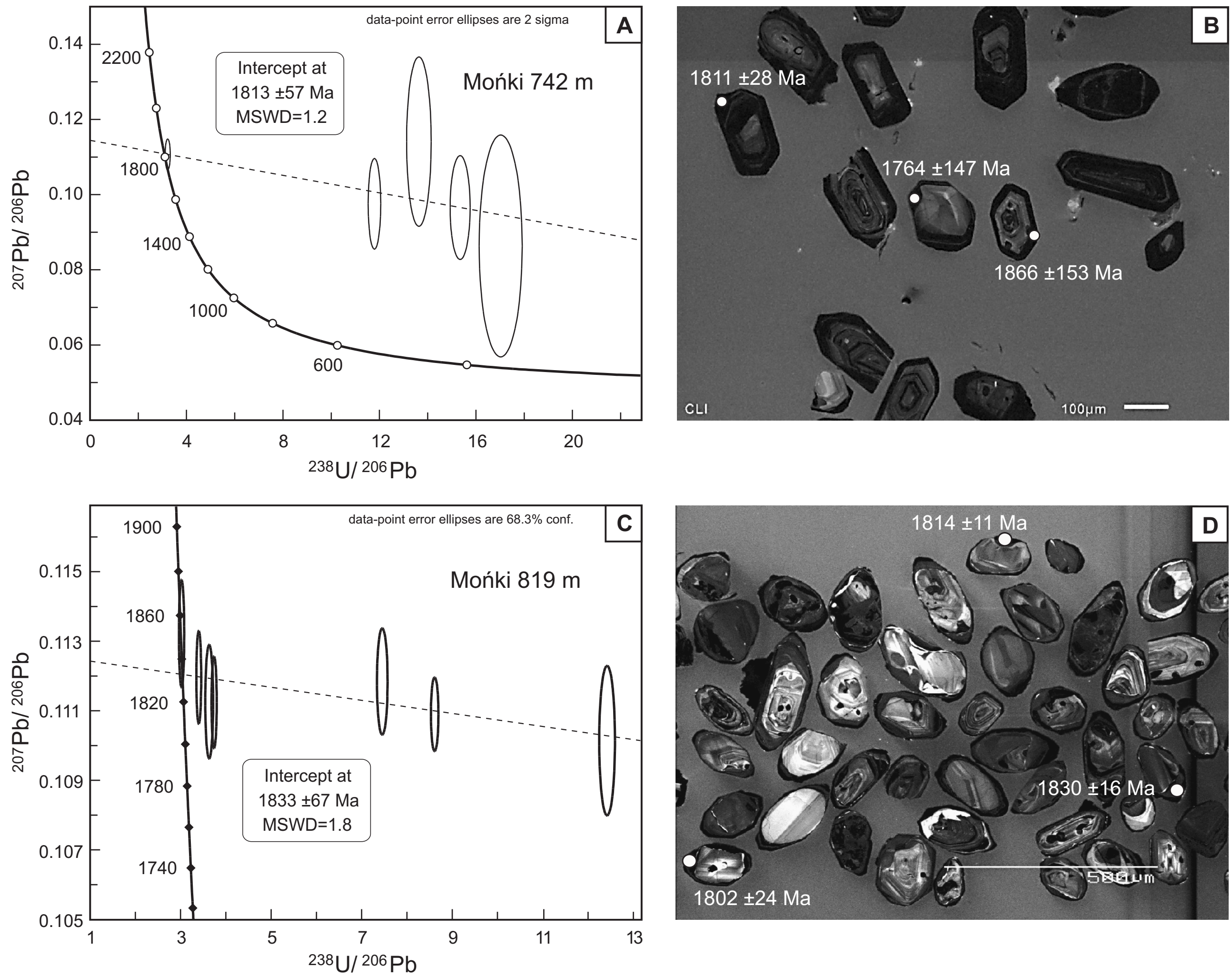


Fig. 7. U-Pb concordia diagrams and CL images for limited number of zircon rims from Mońki IG 2: (A–B) depth 742 m (this study) and (C–D) depth 819 m (data from Williams *et al.*, 2009), documenting the time of Pb-loss due to low-T metamorphic event

Diagramy zgodności wieku U-Pb i obrazy CL obwódek na ziarnach cyrkonu z profilu Mońki IG 2: (**A–B**) głęb. 742 m (niniejsza praca) i (**C–D**) głęb. 819 m (dane z pracy Williamsa i in., 2009), dokumentujące czas utraty ołowiu spowodowanej przez metamorfizm niskotemperaturowy

The detritus younger than ~1.85 Ga was probably delivered from proximal sources. It was related to degradation of the local late Svecofennian rocks in NE Poland, where the most prominent magmatic activity at the pre-Mesoproterozoic time covers the age span of 1.86–1.76 Ga (Krzemińska *et al.*, 2017).

THE JOTNIAN VERSUS LATE PALEOPROTEROZOIC STRATIGRAPHY

The terms “Jotnian” (Finland, Sweden) or “Riphean” (Russia) are used for Mesoproterozoic low-grade metasedimentary rocks spatially associated with large rapakivi intrusions and/or AMCG suites. Extensive rapakivi plutonism with gravitational rise and heating effects was a major tectonic factor that marked the start of grabens development, which were then filled with terrigenous Jotnian sandstones (Amantov *et al.*, 1996; Pokki *et al.*, 2013; Lundmark, Lamminen, 2016). The principal localities of Jotnian sediments are the Satakunta in southwest Finland, Gulf of Bothnia, the Åland Sea, the Lake Ladoga, and also Dala basin in central Sweden. They were sourced from the surrounding regions, which comprises Paleo- and Mesoproterozoic rocks. The dominance of the Paleoproterozoic detritus was documented in Satakunta formation framed by the Svecofennian basement, but these sediments were intruded by numerous mafic dykes at 1256.2 ±1.4 Ma (Söderlund *et al.*, 2006), that give the minimum depositional age consistent with Jotnian signature. In case of the Dala basin, the zircon age data document detritus in range from *c.* 3.1 to 1.52 Ga (Lundmark, Lamminen, 2016). The prominent 1.66–1.52 Ga zircon population (*c.* 1/3 of the grains) of Dala sediments indicates that large amounts of detritus was sourced from the surrounding region, which comprises also Gothian rocks. Similarly ultramature, quartz arenitic conglomerate of the Suursaari Island, Gulf of Finland, Russia, that is one of the oldest known post-Svecofennian sedimentary rocks (Pokki *et al.*, 2013), contains local rapakivi derived zircon grains of 1.65 Ga, that constrain a maximum depositional age just after emplacement of Wiborg rapakivi batholith at 1.65−1.62 Ga and Häme dyke swarm (1665 Ma) northwest of the Wiborg batholith.

The quartz-rich deposits from Mońki and Zabiele (youngest zircon grains of 1757 and 1685 Ma), located near (<100 km) the southern margin of AMCG plutons (1.54–1.49 Ga), which do not contain detrital material from this Mesoproterozoic prominent crustal unit, predate erosion (or emplacement) of AMCG suite. It indicates that previously proposed their genetic and temporal links with Jotnian formation are not so obvious.

SUMMARY

The new detrital zircon data from Mońki and Zabiele quartz-rich metasedimentary rocks have important implications for erosion and sediment dispersion on the scale of the Fennoscandia block. The conclusive observation is the lack of products of AMCG degradation. The genetic relationship with the Jotnian deposition has not been confirmed. The metasediments with youngest grains of 1757 ±24 Ma (Mońki 740 m) and of 1685 ±43 Ma (Zabiele 610 m), provide geological record of successive deposition between end of the Late Svecofennian orogeny (1.79–1.77 Ga) after Fennoscandia-Sarmatia collision and subsequent final stabilization of the EEC but before beginning of denudation of the anorogenic AMCG Mazury suite emplaced at 1.54–1.49 Ga.

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STRESZCZENIE

W artykule zaprezentowano wyniki badań wieku detrytycznego cyrkonu metodą U-Pb i rezultaty analiz proweniencji materiału okruchowego skał metaosadowych ze stropowej części prekambryjskiego profilu otworów wiertniczych Mońki IG 2 i Zabiele IG 1. Podejmuje jednocześnie problem obecności tzw. formacji jotnickiej w podłożu krystalicznym północno-wschodniej Polski. Poziomo ułożone, nieznacznie zdeformowane, bogate w kwarc piaskowce (kwarcyty), zmetamorfizowane w warunkach facji zieleńcowej, zachowały cechy osadów rzecznych. W polskiej literaturze geologicznej kwarcyty z Moniek i Zabieli, opisane jako mezoproterozoiczna molasa wypełniająca rowy i zagłębienia tektoniczne związane z „układem dyslokacji gotyjskich", stanowiły przykład formacji jotnickiej, która miała powstać podczas peneplenizacji plutonicznych masywów kompleksu mazurskiego (Kubicki i in., 1996). Kwarcyty były korelowane z podobnymi bogatymi w kwarc utworami znanymi z północnej części Fennoskandii, młodszymi niż granity rapakiwi (poniżej 1600 mln lat), a starszymi niż żyły diabazowe (1260 mln lat), niekiedy tnące te osady. Główne miejsca występowania utworów jotnickich to m.in. Satakunta w południowo-zachodniej Finlandii, Zatoka Botnicka, Salmi nad jeziorem Ładoga, a także basen Dala w centralnej Szwecji. W ich otoczeniu występują skały zarówno paleo-, jak i mezoproterozoiczne. Chociaż wszystkich tych mineralogicznie dojrzałych skał metaosadowych nie można łączyć z pojedynczym zdarzeniem tektonicznym, jednak większość z nich przestrzennie jest związana z masywami granitoidów

rapakiwi i skałami magmowymi asocjacji AMCG o wieku ok. 1,65–1,50 mld lat.

Skały metaosadowe ze stropu prekambryjskiej części profilu Mońki IG 2 (głęb. 626,0–745,7 m) oraz Zabiele IG 1 (głęb. 557–619 m), sklasyfikowane jako arenity kwarcowe i subarkozy, znajdują się w niewielkiej odległości od rozległego kompleksu mazurskiego, gdzie granitoidy, anortozyty i pozostałe człony asocjacji AMCG zostały posadowione ok. 1,53–1,50 mld lat temu. Parametry geochemiczne skał metaosadowych z Zabieli i Moniek, w tym diagramy dyskryminacyjne wskazują na zmianę środowiska geotektonicznego obszarów źródłowych z aktywnej krawędzi kontynentalnej na krawędź pasywną. Badania geochronologiczne wieku Pb-Pb detrytycznego cyrkonu wykazały, że materiał detrytyczny był dostarczany głównie z paleoproterozoicznych źródeł o wieku między 1,76 a 2,06 mld lat (Mońki) oraz 1,68–2,11 mld lat (Zabiele), a ziarna ze skał archaicznych (starsze niż 2,5 mld lat) są rzadkie. Najmłodsze rozpoznane ziarna datowane są na 1757 ±24 mln lat (Mońki IG 2, głęb. 740 m) i 1685 ±43 mln lat (Zabiele IG 1, głęb. 610 m). Nie ma tu materiału pochodzącego z denudacji kompleksu mazurskiego (ok. 1,50–1,55 mld lat), który był wcześniej uznawany za główne źródło detrytu. Ustalenie maksymalnego wieku depozycji w środowisku geotektonicznym krawędzi pasywnej nie jest proste. Pewnych wskazówek dostarczają cienkie obrosty (obwódki) metamorficzne występujące na ziarnach cyrkonu i wiek metamorfizmu, który zachodził po ustaniu sedymentacji. W tym przypadku obwódki dokumentują epizod termiczny połączony z rozszczelnieniem układu izotopowego U-Pb, mało precyzyjnie datowany na ok. 1813 ±57 mln lat. Pozwala to stwierdzić, że maksymalny wiek depozycji materiału okruchowego prawdopodobnie nie był młodszy niż 1,6 mld lat, a więc bogate w kwarc skały metaosadowe z Moniek i Zabieli są znacząco starsze niż pierwotnie przypuszczano. Niemożliwa jest zatem ich korelacja z osadami mezoproterozoicznej formacji jotnickiej. Wyraźne jest przy tym podobieństwo w rozkładzie populacji wiekowych detrytu w paragnejsach z profilu Mońki IG 2 (głęb. 819 m), które odzwierciedlają depozycję materiału okruchowego w basenie swekofeńskim aktywnym co najmniej do 1833 ±67 mln lat temu. W obu przypadkach materiał pochodził głównie z erozji paleoproterozoicznych skał na krawędziach Fennoskandii i Sarmacji. Znaczący udział w metapiaskowcach materiału młodszego niż 1,80 mld lat wskazuje na kontynuację depozycji po tym czasie oraz zmianą środowiska geotektonicznego obszarów źródłowych. Najbardziej prawdopodobne jest powstanie osadów po kolizji Fennoskandii z Sarmacją (wygasanie orogenezy swekofeńskiej), ale przed denudacją mezoproterozoicznych intruzji AMCG kompleksu mazurskiego.