Acta Geologica Polonica, Vol. 59 (2009), No. 4, pp. 545–565

The Eastern Sudetic Island in the Early-to-Middle Turonian: evidence from heavy minerals in the Jerzmanice sandstones, SW Poland

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ABSTRACT:

Biernacka, J. and Józefiak, M. 2009. The Eastern Sudetic Island in the Early-to-Middle Turonian: evidence from heavy minerals in the Jerzmanice sandstones, SW Poland. *Acta Geologica Polonica*, **59** (4), 545–565. Warszawa.

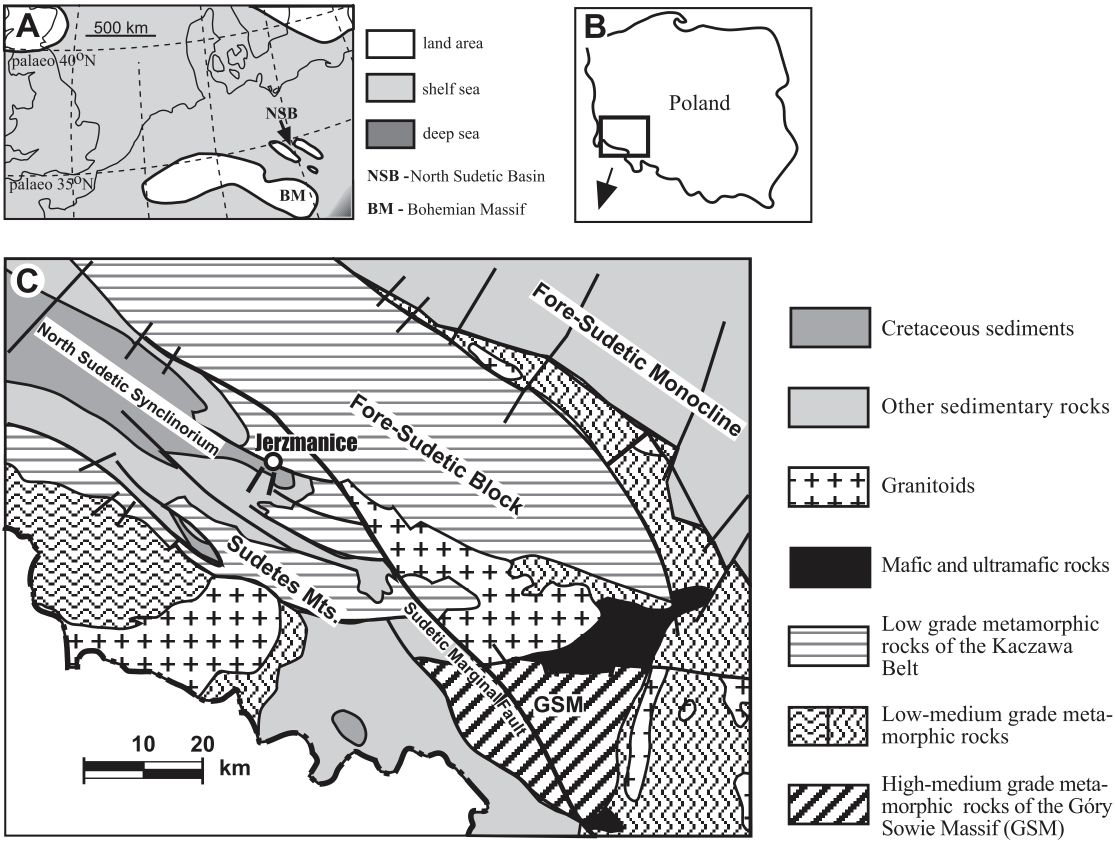
The Eastern Sudetic Island was an emerged area in the Late Cretaceous shelf-sea of Central Europe that delivered coarse siliciclastic material to adjacent basins. The extent of this land area during the Early-to-Middle Turonian has been reconstructed on the basis of a heavy-mineral analysis of the Jerzmanice sandstones from the North Sudetic Basin. The heavy minerals studied predominantly derive from medium to high grade metamorphic rocks, such as granulites and metabasites, calc-silicate rocks, mica schists and gneisses, and from garnet peridotites and pegmatites/granites. The interpretation of various heavy mineral species provides evidence that the major part of the detritus constituting the Jerzmanice sandstones was supplied from a relatively small area of the fore-Sudetic part of the Góry Sowie Massif and its immediate vicinity, approx. 50 km away from the depositional site. Heavy minerals and particularly the chemical characteristics of detrital garnets, Cr-spinels and tourmalines, have turned out to be excellent indicators of the provenance of these mature Late Cretaceous sandstones.

Key words: Late Cretaceous; North Sudetic Basin; Central Europe; Provenance; Heavy minerals; Detrital garnets.

INTRODUCTION

In the Late Cretaceous, a shelf-sea covered almost the whole of Central and Western Europe, except for relatively small islands (Text-fig. 1A). These islands delivered coarse siliciclastic material to the adjacent basins. Farther away from the scarce Cretaceous islands, mainly fine-grained calcareous material was deposited (e.g., Ziegler 1990; Laurin and Uličný 2004; Uličný and Čech 2008). At present, the best preserved siliciclastic deposits of Cenomanian–Santonian age occur in the Bohemian Cretaceous Basin, its prolongation into Saxony, and in the North Sudetic Synclinorium – the remnant of the Late Carboniferous to Late Cretaceous North Sudetic Basin. The latter area was situated to the north of the elevated fragments of the Bohemian Massif (Text-fig. 1A).

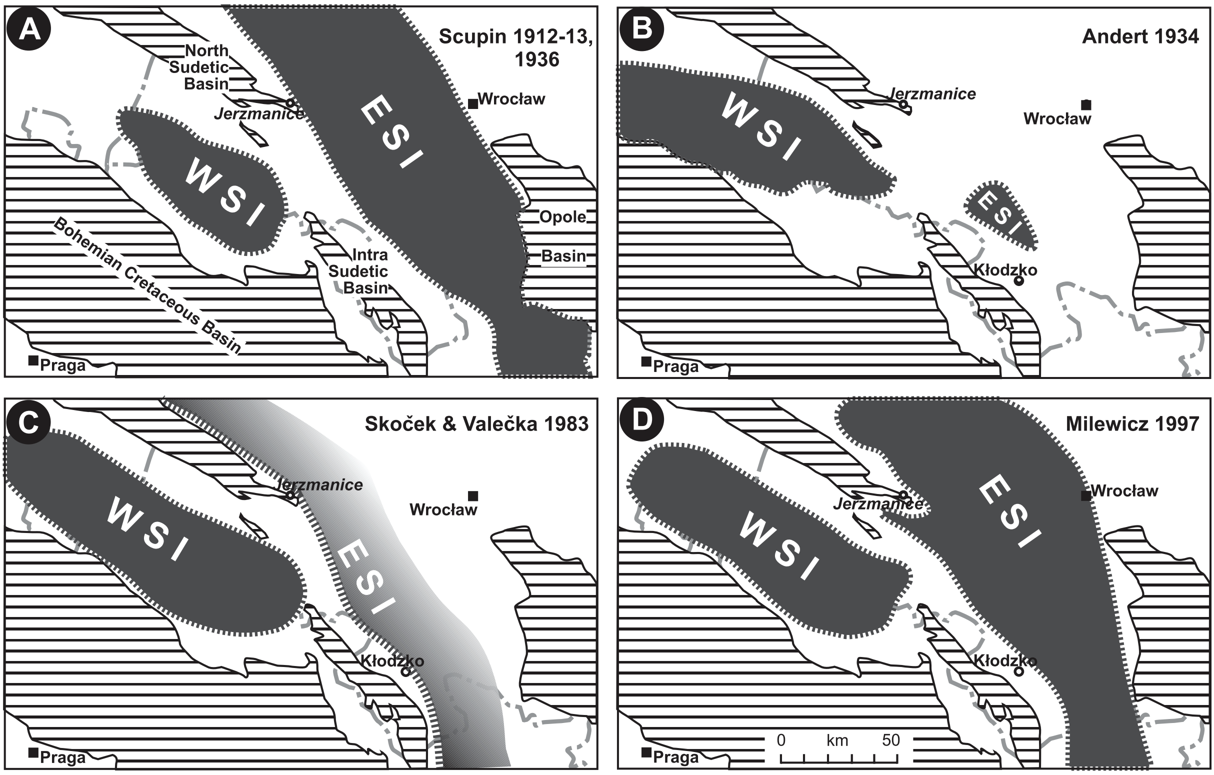
The North Sudetic Basin is thought to have received detritus from two sources: the hypothetical Western and Eastern Sudetic Islands (Scupin 1912-13, 1936; Andert 1934; Milewicz 1965, 1997; Skoček and Valečka 1983). The palaeogeographical position of the former has not been questioned, whereas the latter has been reconstructed in several different ways – even for short time intervals (Text-fig. 2): from a small island corresponding roughly to the present-day Góry Sowie Mts. (Andert 1934) or a not much larger land area (Jerzykiewicz and Wojewoda 1986; Uličný 2001;



Text-fig. 1. A. Palaeogeographic setting of the North Sudetic Basin during the Early Turonian. Simplified after Ziegler (1990), palaeolatitude based on Hay *et al*. (1999). B. Location of the study area. C. Simplified geological map of the North Sudetic Synclinorium and its surroundings; Cainozoic deposits omitted (after Dadlez *et al.* 2000)

Uličný and Čech 2008), to a long, narrow NW-SE strip of land that separated the North Sudetic Basin from the shelf sea of Central Europe (Scupin 1912-13, 1936; Milewicz 1965, 1997; Skoček and Valečka 1983; Valečka and Skoček 1991; Tröger 2004; see also summary in Kędzierski 2005). According to the last interpretation, the area of the North Sudetic Basin was a narrow seaway between the Eastern and Western Sudetic Islands, linking the shelf-sea of Central Europe to the sea of the Bohemian Cretaceous Basin. Skoček and Valečka (1983) estimated the area of the Eastern Sudetic Island at 12,000 km^2.

The Late Cretaceous sandstones of the Bohemian Cretaceous Basin and the North Sudetic Basin are characterized by a high degree of mineralogical maturity (Milewicz 1965; Skoček and Valečka 1983; Jerzykiewicz and Wojewoda 1986; Uličný 2001), so that their monotonous quartz-dominated composition is not indicative of source areas. Skoček and Valečka (1983) claimed that the clastic material was derived mainly from coarse-grained granites, with only a small admixture of metamorphic and sedimentary rocks. Nonetheless, the sandstone composition has not been the principal criterion used to determine the position of the Sudetic Islands. The present distribution of the Late Cretaceous deposits, facies changes, geometry of sandstone wedges and transport directions established on the basis of cross-stratification, have primarily been considered (Scupin 1912-13, 1936; Andert 1934; Milewicz 1965, 1997; Skoček and Valečka 1983; Jerzykiewicz and Wojewoda 1986; Jaskowiak-Schoeneichowa and Krassowska 1988; Uličný 2001; Uličný and Čech 2008). However, these arguments are not always unambiguous because of widespread, late- to post-Santonian erosion that affected the Late Cretaceous sediments over large areas. Besides, cross-stratification shows the direction of local sediment transport, but not necessarily the precise location of a source area. Therefore, another approach is used in this contribution: the land that delivered the siliciclastic material is established on the basis of heavy mineral analysis. In sandstones, heavy minerals are frequently compositionally more diverse than the framework grains and may add valuable information, even if they have been quantitatively and qual-



Text-fig. 2. Palaeogeographic position of the hypothetical Eastern and Western Sudetic Islands (ESI and WSI, respectively) during the Early Turonian according to various authors. Present-day remnants of the Late Cretaceous rocks are marked with striped pattern

itatively reduced by weathering processes (e.g., Hubert 1971; Mange and Maurer 1992; Morton and Hallsworth 1994). On the other hand, a heavy mineral assemblage - as a whole - is rarely diagnostic in itself because of changes caused by sorting of sediments during transport and deposition, and by mineral alteration during weathering/diagenesis (Morton 1985a; Morton and Hallsworth 1999). For these reasons, our conclusions are based on a study of various minerals, principally detrital garnets, Cr-spinels and tourmalines. The diversity of these minerals allows us both to exclude some source regions and to indicate more probable ones.

The heavy mineral analysis was performed for the Early-to-Middle Turonian sandstones exposed at Jerzmanice Zdrój (Text-fig. 1C).

GEOLOGICAL SETTING

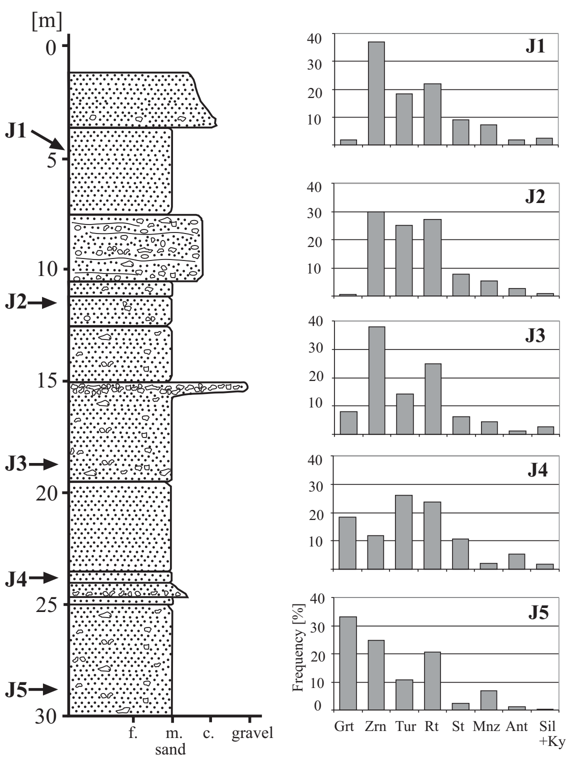
The North Sudetic Basin developed as a Late Palaeozoic intramontane trough at the end of the Variscan orogeny and became filled with Late Carboniferous through Triassic deposits, which in turn were disconformably covered by Late Cretaceous sediments. The present distribution of the Late Cretaceous deposits resulted from block movements and weak folding during tectonic activity within this region in the latest Cretaceous to Palaeocene. The Jerzmanice sandstones are exposed in the south-eastern part of the North Sudetic Synclinorium; in the north they are cut by the Jerzmanice Fault (Text-fig. 1C).

The Jerzmanice sandstones - *Rabendockensandsteine* according to Scupin (1912-13) – contain relatively few fossils, albeit this author reported two inoceramid bivalve species: *I. labiatus* (Schlotheim) and *I. hercynicus* (Petrascheck), which enabled him to date the sandstones as Turonian. These two species are the zonal indexes of the *Mytiloides labiatus* and *Mytiloides hercynicus* zones described by Walaszczyk (1992) for the Central Polish Uplands, i.e. they define the Lower Turonian and lowest Middle Turonian stratigraphic position of the sandstones. Field and borehole data suggest that the Jerzmanice sandstones lie on Lower Turonian fossil-rich marls (Milewicz 1965, 1970) and that their upper parts are lateral equivalents of Middle Turonian marls (*Inoceramus lamarcki* Zone; Milewicz 1965, 1970). The Jerzmanice sandstones form a c. 90 m thick wedge thinning westwards and, 20 km farther to the west, interfingering with basinal muds and marls (Scupin 1912-13; Milewicz 1965, 1970, 1997). Milewicz (1965, 1970,

1997) claims that two sandstone bodies actually merge in the vicinity of Jerzmanice and become interbedded with marls farther towards the west. The upper sandstone wedge, interpreted as Middle Turonian (Milewicz 1965, 1970, 1997), passes into marls several kilometres farther towards the west than the lower one.

The Jerzmanice sandstones have been interpreted as deposited in a shallow-marine environment at a water-depth corresponding roughly to wave base (Milewicz 1997).

Cliffs 30 m high and 300 m long that are exposed at Jerzmanice Zdrój are remains of an old sandstone quarry and currently constitute a nature reserve. The characteristic feature of the sandstones is the orthogonal blocky jointing, which is especially well developed in the lower part of the exposure. Medium- to coarse-grained sandstones are thickly bedded, with individual planar beds up to 5 m thick. Except for normal or reverse grading and bioturbation, other structures are hardly visible; the remnants of cross-stratification can be traced only locally. Individual pebbles reaching 2 cm in diameter are randomly distributed within the sandstones. The exposed strata dip c. 5° towards the south-southwest. Approximately 100 m farther to the north, along the Jerzmanice Fault, the sediments have a tectonic contact with low-grade metamorphic rocks of the Kaczawa Belt (Milewicz 1970). In the vicinity of the contact, they show a steeper inclination and local overturning. The Jerzmanice Fault was reactivated in late- to post-Santonian times, during the tectonic movements in the Sudetes Mts.



Text-fig. 3. Measured section at Jerzmanice with sample locations. Frequency diagrams show the quantitative diversity of translucent heavy minerals. Grt – garnet; Zrn – zircon; Tur – tourmaline; Rt – rutile; St – staurolite; Mnz – monazite; Ant – anatase; Sil+Ky – sillimanite and kyanite

MATERIALS AND METHODS

Five representative samples from the Jerzmanice exposure were taken at more or less equal vertical distances (Text-fig. 3) and analysed.

Petrographic data were obtained using a Jenaskop Zeiss polarizing light microscope. A standard point-counting procedure was executed according to the Glagolev-Chayes method (Galehouse 1971). Framework grains were identified from 300 counts per thin-section.

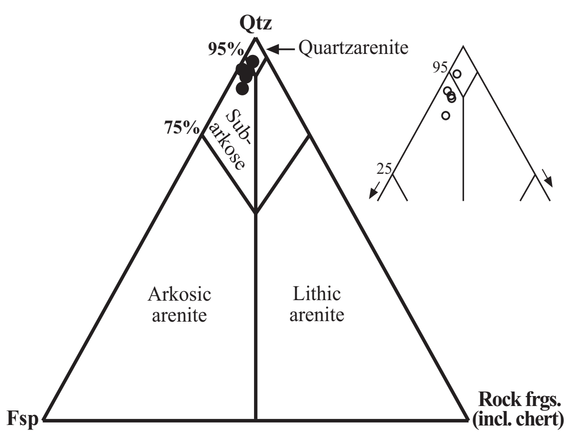
The Jerzmanice sandstones are slightly to moderately lithified, so the samples were rinsed with water and gently crushed before being sieved at 1 phi intervals from –2 to +4 phi (4 to 0.063 mm). Heavy minerals were separated from the 4–3 phi fraction (0.063 to 0.125 mm) using an aqueous solution of sodium polytungstate (specific gravity 2.84). The heavy mineral grains were embedded in Canada balsam and identified with a petrographic microscope. 300 translucent heavy minerals were counted in randomly selected traverses for each sample. In addition, opaque minerals were counted to establish the percentage of this group. Tourmaline colour varieties were quantified based on 100 tourmaline grains.

The chemical compositions of detrital garnets, tourmalines and Cr-spinels were determined in polished thin-sections using a Cameca SX-100 electron microprobe (15 kV accelerating voltage, 20 nA probe current, ~ 1μm beam diameter, 40 s counting time for each element) at Warsaw University. A ZAF matrix correction routine was utilized. The tourmaline and Cr-spinel compositions were analysed in the grain centres, whereas the composition of the garnets, whenever possible, was analysed in both the cores and the margins of the grains (two points per grain). The Fe^{2+}/Fe^{3+} ratio was calculated assuming garnet or spinel stoichiometry respectively (in the latter case after allotting all of the titanium to ulvospinel). For tourmalines, the boron content was not measured directly; three boron atoms were assumed to be present in the structural formula (Henry and Guidotti 1985), so the weight percent of B_2O_5 necessary to produce the three boron atoms was calculated for each analysis. The representative chemical compositions of the detrital garnets, Cr-spinels and tourmalines are shown in Tables 1-3.

Garnet, staurolite and tourmaline grain morphology was studied with a Zeiss EVO 40 scanning microscope (17.1 kV voltage) at the Electron Microscopy Department, Poznań University. The grains were hand-picked up from the J5 sample, placed on a double-sided adhesive tape and coated with gold.

SANDSTONE PETROGRAPHY

The sandstones are medium- to coarse-grained, poorly sorted, with predominantly subangular (to subrounded) grains. In the Pettijohn *et al*. (1987) ternary diagram, they plot in the field of subarkoses and quartzarenites (Text-fig. 4). All samples are rich in quartz grains; the ratio of monocrystalline to polycrystalline quartz grains ranges from 1:1 to 1:1.2. The quartz grains are associated with minor amounts of K-feldspars (8-10% of framework grains). The amount of feldspars decreases to 4% in the upper part of the section. Neither acid volcanic rock fragments, nor rock fragments of metamorphic shales, sandstones, clays and siliceous rocks together exceed 2%. A significant part of the quartz grains (up to 20%) is apparently crushed, which might have been caused by late- to post-Santonian activity of the nearby Jerzmanice Fault. The sandstone matrix is composed of clay minerals and fine quartz grains.



Text-fig. 4. Framework grain composition of the Jerzmanice sandstones from the North Sudetic Basin. Classification diagram after Pettijohn *et al.* 1987. Fsp – feldspars; Qtz – quartz; Rock frgs. – rock fragments

Heavy mineral diversity

The heavy mineral content in the 3–4 phi fraction is moderately high and varies from 1.7 wt% (samples J1 and J5) to 0.5 wt% (sample J4). All samples show low-diversity mineral assemblages consisting mainly of zircon, rutile, tourmaline, garnet, staurolite and monazite (Text-fig. 3). Anatase, sillimanite and kyanite occur in low amounts, typically below 2% of the entire translucent heavy mineral population. Pyroxenes, amphiboles, epidotes, apatites and chlorites are totally absent. The opaque mineral content ranges from 26% (sample J3) to 76% (sample J1). The high percentage of opaque minerals is caused by the occurrence of weathered, hematite-rich grains in the upper part of the section.

The ZTR maturity index (sum of the percentage content of zircon, tourmaline and rutile – Hubert 1962) is high and increases upward in the section from 56% to 82%. The ZTR index shows a trend opposite to that of the garnet content.

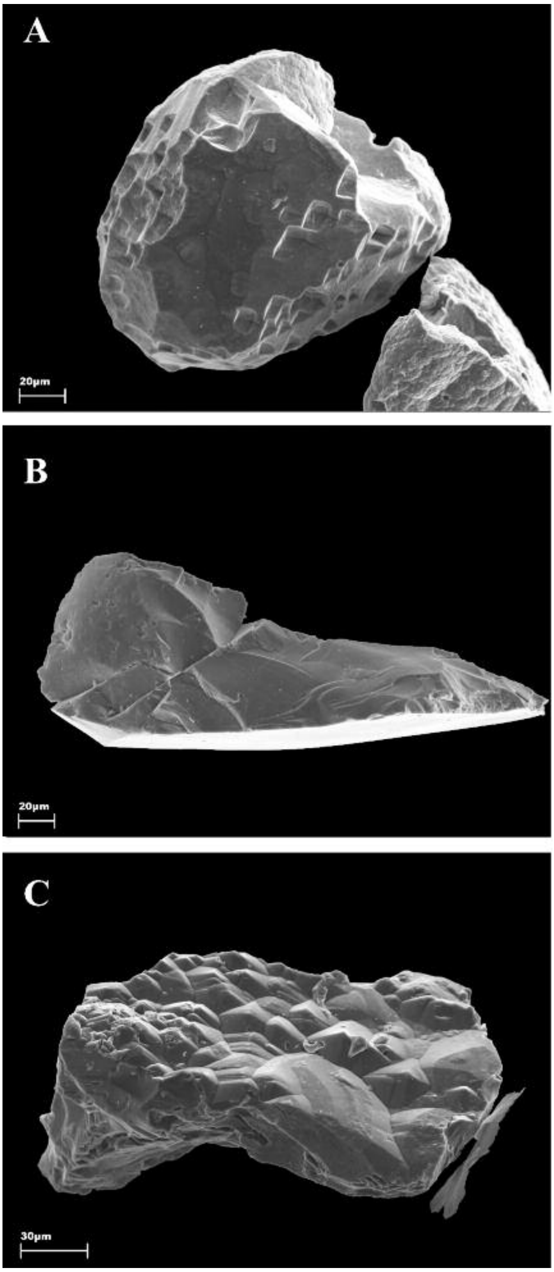
Zircon and rutile are the most abundant translucent heavy minerals. The rutile/zircon and monazite/zircon ratio parameters ((100x rutile)/ (rutile + zircon), (100x monazite)/ (monazite + zircon); Morton and Hallsworth 1994, 1999) fluctuate slightly throughout the section but do not exhibit any unambiguous trend. A similar consistency throughout the section is observed with regard to zircon morphology (euhedral vs. rounded grains) and other features of this mineral (elongation, inclusions, zoning). The amount of rounded grains does not exceed 20% of the entire zircon population. 20% of the zircon grains are angular.

The tourmaline content varies from 10% (sample J5) to 25% (sample J2). Virtually all the tourmaline grains are angular and sharp-edged (Text-fig. 5B). Of the scarce non-angular grains, euhedral varieties prevail over rounded ones. Five tourmaline colour varieties have been recognized and counted: brown, pink-black, green, colourless-yellow, and blue. No clear-cut differences in colour varieties exist between the samples.

Detrital garnets are the most abundant heavy minerals in the lower part of the section. However, the quantity of garnets decreases dramatically from 33% to ca. 1% in the upper part of the section. Common etch pits and corrosion-induced facets in the majority of the garnet grains (Text-fig. 5A) suggest extensive dissolution. Fragile remnants of garnets prove that dissolution, at least partly, occurred in the sediment after deposition.

Staurolite occurs in approximately equal quantities (ca. 9% of the translucent heavy minerals) throughout the section. The staurolite grains also show traces of dissolution (Text-fig. 5C).

The opaque minerals consist predominantly of ilmenite, iron oxides and Cr-spinels. The last mineral amounts to ca. 5% of the opaque suite. In samples from the upper part of the section, the opaque minerals are



Text-fig. 5. Scanning electron microscope micrographs of selected detrital heavy minerals from the Jerzmanice sandstones (sample J5). A – garnet; B – tourmaline; C – staurolite

weathered, non-stoichiometric and rich in iron oxide. Some of them contain several percents of Cr_2O_3.

Mineral chemistry

Garnets

The chemical compositions of the detrital garnets are shown in four ternary diagrams, with almandine, pyrope, grossular and spassartine corners respectively (disassembled tetrahedron, Text-fig. 6). Other garnet end-members, andradite and uvarovite, are omitted in the diagrams because of their low content (see Table 1).

The majority of the garnet grains belong to the pyrope-almandine series and have a significant pyrope molecule content (>25 mol%). As a rule, garnets rich in pyrope contain low amounts of the spessartine end-member (<3 mol%). Most of them also exhibit a low grossular content, typically below 10 mol%; a separate group contains higher amounts of Ca, with the grossular component up to 37 mol%. Single almost pure grossular grains have also been observed. Pyropes (py >60 mol%) constitute a distinct, not so large (c. 10% of all the garnets analyzed) assemblage among the detrital garnets. The majority of them are chrome-pyropes (>4 mol% of the uvarovite component) with a maximum of 11 mol% of uvarovite. All the garnets studied do not show any significant zonation: the observed differences between the molar composition of the grain centres and rims are within the 1% interval.

Spessartines and spessartine-rich garnets constitute only a few percent of the entire detrital garnet population. This group may also be enriched in pyrope or grossular end-members (even up to 25 mol%).

No significant differences with respect to the garnet composition between the samples has been detected, but only a statistically non-significant number of garnet grains could be analysed in the garnet-poor samples from the upper part of the section.

The chemical compositions of the detrital garnet grains are compared in the following using only two ternary diagrams: pyrope-almandine-grossular and pyrope-almandine-spassartine.

Tourmalines

The detrital tourmalines studied all belong to the schorl-dravite series. Grains from the J5 and J1 samples were characterized using the Al-Fe_{total}-Mg and Ca-Fe_{total}-Mg diagrams devised by Henry and Guidotti (1985) to discriminate tourmalines from different rock types. No significant differences with respect to the tourmaline compositions between the samples have been detected. Most tourmalines plot in the field of Al-rich and Ca-poor varieties typical of metapelites and metapsammites (Text-fig. 7). A few percent of the tourmalines plot in the field of granitoids and pegmatites. Brown and green colour varieties do not exhibit differences in composition with regard to major elements and may be derived from either metamorphic rocks or granitoids (Text-fig. 7). Single, intensively coloured blue tourmalines have a higher iron content and plot in the field of granitoids. Three exceptionally Mg-rich grains plot in the field of ultramafic rocks. Their distinct chemical composition is also emphasized by a particularly high chromium and vanadium content (Cr_2O_3 and V_2O_3 up to 3.7 wt% and 0.8 wt%, respectively). The amounts of Cr_2O_3 and V_2O_3 in other grains are much lower than 0.1 wt%. All tourmalines analyzed show a low manganese content, with MnO reaching maximally 0.2 wt%.

Cr-spinels

On the basis of the proportion of Cr, Al and Fe^{3+} ions, the detrital Cr-spinels are classified as dominant chromian spinels and minor aluminian and ferrian chromites (Text-fig. 8A). The grains analyzed show medium to low magnesian numbers (#Mg = $Mg/(Mg+Fe^{2+})$) between 0.64 and 0.16, most commonly oscillating around 0.55. The chromian number (#Cr = Cr/(Cr+Al)) ranges between 0.31 and 0.94 (Text-fig. 8B). With one exception, the Fe_2O_3 content is low and lies in the 0.0–7.0 wt% interval.

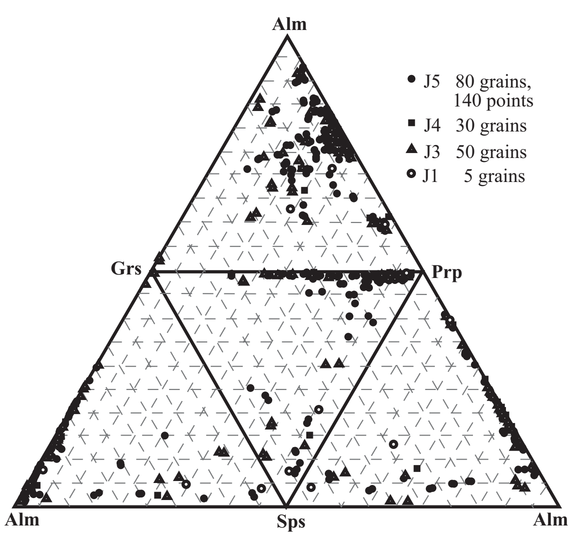
Sample	J5_67	J4_3	J3_8c	J5_30	J4_8	J5_97	J4_1	J3_3	J5_8	J3_36
SiO_2	39.76	38.91	39.50	38.86	39.35	42.23	41.09	41.76	37.45	37.41
TiO_2	0.05	0.09	0.02	0.05	0.22	0.26	0.18	0.18	0.03	0.13
Al_2O_3	22.60	22.66	22.93	22.12	22.41	22.40	20.66	23.20	21.42	21.35
Cr_2O_3	0.08	0.02	0.06	0.02	0.02	1.81	3.81	0.04	0.02	0.00
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.21	0.11	0.56	0.00	0.00
MgO	12.98	9.97	11.63	8.95	8.97	20.19	18.40	19.42	4.07	2.49
CaO	0.95	0.89	2.43	4.24	9.07	5.03	5.40	4.32	1.20	7.55
MnO	0.65	0.59	0.29	0.40	0.44	0.26	0.46	0.30	17.47	27.06
FeO	22.46	27.17	23.31	25.29	19.63	7.88	9.57	9.78	18.63	3.98
Na_2O	0.02	0.01	0.00	0.00	0.03	0.01	0.02	0.01	0.02	0.03
K_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	99.55	100.29	100.17	99.94	100.13	100.29	99.70	99.56	100.32	100.00
	Number of ions on the basis of 24 oxygens									
Si	5.988	5.945	5.951	5.967	5.955	5.992	5.968	5.983	5.969	5.952
Ti	0.006	0.010	0.002	0.006	0.025	0.028	0.020	0.019	0.004	0.015
Al	4.012	4.080	4.071	4.002	3.998	3.746	3.536	3.918	4.024	4.004
Cr	0.009	0.003	0.007	0.003	0.002	0.203	0.438	0.004	0.002	0.000
Fe^{3+}	0.000	0.000	0.000	0.000	0.000	0.022	0.012	0.060	0.000	0.000
Mg	2.914	2.270	2.612	2.049	2.024	4.270	3.983	4.149	0.967	0.591
Ca	0.153	0.145	0.392	0.698	1.471	0.765	0.841	0.663	0.204	1.287
Mn	0.082	0.076	0.038	0.051	0.056	0.031	0.056	0.036	2.358	3.647
Fe^{2+}	2.828	3.472	2.936	3.247	2.484	0.935	1.163	1.171	2.483	0.530
Na	0.006	0.004	0.001	0.000	0.008	0.003	0.005	0.003	0.007	0.010
K	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
	15.998	16.005	16.010	16.023	16.023	15.995	16.023	16.006	16.018	16.036
	Mole percent of end-members									
py	48.8	38.1	43.7	33.9	33.5	71.2	65.9	68.9	16.1	9.8
sp	1.4	1.3	0.6	0.8	0.9	0.5	0.9	0.6	39.2	60.2
alm	47.3	58.2	49.1	53.7	41.2	15.6	19.2	19.5	41.3	8.8
uv	0.2	0.1	0.2	0.1	0.1	5.1	11.0	0.1	0.1	0.0
and	0.1	0.2	0.0	0.2	0.6	1.3	0.8	2.0	0.1	0.4
gro	2.2	2.1	6.3	11.3	23.7	6.4	2.1	8.9	3.2	20.9

Table 1. Representative chemical compositions of detrital garnets

Grain no.	#1	#2	#30	#14	#21	#16	#11	#19	#24	#5*
B_2O_5 **	10.42	10.64	10.45	10.72	10.83	10.53	10.67	10.58	10.41	10.79
SiO_2	34.57	35.66	34.84	36.61	36.80	35.38	36.40	35.65	35.52	36.88
Al_2O_3	33.05	32.74	33.54	31.60	33.42	32.42	31.61	33.22	33.76	28.68
Cr_2O_3	0.00	0.00	0.01	0.05	0.07	0.02	0.09	0.02	0.02	3.69
TiO_2	0.64	1.30	1.06	1.05	0.69	0.36	0.65	0.84	0.21	1.51
FeO	11.74	7.84	11.73	5.52	4.57	8.00	5.69	9.28	14.58	1.29
MnO	0.04	0.00	0.03	0.03	0.04	0.08	0.01	0.05	0.21	0.00
MgO	3.47	5.85	2.61	8.11	7.70	6.65	7.93	4.57	0.72	10.13
CaO	0.51	0.90	0.55	1.15	0.82	0.91	1.42	0.58	0.09	1.74
Na_2O	2.31	1.91	1.80	1.97	2.06	2.05	1.88	1.97	1.73	1.90
K_2O	0.10	0.06	0.06	0.01	0.00	0.04	0.06	0.04	0.02	0.03
Total	96.82	96.86	96.62	96.76	96.95	96.44	96.36	96.74	97.23	96.55
Cations on the basis of 31 anions										
B	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000	3.000
Si	5.768	5.827	5.794	5.933	5.904	5.838	5.931	5.858	5.930	5.940
Al	6.499	6.305	6.573	6.036	6.319	6.305	6.070	6.434	6.643	5.444
Cr	0.000	0.000	0.001	0.006	0.009	0.003	0.012	0.003	0.003	0.470
Ti	0.080	0.160	0.133	0.128	0.083	0.045	0.080	0.104	0.026	0.183
Fe	1.638	1.071	1.631	0.748	0.613	1.104	0.775	1.275	2.036	0.174
Mn	0.006	0.000	0.004	0.004	0.005	0.011	0.001	0.007	0.030	0.000
Mg	0.863	1.425	0.647	1.959	1.842	1.636	1.926	1.119	0.179	2.432
Ca	0.091	0.158	0.098	0.200	0.141	0.161	0.248	0.102	0.016	0.300
Na	0.747	0.605	0.580	0.619	0.641	0.656	0.594	0.628	0.560	0.593
K	0.021	0.013	0.013	0.002	0.000	0.008	0.012	0.008	0.004	0.006

* contains 0.84% V_2O_3 **calculated by stoichiometry

Table 2. Representative chemical compositions of detrital tourmalines



Text-fig. 6. Compositions of detrital garnets from the Jerzmanice sandstones shown in grossular-pyrope-spessartine-almandine disassembled tetrahedron

The TiO_2 content is between 0.01 and 2.34 wt%. All the grains exhibit a low content of ZnO (max. 0.37 wt%).

PROVENANCE

The high mineralogical maturity of the Jerzmanice sandstones, expressed by the high quartz content, hinders a direct interpretation of their provenance. On the other hand, the abundant polycrystalline quartz grains suggest a considerable contribution of metamorphic rocks. The subangular forms of most of the detrital grains point to a relatively short transport distance.

A straightforward determination of the provenance on the basis of the whole heavy mineral population is not possible for several reasons: (1) the probable severe modification of the original assemblage by weathering/diagenetic processes, as suggested by the lack of unstable/semistable minerals; (2) the heavy

Sample	J3_1	J5_5	J3_2	J3_5	J5_3	J4_1	J5_1	J5_2	J3_1
SiO_2	0.08	0.02	0.09	0.01	0.01	0.03	0.02	0.07	0.00
TiO_2	2.01	0.43	1.99	0.07	0.21	0.48	1.13	2.34	0.26
Al_2O_3	32.82	19.32	32.04	39.49	37.11	24.72	14.49	28.35	1.60
V_2O_3	n.d.	0.20	n.d.	n.d.	0.17	n.d.	0.45	0.21	0.44
Cr_2O_3	23.88	45.29	24.90	28.23	29.88	41.62	43.82	28.23	36.23
Fe_2O_3	9.52	3.86	9.10	0.64	1.76	1.15	7.26	6.27	29.31
MgO	14.08	9.69	13.08	13.91	14.14	9.37	6.15	10.31	2.78
CaO	0.00	0.03	0.00	0.00	0.00	0.07	0.00	0.01	0.03
MnO	0.25	0.12	0.23	0.11	0.10	0.22	0.45	0.22	0.65
FeO	16.95	20.13	18.46	16.69	16.15	21.55	24.80	21.74	26.30
NiO	n.d.	0.00	n.d.	n.d.	0.04	n.d.	0.00	0.14	0.08
ZnO	0.13	0.16	0.00	0.23	0.09	0.14	0.33	0.27	0.21
Total	99.72	99.25	99.88	99.37	99.66	99.35	98.89	98.14	97.90
Number of ions on the basis of 32 oxygens									
Si	0.018	0.005	0.020	0.003	0.002	0.008	0.004	0.016	0.000
Ti	0.355	0.082	0.354	0.013	0.037	0.092	0.230	0.437	0.059
Al	9.119	5.845	8.970	10.707	10.117	7.311	4.609	8.312	0.566
V		0.041			0.031		0.097	0.042	0.106
Cr	4.452	9.191	4.675	5.135	5.466	8.259	9.349	5.553	8.587
Fe^{3+}	1.689	0.745	1.626	0.110	0.306	0.217	1.474	1.173	6.610
Mg	4.948	3.706	4.632	4.770	4.875	3.506	2.473	3.823	1.242
Ca	0.000	0.008	0.000	0.000	0.001	0.019	0.000	0.003	0.010
Mn	0.051	0.027	0.046	0.022	0.019	0.048	0.104	0.047	0.164
Fe^{2+}	3.342	4.322	3.666	3.210	3.124	4.523	5.598	4.524	6.594
Ni		0.000			0.008		0.000	0.027	0.020
Zn	0.022	0.030	0.000	0.039	0.016	0.026	0.065	0.049	0.047
Total	23.996	24.002	23.989	24.009	24.002	24.007	24.003	24.006	24.005
$\#Mg=Mg/(Mg+Fe^{2+})$	0.60	0.46	0.56	0.60	0.61	0.44	0.31	0.46	0.16
#Cr=Cr/(Cr+Al)	0.33	0.61	0.34	0.32	0.35	0.53	0.67	0.40	0.94

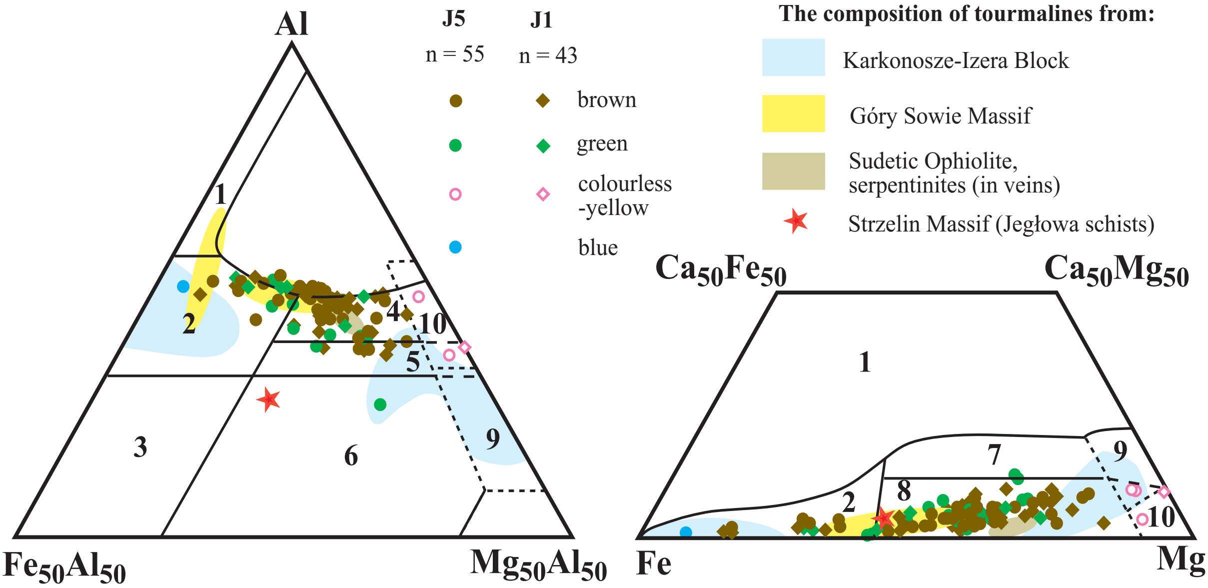
Table 3. Representative chemical compositions of detrital spinels

minerals are common minerals, in the majority not characteristic of any individual lithology; (3) hydrodynamic sorting of heavy minerals during transport and deposition is a well recognized, common and effective process which can significantly change the original mineral assemblage. To overcome these obstacles, another approach is used here – identification of the sandstone provenance based on the chemistry of individual minerals (Mange and Morton 2007).

Detrital garnets

Garnet is an exceptionally suitable mineral for provenance studies, not only because it is a common rock-forming mineral occurring in many crystalline rocks, but also because it has a wide range of potential compositions reflecting conditions of crystallization. For these reasons, it has been widely used as a provenance indicator (e.g., Morton 1985b; Aubrecht and Méres 2000; Takeuchi *et al.* 2008).

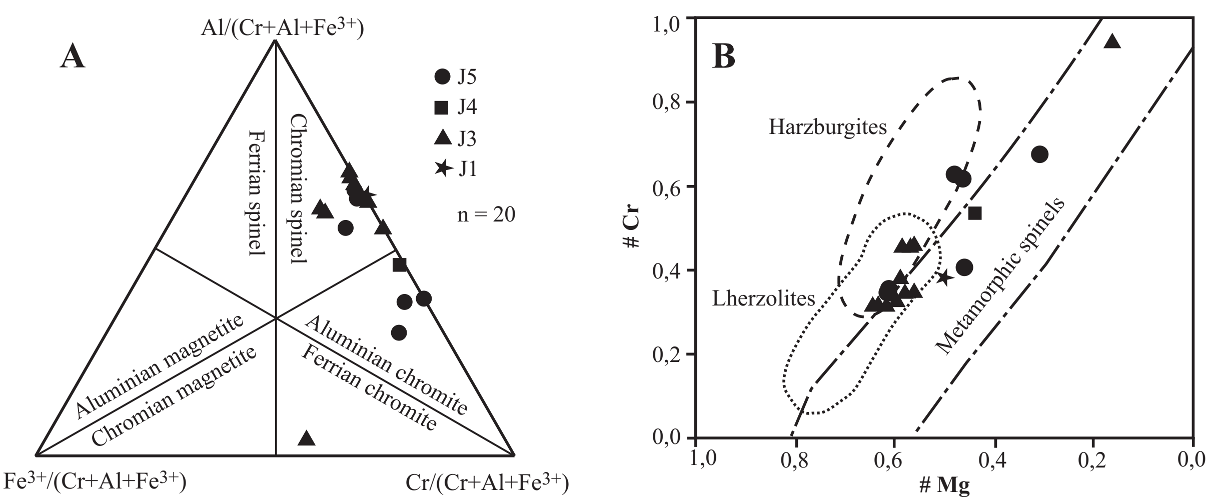
The Sudetic part of the Bohemian Massif, which most probably delivered detrital material to the North Sudetic Basin in the Late Cretaceous, consists of a mosaic of lithologically and structurally distinct geological units. The lithological composition of the individual units has been recognized since the 19th century and is relatively well established (see Mazur *et al.* 2006). Moreover, representative chemical analyses of garnets from different metamorphic and igneous rocks have been published during the last twenty years. The approach followed in the present contribution is to compare the known composition of Sudetic



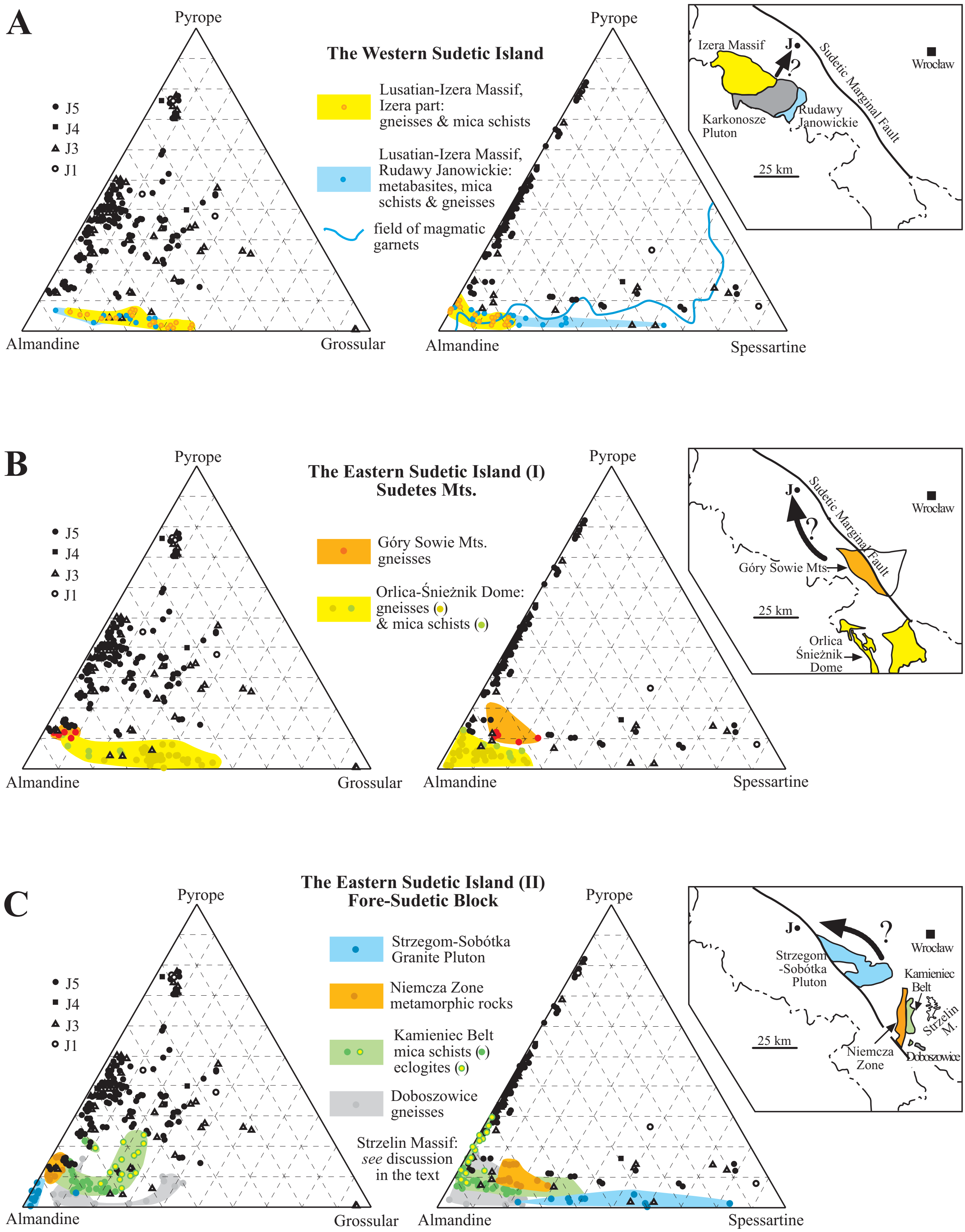
Text-fig. 7. Compositions of detrital tourmalines from the Jerzmanice sandstones (samples J1 and J5) shown in the Al-Fe-Mg and Ca-Fe-Mg diagrams after Henry and Guidotti (1985). The compositional range of tourmalines from selected Sudetic geological units after Pieczka (1996), Pieczka *et al.* 2004, Słaby and Kozłowski (2005), Pieczka and Kraczka (1999). Discrimination fields: (1) Li-rich granitoid pegmatites and aplites; (2) Li-poor granitoids; (3) hydrothermally altered granites; (4) Al-rich metapelites and metapsammites; (5) Al-poor metapelites and metapsammites; (6) Fe^{3+} -rich metapelites and calc-silicate rocks; (7) Ca-rich metapelites and metapsammites; (8) Ca-poor metapelites and metapsammites; (9) metacarbonates and metapyroxenites; (10) metaultramafics

garnets with that obtained for the detrital garnets coming from the Cretaceous sandstones. In the following, we use the terminology proposed by Żelaźniewicz and Aleksandrowski (2008) for the tectonic units of SW Poland.

Text-fig. 9A demonstrates that the detrital garnets studied cannot have come from the Western Sudetic Island because rocks from the Lusatian-Izera Massif contain different garnets from those of the Jerzmanice sandstones. No published data on the chemical composition of garnets are available from the Karkonosze Granite Pluton, but garnet is a very rare mineral in this plutonic body and, if present, shows a typical igneous almandine-spessartine composition (Kozłowski and Sachanbiński 2007). Garnet is a common accessory mineral in the so called Tanvald gran-



Text-fig. 8. Detrital spinel compositions shown in (A) Al-Fe^{3+}-Cr triangular diagram and (B) #Cr *vs*. #Mg diagram after Pober and Faupl (1988). #Cr = Cr/(Cr+Al); #Mg = Mg/(Mg+Fe)



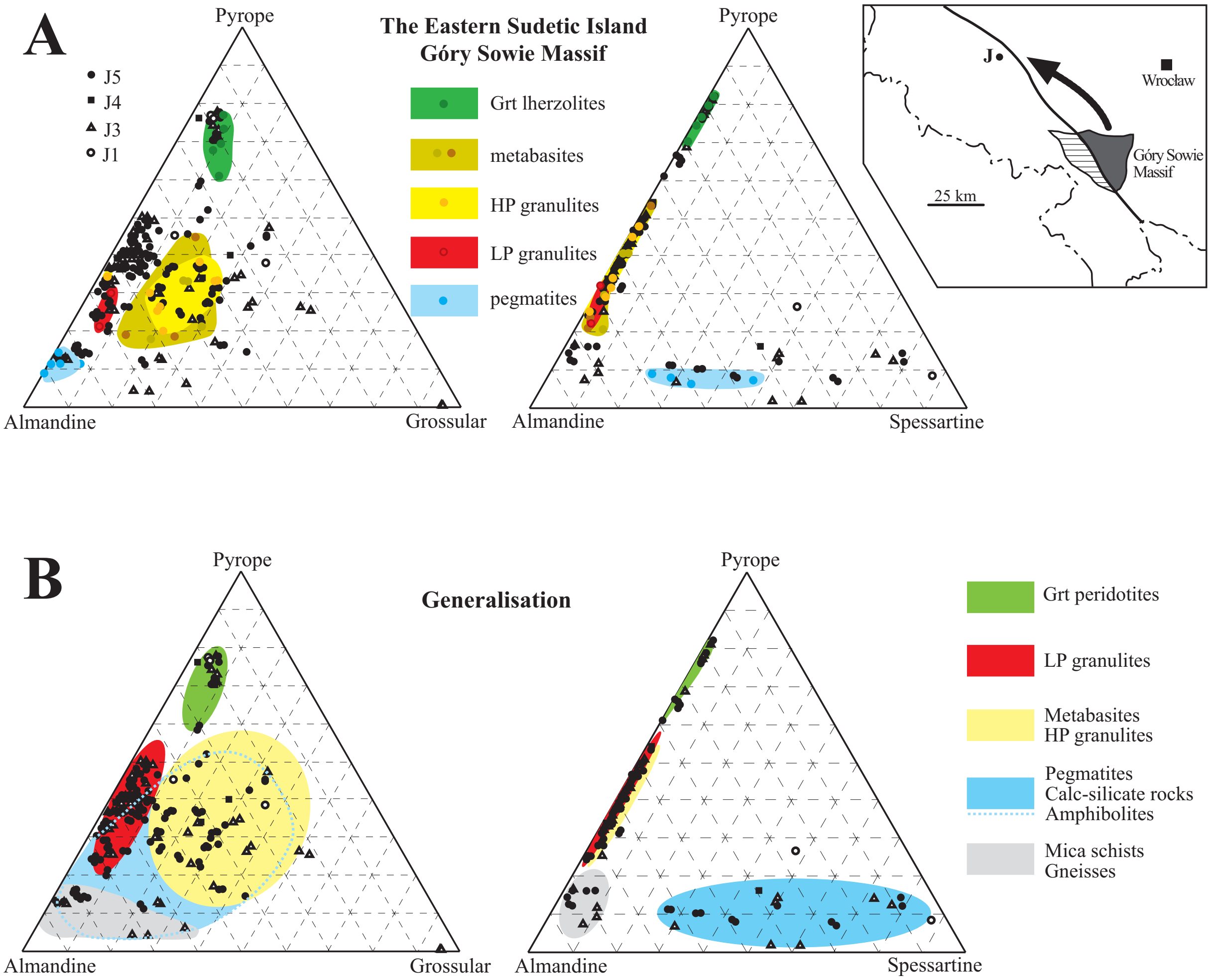
Text-fig. 9. Comparison of the chemical compositions of garnets from the Jerzmanice sandstones with those from various Sudetic rocks. The 'primary' garnet compositions according to: (A) Oberc-Dziedzic (1991); Makała (1994); Kryza and Mazur (1995); field of magmatic garnets after Miller and Stoddard (1981), (B) Budzyń *et al.* (2004); data of Kryza in Felicka (2000); Grześkowiak (2004); Szczepański (2002); Jastrzębski (2008), (C) Pieczka *et al.* (2004); Janeczek and Sachanbiński (1989); Puziewicz (1990); Janeczek (1985); Żabiński (1963, 1966); Fajklewicz (1969); Mazur and Puziewicz (1995); Józefiak (1998); Nowak (1998); Achramowicz *et al.* (1997); Bakun-Czubarow (1998); Puziewicz and Rudolf (1998); Puziewicz *et al.* (1999)

ite – the two mica alkali-feldspar granite rimming the SW periphery of the Karkonosze Pluton (Fediukova *et al.* 2008). However, also this garnet exhibits typical igneous signature (Fediukova *et al.* 2008). Most spessartines and spessartine-rich detrital garnets from the Jerzmanice sandstones have uncommon compositions: they are enriched in grossular or pyrope molecules that do not match with igneous spessartine-almandines (for comparison, see e.g. Miller and Stoddard 1981; Deer *et al*. 1997). In consequence, the Karkonosze Pluton may be excluded as a potential source for the detrital garnets.

Text-fig. 9B provides evidence that the parent rocks for the garnets studied did not lie in that part of the Eastern Sudetic Island which at present constitutes the Sudetes Mts.: neither gneisses and mica schists from the Orlica-Śnieżnik Dome nor – which is even more unexpected – gneisses from the Góry Sowie Mts. were the source for the detrital garnets. These minerals were not supplied from the Strzegom-Sobótka Pluton either (Text-fig. 9C), although this large granitoid body, situated close to Jerzmanice, would seem to be an ideal candidate for the source of detrital input. Other garnet-bearing rocks from the Fore-Sudetic Block (mylonites of the Niemcza Shear Zone, mica schists and eclogites from the Kamieniec Belt, Doboszowice gneisses) that did not really contribute to the detrital garnet assemblage are indicated in Text-fig. 9C. The compositions of the Jerzmanice garnets and of the Kamieniec mica schist (and eclogite) garnets show only a small overlap. We exclude the Strzelin Massif as the land supplying garnets: not only do the Strzelin crystalline rocks contain only minor amounts of garnets or lack them at all (Oberc-Dziedzic 1999a,b; Oberc-Dziedzic and Madej 2002), but the composition of these minerals differs from that in the Jerzmanice sandstones. The garnets from various Strzelin metamorphic rocks (gneisses, mica schists, amphibolites, pegmatites) are too poor in the pyrope component and too enriched in the spessartine molecule in relation to the majority of detrital garnets studied (T. Oberc-Dziedziec and S. Madej unpublished data).

Nevertheless, there is one (relatively small) area with a diverse lithology that contains various types of garnet that fit surprisingly well: a part of the Góry Sowie Massif (Text-fig. 10A). Not only does this area contain pyrope-bearing peridotites (Bakun-Czubarow 1983) but also metabasites and HP granulites with pyrope- and grossular-rich almandines (Dziedzic 1996; Kryza *et al*. 1996; O'Brien *et al*. 1997; Kryza and Pin 2002), spessartine-bearing pegmatites (Pieczka *et al*. 1997), and small pods of grossular-bearing calc-silicate rocks (Żelaźniewicz 1995). Most of this area is composed of garnet-bearing paragneisses and migmatites. The Góry Sowie Massif, considered as a geological entity, is divided nowadays by the Sudetic Marginal Fault (Variscan, rejuvenated during the Alpine orogeny) into two morphologically distinct parts: the mountainous Góry Sowie Mts. in the Sudetes Mts. and the peneplained, low-relief area in the Fore-Sudetic Block. It has been shown above that the paragneisses from the Góry Sowie Mts., the dominating rock-type in this unit, cannot have been the source for the detrital garnets. Therefore, the present-day mountainous part of the Góry Sowie Massif is excluded as an emerged area supplying detritus. However, as interpreted from the regional Moho depths (Cwojdziński and Żelaźniewicz 1995), the fore-Sudetic part may represent a 5 km deeper crustal level than its counterpart in the Sudetes Mts. This is probably the reason for the much more extensive occurrence of (retrograded) granulites in the fore-Sudetic domain (Żelaźniewicz 1995) than in the Góry Sowie Mts. As the garnets in these granulites are rich in pyrope and poor in grossular components (Żelaźniewicz 1995), we call these rocks 'LP granulites'. The composition of the garnets in the LP granulites fits the composition of the majority of garnets in the Jerzmanice sandstones. At present, the fore-Sudetic part of the Góry Sowie Massif is covered by thick Cenozoic sediments and is poorly exposed (in contrast to the mountainous Góry Sowie, it has never been the subject of a detailed petrological study). No garnet peridotites or HP granulites have so far been recognized in the fore-Sudetic part. On the basis of the detrital garnet record, one may assume that pyrope peridotites and HP granulites also occur(red) in this domain. We interpret the unusual grossular- and pyrope-rich spessartine-almandines as coming from calc-silicate rocks (erlans) or amphibolites (see the overview of different garnet compositions in Deer *et al.* 1997). Both calc-silicate rocks and amphibolites are known from the fore-Sudetic part of the Góry Sowie Massif (Żelaźniewicz 1995). The mineralogical composition of these rocks has, however, not yet been studied in any detail.

Text-fig. 10B summarizes schematically the origin of the Jerzmanice detrital garnets. All the rock types distinguished occur in the Góry Sowie Massif. The percentages of garnets coming from different parent rocks are presented in Text-fig. 11. Keeping in mind that garnet is present in variable amounts in the various parent rocks, the relative abundances are consistent with the known lithological diversity of the fore-Sudetic part of the Góry Sowie Massif.



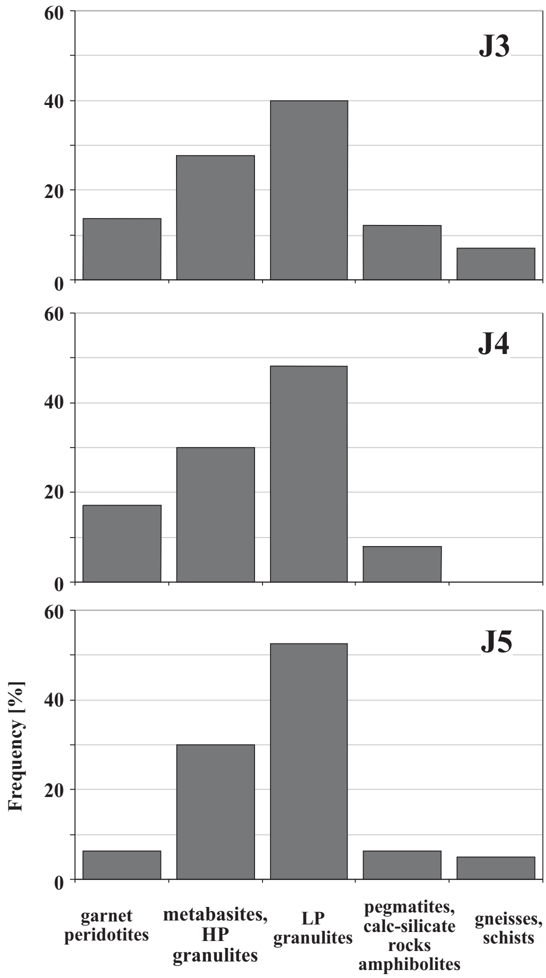
Text-fig. 10. Interpretation of the parent rocks for the detrital garnets from the Jerzmanice sandstones. A. Comparison of the detrital garnet compositions with those from the rocks of the Góry Sowie Massif. Data from: Bakun-Czubarow 1983; Dziedzic 1996; Kryza and Pin 2002; Kryza *et al.* 1996; O'Brien *et al.* 1997; Żelaźniewicz 1995; Pieczka *et al.* 1997. B. Generalized garnet compositions for various source rocks

During the Permian–Mesozoic, the fore-Sudetic part of the Góry Sowie Massif was presumably situated in an elevated hanging-wall position in relation to the footwall position of its counterpart in the Sudetes Mts. Our results are in accordance with this interpretation.

The proportion of major elements in the prevailing pyrope-almandines studied from the Cretaceous sandstones is also similar to that of garnets in the granulites in the Moldanubian Zone of the Bohemian Massif (mainly the Gföhl Unit – e.g., Čopjaková *et al.* 2005). The Moldanubian Zone with its common granulites, eclogites, garnet peridotites, with the nearby garnet-bearing Třebič pluton (René and Stelling 2007), might be considered as a potential source region. However, a much longer distance (c. 150 km), unsuitable geometries of sandstone wedges (Uličný 2001) and other premises discussed farther in the text force us to omit this area as a source area. On the other hand, the Moldanubian Zone has usually been indicated as a source region for the detrital pyrope-almandines that occur in sediments of different ages in Central Europe (e.g., Aubrecht and Méres 2000; Hartley and Otava 2001; Čopjaková *et al.* 2005; Aubrecht *et al.* 2007; Martínek and Štolfová 2009). The contribution of the Sowie Góry Massif seems to be underestimated in some cases, especially for sedimentary rocks situated not far away from it.

Detrital tourmalines

Judging from Henry and Guidotti's (1985) discrimination diagrams, three types of parent rocks were the source for the detrital tourmalines: metapsammites



Text-fig. 11. Frequencies of detrital garnets coming from the presumed source rocks shown for the individual samples of the Jerzmanice sandstones

and metapelites (81%), granites and pegmatites (15%), and ultramafic rocks (4%) (Text-fig. 7). The result is surprisingly consistent with the Góry Sowie Massif lithologies. Moreover, the known regional diversity of the chemical compositions of the Sudetic tourmalines (Pieczka 1996) allows a direct designation of the source region. The result is the same: the Góry Sowie Massif. Pieczka (1996) claims that two Sudetic regions are particularly rich in tourmalines: the Karkonosze Pluton and its adjacent areas, and the Góry Sowie Massif. Not only can we exclude the former region on the basis of his studies, but Słaby and Kozłowski (2005) thoroughly investigated the compositions of tourmalines from the Karkonosze Pluton and its surroundings and their results differ from ours (Text-fig. 7). Therefore, we may unambiguously conclude that the Western Sudetic Island did not supply the detrital tourmalines to the Jerzmanice sandstones.

The known compositions of tourmalines coming from the granitoid Strzegom-Sobótka Pluton (Janeczek 1985; Pieczka 1996) are also inconsistent with the results obtained here. The composition of tourmalines from the Jegłowa metamorphic schists (Strzelin Massif) is also different (Text-Fig. 7; Pieczka 1996; Pieczka and Kraczka 1999). Furthermore, orthogranulites from the Moldanubian Zone could not be the source of tourmalines with compositions typical for metapsammites and metapelites. Tourmaline is a common mineral in the leucocratic granites from Moldanubicum (Buriánek and Novák 2007) but it is more iron-rich than the tourmalines studied.

Summing up, the interpretation of the provenance of detrital tourmalines is exactly in line with that of the detrital garnets.

Detrital Cr-spinels

Detrital Cr-spinels have a chemical composition typical of mantle-derived lherzolites and harzburgites (Text-fig. 8B). Only a minor part shows compositions that are characteristic of metamorphic spinels, i.e. those derived from serpentinized peridotites.

The composition of both groups exactly resembles that of spinels occurring in ultramafic rocks constituting numerous small bodies among the Góry Sowie paragneisses (Dubińska *et al*. 1999). In the Cretaceous, such spinel peridotites might well have occurred on the surface of the fore-Sudetic part of the Góry Sowie Massif. Therefore, the detrital Cr-spinels are not in contradiction to the hypothesis that the Sowie Góry Massif was the source region.

On the other hand, similar spinel compositions have been reported from the ultramafic rocks of the Sudetic Ophiolite (occurring in the surroundings of the Góry Sowie Massif; Gunia and Lebda 1994; Dubińska *et al*. 1999). The low content of Cr-spinels among the heavy minerals in the Jerzmanice sandstones would rather suggest that the ophiolites did not deliver detritus in large quantities (for example, heavy mineral spectra of the Cretaceous synorogenic sandstones in the Eastern Alps are dominated by Cr-spinels, reaching up to 96% of all heavy minerals – von Eynatten and Gaupp 1999). However, the contribution of the Sudetic Ophiolite cannot be excluded. We assume that the ophiolites, at least partly, were also exposed at the surface in the time interval studied.

In contrast to the Cr-spinels from the Jerzmanice sandstones and the Góry Sowie Massif, the majority of Cr-spinels from the Moldanubian Zone lost their igneous signature. Their composition is typical of metamorphic spinels (Čopjaková *et al*. 2005).

Other heavy minerals

Most of the other heavy minerals fit the hitherto obtained conclusions. Zircon, rutile and monazite are common accessory minerals in the paragneisses/granulites of the Góry Sowie Massif (e.g., Kryza 1981; O'Brien *et al*. 1997; Budzyń *et al*. 2004). In addition, the morphology of the detrital zircons (prevailing subhedral to subrounded grains, minor share of euhedral and rounded ones, predominance of short-prismatic crystals, occurrence of ca. 20% of angular grains) corresponds to that of the zircons from the Góry Sowie rocks (O'Brien *et al*. 1997; Timmermann *et al*. 2000; Klimas *et al*. 2003). Both sillimanite and kyanite are typical metamorphic minerals present in the paragneisses/granulites (e.g., Kryza 1981; Żelaźniewicz 1995). Ilmenite is the most abundant opaque mineral in the metabasites and HP granulites (Dziedzic 1996; O'Brien *et al*. 1997; Kryza and Pin 2002).

The only heavy mineral which apparently does not match the Góry Sowie mineral assemblage is staurolite, a typical component of mica schists. Staurolite-garnet mica schists are known from several localities in the Sudetic area, the one closest to the Góry Sowie Massif being situated approx. 15 km to the south-east, in the vicinity of Kamieniec Ząbkowicki (Fore-Sudetic Block). The chemical compositions of the garnets in the staurolite-bearing high-pressure mica schists from this locality (Nowak 1998) are similar to the chemical compositions of some Jerzmanice detrital garnets (compare Text-fig. 9C). Therefore, some small regions, other than the Góry Sowie Massif but close to it, presumably supplied sediments in the Early-to Middle Turonian. On the other hand, staurolite is a very resistant heavy mineral, more stable than garnet under weathering conditions (e.g., Morton and Hallsworth 1999). Its abundance increases with the mineralogical maturity of sediments. Accordingly, the contribution from the staurolite-bearing rocks might be minor.

DISCUSSION

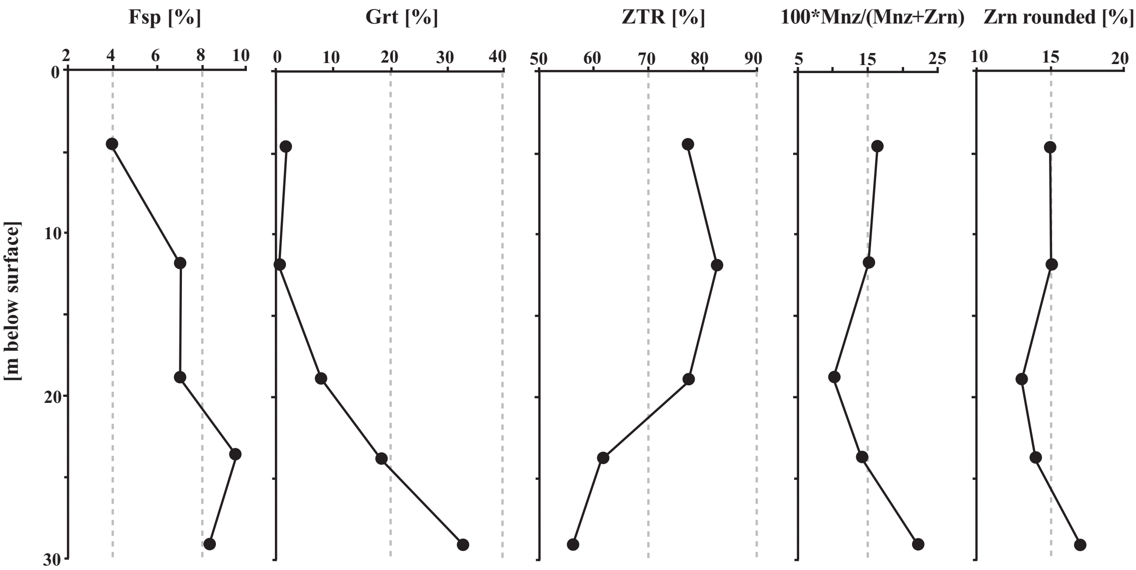
Garnet depletion in the upper part of the section

The basis for the conclusion reached in the present contribution is the diversity of the chemical compositions of the detrital garnets. However, the amounts of these minerals decrease dramatically to less than 1% in the upper part of the section. This suggests a change in the sediment delivery pattern and, consequently, a change in palaeogeography. Nonetheless, we present below some arguments for another explanation, *viz.* the effect of weathering on the composition of the sediments.

Minerals resistant to weathering definitely prevail in the upper part of the Jerzmanice section. The depletion in garnet is associated with a decrease in feldspar and an increase in quartz content. In addition, Cr-spinels disappear almost totally. In distinct contrast to the garnets, the amounts of zircon, tourmaline and rutile increase. No other unambiguous trend has been observed (Text-fig. 12): neither the grain morphology nor the relative content of rutile and monazite (referred to zircon abundances) change substantially. The proportions between the various tourmaline colour varieties are the same throughout the section (Text-fig. 13). The chemical compositions of tourmalines from the lower and the upper part of the exposure are similar (Text-fig. 7). The garnet content decreases gradually towards the top of the exposure (Text-fig. 12). Single garnet grains in the upper part are still rich in a pyrope component. Both garnet and staurolite grains show traces of dissolution, even in the lower part of the section (Text-fig. 5A, 5C). Moreover, the sandstones from the upper part contain numerous weathered non-stoichiometric opaque grains. A few specimens exhibit an increased content of Cr_2O_3 and may be weathered remnants of Cr-spinels.

Identical changes were observed in the 10-15 m thick upper part of Upper Cretaceous sands from the south-eastern United States; they were interpreted as an effect of post-depositional subaerial weathering (Hester 1974). As emphasized by Morton and Hallsworth in their review paper (1999), "source-area weathering does not significantly affect the diversity of heavy mineral suites prior to incorporation of sediment into the transport system". The same authors claim that garnet is semistable under acidic conditions and prone to dissolution.

In our opinion, the observed mineralogical diversity in the Jerzmanice section is also an effect of post-depositional weathering. This conclusion implies the problem of whether weathering removed the various garnet varieties in equal percentages, i.e. whether or not the garnet population studied is biased towards the more resistant chemical varieties. There are almost no published data on this topic except for the observation that grossular is more prone to diagenetic alteration than other garnets (Morton 1987). The multitude and diversity of garnets in the lower part of the Jerzmanice section, where garnet is the dominant heavy mineral, allow us to treat this population tentatively as representative for the source area.

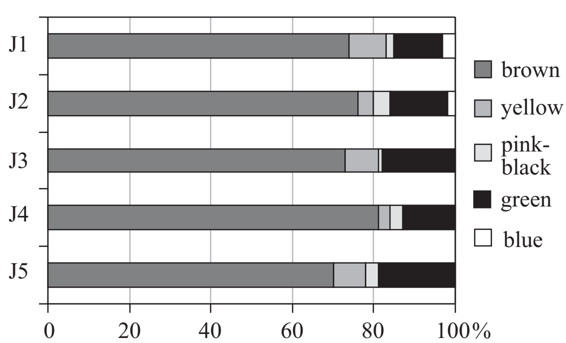


Text-fig. 12. Trends in abundances of selected minerals with increasing depth for the Jerzmanice exposure. Fsp – feldspar; Grt – garnet; ZTR – sum of zircon, tourmaline and rutile; Mnz – monazite; Zrn – zircon

Primary source vs. recycling of older sediments

The Turonian sandstones from Jerzmanice in the North-Sudetic Basin are interpreted to have been derived from a relatively small area corresponding roughly to the Góry Sowie Massif, specifically to its fore-Sudetic part, and its surroundings. The distance from Jerzmanice to the edge of the Góry Sowie Massif amounts to some 50 km. However, the high mineralogical maturity of the sandstones might indicate recycling of older sediments. In that case, we would rather interpret the provenance of older deposits, as the Turonian sandstones would have inherited a provenance along with the grains.

Undoubtedly, we may exclude Devonian and Carboniferous clastic rocks. Their immature lithology and apparently different garnet compositions (e.g., Otava and Sulovsky 1998; Felicka 2000) prove this unambiguously. Lower Permian sandstones are locally enriched in volcanic rock fragments which are exceptionally rare in the Jerzmanice sandstones.



Text-fig. 13. Quantitative diversity of tourmaline colour varieties in individual samples from the Jerzmanice exposure

The most similar compositions to those of the Cretaceous sandstones are shown by Triassic (Buntsandstein) sandstones (Mroczkowski 1972). As a matter of fact, in many places where Cretaceous sandstones overlie Triassic ones paraconformably, the boundary between them is often not clear (Mroczkowski 1972). Milewicz (1965, 1997) suggested, on the basis of comparable grain-size distributions, incorporation of Buntsandstein grains in Cenomanian sandstones. Nevertheless, detailed studies by Chorowska (1962) of the heavy minerals in the Triassic and Cretaceous sandstones from the North-Sudetic Basin provide evidence that the heavy minerals were not recycled. Not only do the Triassic sediments lack garnet, sillimanite and kyanite, in contrast to the Turonian sandstones, but also the majority of the tourmaline grains in the Triassic sediments show rounding. Moreover, zircons in the Triassic sandstones occur in the form of long-prismatic semi-rounded grains that are not prevalent in the Jerzmanice detrital zircon assemblage.

Low-grade metamorphic Kaczawa Belt as a detritus source?

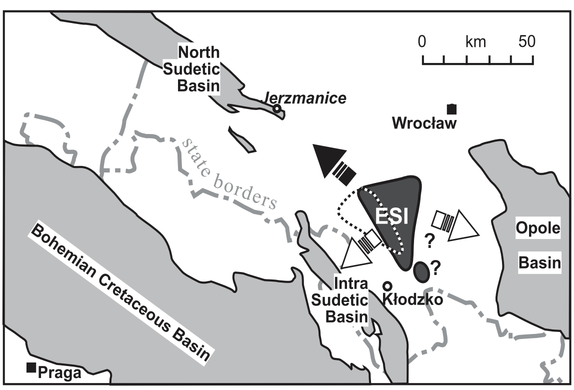
The Jerzmanice sandstones are surrounded nowadays in the north by the low-grade metamorphic Kaczawa rocks: phyllites, metasandstones, lydites, greenstones and other low-grade metavolcanic rocks (Text-fig. 1C). According to Scupin (1912-13, 1936) and

Milewicz (1965, 1997) the Kaczawa Belt constituted a major part of the Eastern Sudetic Island. In Milewicz's palaeogeographical reconstruction (*op. cit.*), the Jerzmanice sandstones were deposited in a relatively small bay surrounded by land built of the Kaczawa rocks. If this reconstruction is correct, it should be reflected in the sandstone composition. Characteristic heavy minerals of low-grade metamorphic rocks comprise epidote, chlorite, actinolite, muscovite, hematite and magnetite. The first three species are totally absent from the sandstones and the others are scarce. This seems to exclude the Kaczawa Belt as a source area, but one should consider the possibility that the lack of some of the mineral species is a result of dissolution during weathering/diagenesis. A much stronger argument is the presence of only trace amounts of (meta)siliceous and (meta)volcanic rocks (<1%) and the lack of fine-grained phyllites among the framework grains. This excludes the Kaczawa rocks unambiguously.

Additional remarks

The term 'island' which we use here means 'source area'. The source area was not necessarily identical with an emerged piece of land, since part of this land might have been earlier covered with sediments coming from the source, and thus might deliver the same material as the source area did. In these terms, the reconstructed island reflects the minimum extent of the land.

The extent of the Eastern Sudetic Island as presumed in the present contribution (Text-fig. 14) is closest to Andert's (1934) interpretation. The only difference is that the latter author mainly suggested the mountainous part of the Góry Sowie Massif and not the fore-Sudetic part. We have not found any evidence for the occurrence of a large island. On the contrary, the source area, located approx. 50 km from the Jerzmanice site, did not exceed some 500 km^2 in extent.



Text-fig. 14. Interpretation of the source area for the Jerzmanice sandstones. ESI – the presumed East Sudetic Island in the Early-to-Middle Turonian. Present-day remnants of the Late Cretaceous sediments are shown in grey. The outline of the East Sudetic Island according to Andert (1934) is marked with the dashed line

The Turonian Jerzmanice sandstones, classified as subarkosic arenites, differ significantly in composition from the Cenomanian and Coniacian sandstones of the North-Sudetic Basin, as the latter are pure quartz arenites (Milewicz 1997, our unpublished data). On the other hand, the lithology of the sandstones is similar to that of the Middle Turonian Radków sandstones from the Intrasudetic Basin (northeastern part of the Bohemian Cretaceous Basin; Jerzykiewicz 1975; Radków Bluff Sandstone according to Wojewoda 1986, 1997). The Radków sandstones also differ in their slightly immature composition from other Cretaceous sandstones of the Intrasudetic Basin (Jerzykiewicz 1975; Wojewoda 1997). Similar Middle Turonian sandstones enriched in feldspars also occur in the Czech Republic and are lateral equivalents of the Radków sandstones (the Broumov Cliff sandstones, Jizera Formation – Uličný 2001). All these sandstones show foreset dip directions towards the southwest, thus suggesting the Eastern Sudetic Island as the source area (Jerzykiewicz 1975; Jerzykiewicz and Wojewoda 1986; Wojewoda 1986; Uličný 2001). It is therefore possible that all these sediments were derived from the land described in the present contribution: the fore-Sudetic part of the Góry Sowie Massif and its adjacent areas (Text-fig. 14). The same land should have delivered detritus to the basin located on its eastern side, i.e. to the Opole region. Although the present-day Opole Trough is an erosional relic of much larger sedimentary cover, the occurrence of sandstone admixtures among the Middle Turonian marls on the west, and their disappearance towards the east (Kotański and Radwański 1977), suggest the Eastern Sudetic Island as the source area (Text-fig. 14). Indeed, Kotański and Radwański (1977) supposed that it might have been the Góry Sowie Massif.

CONCLUSIONS

- The fore-Sudetic part of the Góry Sowie Massif and its immediate vicinity (Sudetic Ophiolite, Kamieniec Belt) delivered detrital material for the Jerzmanice sandstones. The source area, located ca. 50 km from the Jerzmanice site, presumably did not exceed 500 km^2 in extent. The area between this source area and Jerzmanice was either covered with similar sands or served as a transit route not participating in sediment delivery.

- Our results do not support the hypothesis of a large, elongated Eastern Sudetic Island in the Early-to-Middle Turonian. The palaeogeographical reconstruction presented here is instead closest to Andert's (1934) idea of a small island in a shelf-sea.
- Detrital garnets carry the most valuable provenance information. However, they are the most prone to dissolution of the entire stable heavy-mineral assemblage described from the Jerzmanice sandstones.
- The frequencies of the various compositions of the detrital garnets provide insight into the complete lithology of the fore-Sudetic part of the Góry Sowie Massif, at present largely covered by thick Cenozoic deposits. They suggest the predominance of LP granulites (retrograded into gneisses?), smaller amounts of metabasites, and minor occurrences of garnet peridotites, calc-silicate rocks and granites/pegmatites. The results provide evidence that in the Early-to-Middle Turonian the fore-Sudetic part of the Góry Sowie Massif was situated in an elevated position with respect to its counterpart in the Sudetes Mts.
- The mineral assemblage described for the Jerzmanice section may serve as comparative material for farther research. Heavy minerals, particularly detrital garnets, Cr-spinels and tourmalines, are excellent indicators of the provenance of the mature Late Cretaceous sandstones in Central Europe.

Acknowledgements

Dr. Piotr Dierżanowski and Lidia Jeżak, MSc., Warsaw University, are greatly acknowledged for their patient help with microprobe analyses. We thank Prof. Teresa Oberc Dziedzic and Stanisław Madej, MSc., Wrocław University, for making the unpublished chemical analyses of garnets from Strzelin metamorphic rocks available for us. We are also indebted to Prof. Andrzej Żelaźniewicz and Dr. Joanna Kostylew, AGP reviewers, whose comments helped to improve the manuscript. Last but not least, we are grateful to Prof. Tom van Loon, Poznań University, for the linguistic correction of the text.

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Manuscript submitted: 25th March 2009
Revised version accepted: 30th October 2009