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A vestige of an Early Devonian active continental margin in the East Sudetes (SW Poland) — evidence from geochemistry of the Jegłowa Beds, Strzelin Massif

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The Early Devonian metasandstones of the Jegłowa Beds (Strzelin Massif, NE Bohemian Massif) are low- to medium-grade metamorphosed siliciclastic deposits showing differences in modal composition, especially in the amount of micas and feldspars. Despite the similarity in relative concentrations of trace elements, three chemical groups can be distinguished among the metasandstones that differ in the total amounts of major and trace elements. The negative Ta and Nb anomalies visible on a spider plot normalised to the average upper continental crust and specific ratios of e.g. Th, Zr, Hf, La/Th and Ti/Sc characterize the majority of the metasandstones, indicating the provenance of their sedimentary precursors from a subduction-related tectonic setting. However, few of the samples analysed show strongly differentiated geochemical characteristics with high Zr and Hf contents. This suggests input of relatively strongly reworked material. Thus, it seems that a back-arc setting can account for the mixed nature of the inferred source areas with old basement and arc-related detritus respectively as the end-members of the mixtures. The composition of the metasandstones indicates deposition of the siliciclastic material near an Early to Middle Devonian volcanic arc that was superimposed on rocks originally forming a part of the pre-Devonian continental margin of the Brunovistulicum microplate. A plausible tectonic scenario involves formation of the Devonian arc due to east-directed subduction of an oceanic domain between the Brunovistulian microcontinent in the east and the Central Sudetic terrain located further west.

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INTRODUCTION

A significant relationship between the framework mineralogy of terrigenous clastic sediments and the tectonic setting of their deposition has been documented (Schwab, 1975; Dickinson and Suczek, 1979; Dickinson and Valloni, 1980; Maynard *et al*., 1982). Despite the significant influence of weathering, sedimentary transport and diagenesis on the composition of terrigenous clastic rocks, the provenance of detritus has a primary control on the mineralogy and geochemistry of the deposits. Furthermore, the chemical composition of clastic deposits can be indicative of the tectonic setting of the source area and thus also of the sedimentary basin itself (e.g. Bhatia, 1983, 1985; McLennan and Taylor, 1991). Thus, the composition of clastic sedimentary sequences is useful for recognizing both the nature of old sedimentary basins and the history of ancient foldbelts (Taylor and McLennan, 1985; Bhatia and Crook, 1986; McLennan and Taylor, 1991).

This study provides new constraints on the tectonic setting of a basin in which was deposited the Early to Mid-Devonian clastic succession of the Brunovistulian microplate. The data presented in the paper come from the Early Devonian metasandstones of the Jegłowa Beds exposed within the Strzelin Massif (NE Bohemian Massif) and belonging to the East Sudetic nappe pile (Fig. 1). The data on the modal and chemical compositions of the metasandstones allow evaluation of the provenance of their protolith. Moreover, they shed new light on the geodynamic scenario of the convergence between the Brunovistulian microplate and terranes included in the Variscan belt.

GEOLOGICAL SETTING

The easternmost margin of the Bohemian Massif, termed the Moravo-Silesian Zone (Svoboda *et al*., 1966; Cháb, 1986), is composed of deformed and metamorphosed rocks of the

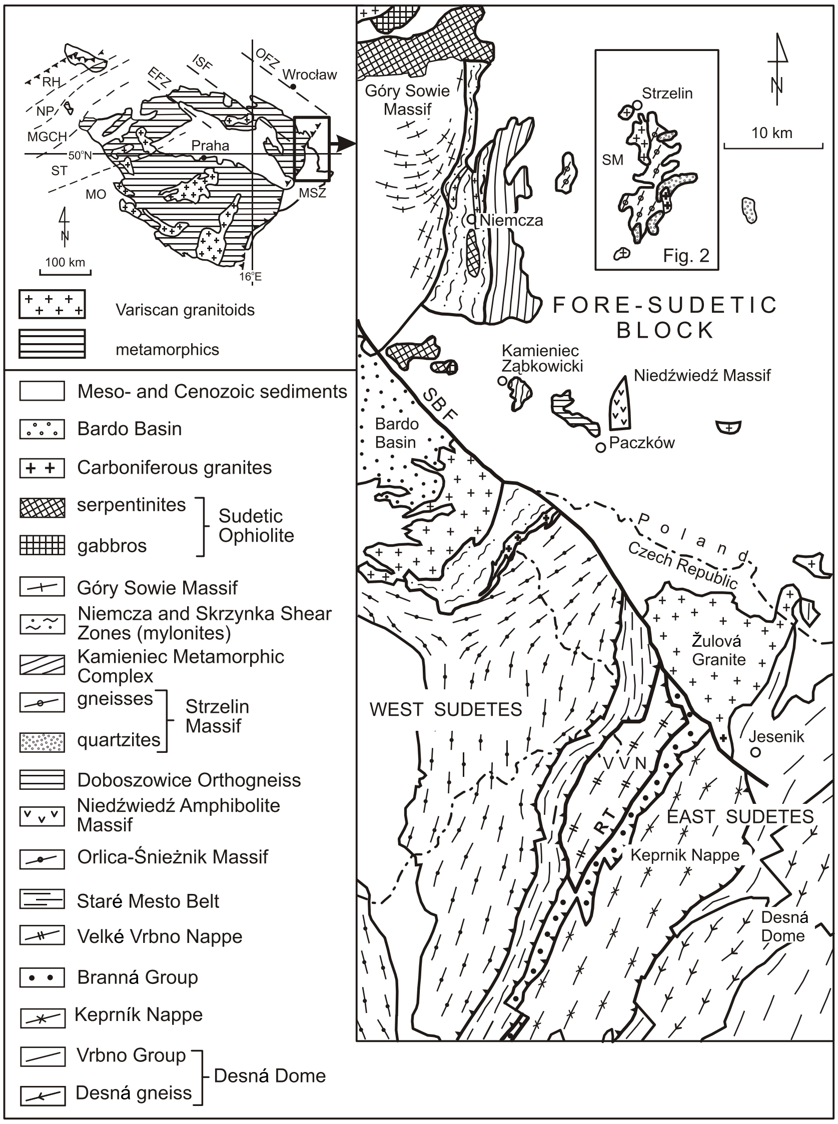

Fig. 1. Sketch map of the northeastern part of the Bohemian Massif (after Puziewicz *et al.*, 1999) showing regional setting of the study areathe inset shows location of the East Sudetes on the map of the Bohemian Massif

EFZ — Elbe Fault Zone; ISF — Intra Sudetic Fault; ST — Saxo-Thuringian Zone; MGCH — Mid-German Crystalline High; MO — Moldanubian Zone; MSZ — Moravo-Silesian Zone; NP — Northern Phyllite Zone; OFZ — Odra Fault Zone; RH — Rheno-Hercynian Zone; RT — Ramzová Thrust; SBF — Sudetic Boundary Fault; SM — Strzelin Massif; VVN — Velké Vrbno

Brunovistulicum microcontinent (Dudek, 1980). The Silesian part of the zone (also called the Eastern Sudetes) is occupied by the Jeseníky Mts. and its northern continuation represented by the Strzelin Massif (Fig. 1). Early to Mid-Devonian quartzose conglomerates and sandstones are widespread across the Brunovistulian microplate, uncomformably overlying the Lower Palaeozoic deposits or directly resting on the metamorphosed Proterozoic basement (Svoboda *et al.*, 1966). Variably metamorphosed equivalents of these rocks are included in the Moravo-Silesian nappe complex straddling the eastern margin of the Bohemian Massif (Fig. 1). Therein, they form individual metasedimentary thrust sheets or are linked through primary sedimentary contacts to slices of the Proterozoic basement derived from the Brunovistulian plate (Cháb, 1986; Cháb *et al.*, 1994). In the mountainous part of the East Sudetes (Jeseníky Mts.), the Early to Mid-Devonian quartzites mostly belong to the allochthonous succession of the Vrbno Group (Cháb *et al.*, 1994). This succession is formed by quartz-rich deposits palaeontologically dated as Pragian (Hladil, 1986; Chlupač, 1989) overlain by a volcano-sedimentary sequence rich in mafic to felsic metavolcanic rocks. The metavolcanic rocks bear a geochemical signature characteristic of an arc-related environment and/or back-arc spreading (Patočka, 1987; Patočka and Valenta, 1996; Janoušek *et al.*, 2006*a*). Further to the north, petrographically and geochemically similar metasedimentary siliciclastic rocks (Patočka and Szczepański, 1997), termed the Jegłowa Beds (Oberc, 1966), crop out in the Strzelin Massif (Fig. 2) emerging from beneath the Cenozoic deposits of the Fore-Sudetic plain. The massif is generally believed to have a domal structure with higher-grade rocks in its core and lower-grade rocks on the limbs. Despite the lack of palaeontological evidence, the Jegłowa Beds, comprising quartzites, metaconglomerates and quartz-sillimanite-biotite schists derived from shallow-marine protoliths (e.g. Oberc, 1966; Oberc-Dziedzic, 1995; Szczepański, 2001), are commonly considered as equivalent to the quartzites of the Vrbno Group (Meister and Fischer, 1935; Oberc, 1966; Oberc-Dziedzic, 1995; Patočka and Szczepański, 1997; Szczepański, 2001).

In the Strzelin Massif, the Jegłowa Beds reach a total thickness of 600 m (Dziemiańczuk and Wojnar, 1984) and are tectonically interleaved with widespread orthogneisses and minor schists (Fig. 2). The orthogneisses have both Proterozoic and Lower Palaeozoic protoliths dated at 600–568 Ma and 504 ± 3 Ma, respectively (Oliver *et al.*, 1993; Oberc-Dziedzic *et al.*, 2003). The schists include mica schists, paragneisses and amphibolites of unknown, probably Neoproterozoic age (Oberc, 1966). The protolith of the amphibolites was compared to tholeiitic within-plate basalts emplaced on an attenuated Early Palaeozoic continental margin (Szczepański and Oberc-Dziedzic, 1998). Metamorphic rocks of the Strzelin Massif were intruded by Variscan granitoids controversially dated to *ca*. 330–347 Ma by the Rb-Sr whole-rock method (Oberc-Dziedzic *et al.*, 1996) or to *ca*. 300 Ma by the Rb-Sr mineral (plagioclase + biotite; Pietranik and Waight, 2006) and Pb-Pb zircon evaporation methods (Turniak, pers. com.).

The Strzelin Massif was subjected to three Variscan tectonometamorphic events (Szczepański, 2001; Szczepański and Mazur, 2004). The first (D_1) involved E to NE-directed thrusting of nappe units under prograde greenschist facies conditions and was soon followed by regional folding due to E–W compression

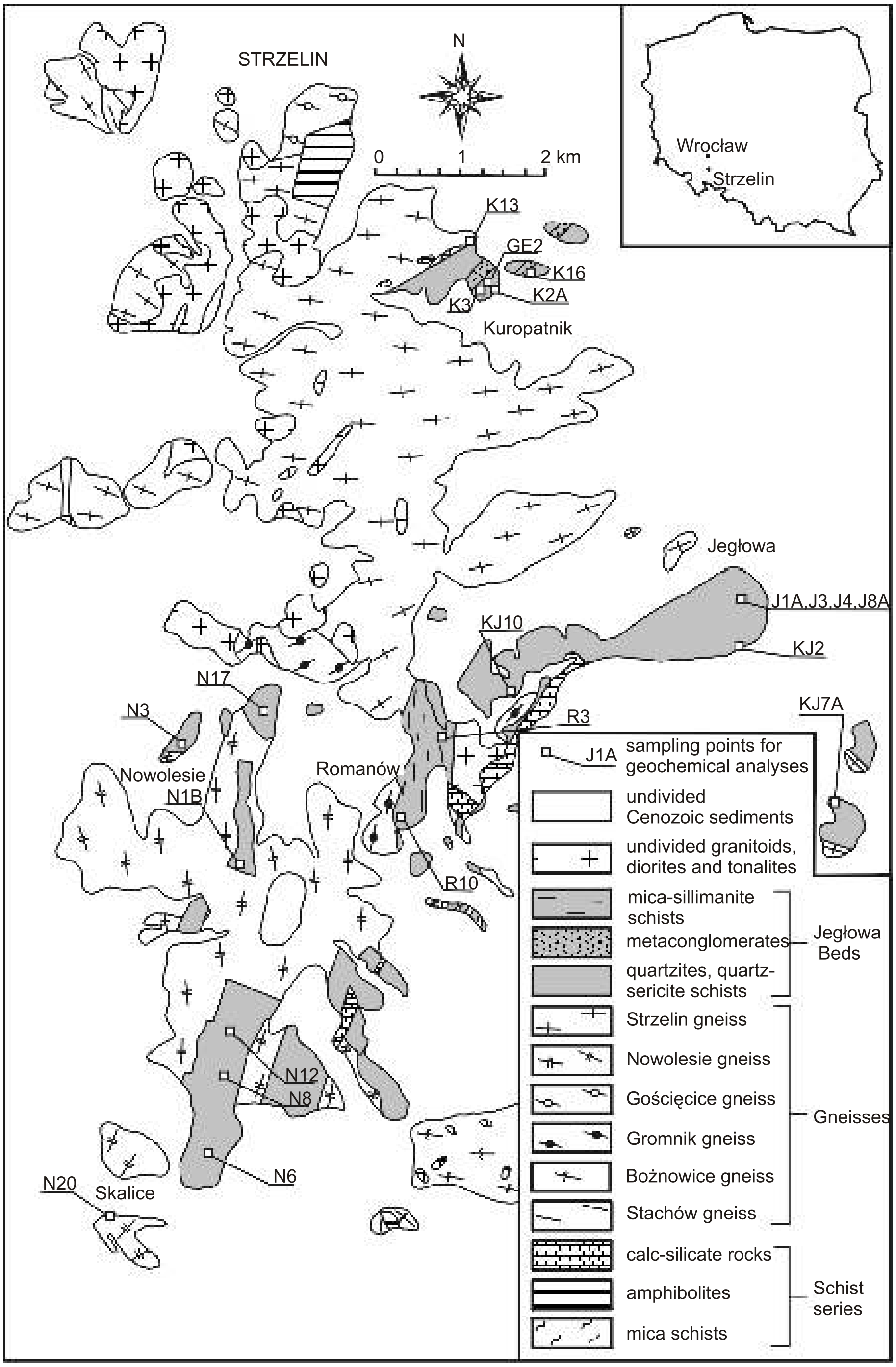

Fig. 2. Geological sketch map of the Strzelin Massif (after Oberc *et al*., 1988); the inset shows location of Strzelin on the map of Poland

(D_2). The final (D_3) event was related to late-orogenic gravitational collapse and the development of a metamorphic core complex. During this event MT/LP amphibolite facies conditions were attained in the southern part of the Strzelin Massif.

SAMPLING AND ANALYTICAL METHODS

A total of 19 metasandstone and 3 gneiss samples were collected, mostly from the quarries or large exposures on the Strzelin Massif (see Appendix). However, two specimens GE2 (3.6) and GE2 (183.6) came from a borehole core (Fig. 2).

Modal analyses of the metasandstones studied were performed using the Gazzi and Dickinson point-counting method (Ingersoll *et al*., 1984). A total of 1 000 or 500 points were counted for each of the thin sections depending on its size. Selected modal analyses of the metasandstones are shown in Table 1.

Samples were analysed at Activation Laboratories Ltd. (Ancaster, Ontario, Canada). Major-element concentrations were determined using ICP-ES following a lithium

Table 1

Modal analyses of selected Jegłowa Beds metasandstones

Sample	N6	KJ10	N1B	N12	K2A	GE2(3.6)	R10	J1A
quartz	88.3%	81.8%	77.2%	74.5%	63.9%	48.1%	47.3%	43.5%
plagioclase	0.6%	0.0%	4.2%	0.7%	2.3%	1.1%	0.0%	4.7%
K-feldspar	2.6%	6.0%	1.5%	6.9%	2.7%	0.2%	0.0%	7.5%
muscovite	5.2%	7.9%	1.9%	0.5%	20.6%	33.3%	12.7%	4.5%
biotite	2.0%	1.7%	0.4%	3.1%	9.9%	10.1%	19.8%	6.9%
zircon	0.1%	0.0%	0.1%	0.1%	0.1%	0.2%	0.2%	0.1%
tourmaline	0.0%	0.0%	0.0%	0.0%	0.5%	0.2%	0.0%	0.0%
rutile	0.0%	0.0%	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%
apatite	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
andalusite	0.0%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
syllimanite	1.0%	1.8%	13.9%	13.5%	0.0%	0.0%	19.1%	29.7%
opaque minerals	0.2%	0.5%	0.9%	0.7%	0.1%	6.7%	0.9%	3.0%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

metaborate fusion and nitric acid digestion of a 0.2 g sample. Loss on ignition (LOI) was established by weight difference after ignition at 1000°C. For Nb and Rb abundances a separate 6 g split was digested in polyvinyl alcohol and analysed by the XRF method. Concentrations of high field strength elements (HFS) including rare earth elements (REE) were determined using the INAA method. Accuracy is within 5% for major and minor elements; the exceptions are abundances of MnO and P_2O_5 for which it decreases to 15%. For trace elements the accuracy is 5–10%. The major- and trace-element compositions of the representative metasandstone and gneiss samples are given in Table 2. All the diagrams were made using the system GCDkit (Janoušek *et al.*, 2006*b*).

PETROGRAPHY

Numerous relics of primary psammitic grains in the metasandstones of the Jegłowa Beds indicate sandstones as their sedimentary precursor (Fig. 3). Moreover, the protolith of the metasandstones experienced regional metamorphism and ductile deformation of variable intensity resulting in overall quartz recrystallization, growth of secondary micas and changes in feldspar composition. The consequent alteration obscured the primary framework mineralogy, matrix composition and relative proportions between matrix and framework grains. Therefore, the discrimination between lithic quartzitic fragments and monocrystalline quartz is presently unfeasible. Furthermore, the origin of micas remains enigmatic since they may represent primary lithic grains or, less probably, recrystallized clay minerals. On the other hand, feldspars (both plagioclase and K-feldspar) probably represent primary framework grains since their content varies significantly between individual metasandstone layers. Taking into account these limitations, only a rough indication of the provenance of the metasandstones protolith may be obtained from the framework composition.

The metasandstones include mica-rich and mica-poor varieties (Table 1). Both were metamorphosed under greenschist- and amphibolite-facies conditions in the areas of Kuropatnik–Jegłowa and Nowolesie–Skalice, respectively (Fig. 2). The latter contain sillimanite as a characteristic component. A few andalusite-bearing samples of metasandstones (R3 and R10) show evidence for contact metamorphism, the ef-

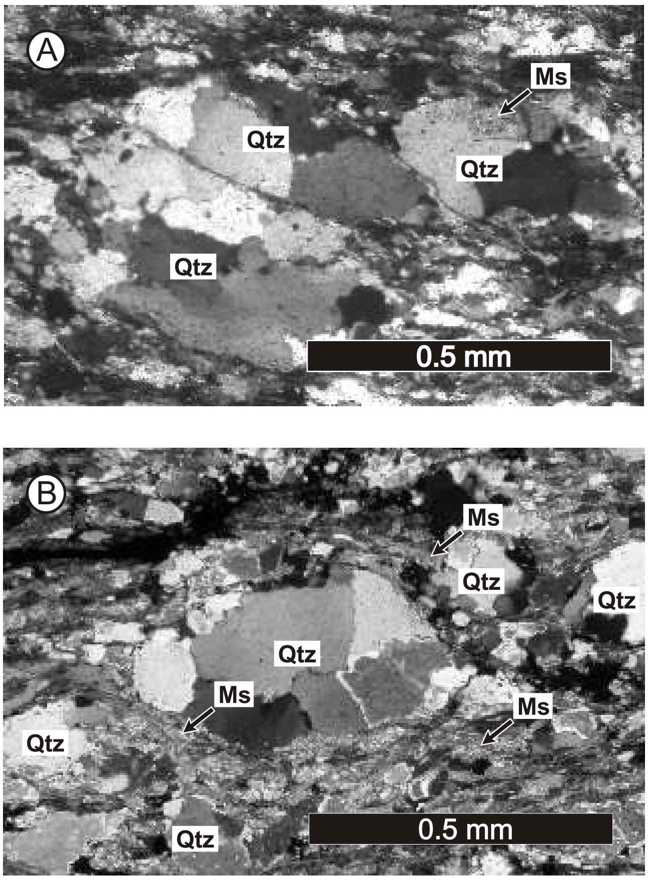

Fig. 3. Thin section microphotographs of the Jegłowa Beds metasandstones

A — recrystallised framework quartz grains within a matrix composed mainly of quartz (Qtz), mica-poor metasandstones (Ms); **B** — recrystallised framework quartz grains within matrix composed mainly of micas and quartz, mica-rich metasandstones fects of which overprint the older amphibolite-facies fabric (Romanów area; Fig. 2).

The mica-rich metasandstones consist of quartz + muscovite (sericite) + biotite ± K-feldspar ± plagioclase + zircon + tourmaline + opaque minerals. The main rock-forming minerals are quartz and white mica together with variable amounts of K-feldspar and plagioclase. Two metasandstone samples, R10 and R3, composed of quartz + biotite + muscovite + sillimanite + andalusite + K-feldspar + zircon + opaque minerals + tourmaline are also included into the mica-rich variety. They represent strongly recrystallized medium- to coarse-grained rocks subjected to contact metamorphism within an aureole of a granite intrusion near Romanów. Their main components are quartz and biotite, whereas sillimanite forms both individual needles and larger aggregates. Large isolated crystals of andalusite and K-feldspar are subordinate.

The mica-poor variety is represented by metasandstones containing variable amounts of feldspars (plagioclase and K-feldspar). In two cases also sillimanite is one of the main mineral phases. Well-rounded zircon, rutile grains and opaque minerals are accessory phases. In some of the mica-poor samples, deformation effects are weak enough to allow recognition of the primary relationship between matrix and framework grains. Matrix forms less than 5% of the rocks whereas quartz grains belong exclusively to the framework and form up to 85% of the total rock volume.

GEOCHEMISTRY

The metasandstones studied are characterized by variable SiO_2 and Al_2O_3 concentrations (Table 2, Fig. 4) allowing rough chemical discrimination of the rocks examined. The mica-rich metasandstones show the lowest silica and the highest alumina abundances ranging from 69 to 79 wt.% and 9 to 14 wt.%, respectively. The mica-poor metasandstones are characterized by SiO_2 abundances ranging from 83 to 98 wt.% and the lowest Al_2O_3 contents of 0 to 9 wt.%. Furthermore, the mica-poor group may be chemically subdivided into two subgroups (namely the medium- and high-silica content) showing different concentrations of SiO_2 and Al_2O_3 (Fig. 4).

Rare-earth patterns normalized to chondrite (Nakamura, 1974) generally are similar (Fig. 5) showing: (1) strong light REE enrichment (La_N/Yb_N = 6.7–18.2 with a mean value of 11.3); (2) a lack or presence of very small negative Eu anomalies and (3) flat, uniform heavy REE patterns. Sample KJ2 departs from this picture due to the very small value of La_N/Yb_N = 3.1. Samples from the mica-rich group are characterized by generally higher concentrations of REEs compared to the mica-poor group.

The multielement diagram (Fig. 6A) normalised to an average upper continental crust composition (Taylor and McLennan, 1985) shows several interesting features. The low-Q group includes: (1) a concentration of elements from K to Th and Zr to Sc typical of the upper continental crust, the same applying to the abundance of Ce; (2) relatively strong negative Nb and Ta anomalies; (3) P trough and (4); low Sr concentrations. Samples with medium quartz contents (belong-

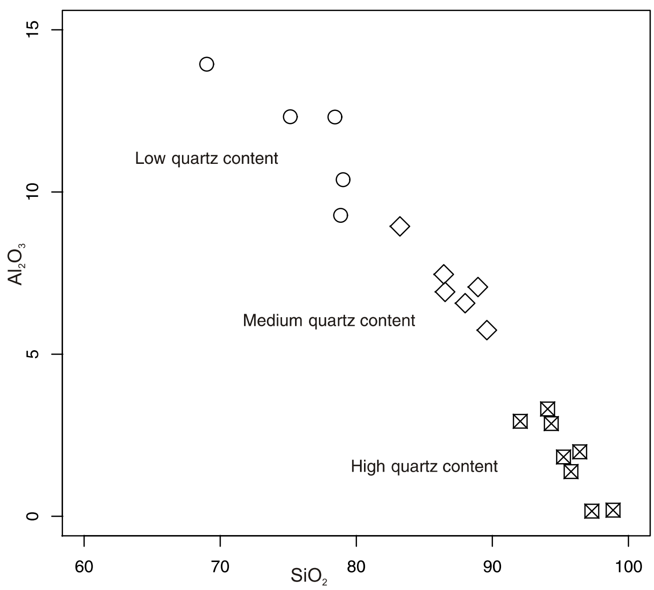

Fig. 4. Metasandstones of the Jegłowa Beds in the SiO_2 *vs.* Al_2O_3 diagram

Open circles — mica-rich metasandstones, diamonds and rectangles — mica-poor metasandstones differentiated according to silica concentration; further explanations see in the text

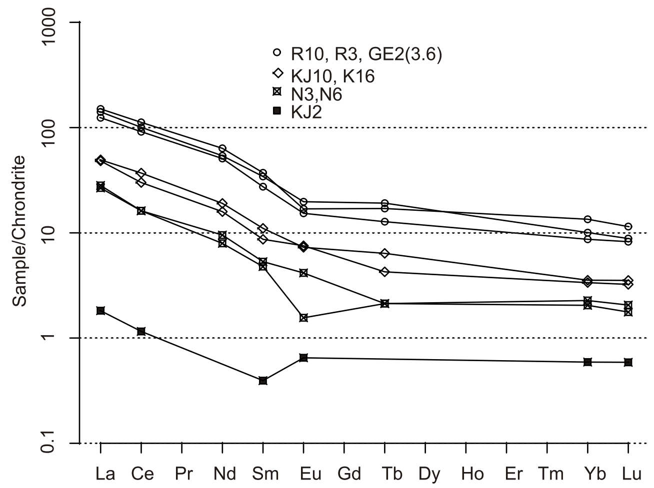

Fig. 5. Chondrite-normalised REE plot for selected samples from the Jegłowa Beds, normalisation factors from Nakamura (1974)

ing to the mica-poor group) show similar features as described for the low-Q group but they are characterized by concentrations of elements from Th to Sc slightly lower than 1 compared to the composition of upper continental crust (Taylor and McLennan, 1985). The high-quartz content group (belonging to the mica-poor variety) is chemically more varied, showing concentrations of trace elements considerably lower than 1 compared to an upper continental crust (Fig. 6C). Samples N3 and N6 are characterized by trace-element patterns similar to those revealed by the mica-rich group. Samples KJ7A, KJ2 and K3 show a pattern dominated by robust positive Zr and Hf anomalies (Fig. 6C). Finally, sample J1A has a fairly flat pattern with slight negative P, Zr and Hf anomalies and minor Ti and Rb peaks (Fig. 6C).

Representative chemical analyses of Jegłowa Beds

Sample	J8A	KJ10	N12	N1B	N6	N8	N17	KJ7A	K16	KJ2	K3
Type	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS	MS
CIA	0.73	0.70	0.73	0.72	0.69	0.68	0.71	0.70	0.57	0.81	0.72
SiO_2	83.21	88.00	86.53	88.94	94.06	89.60	95.78	98.87	86.43	97.31	92.05
TiO_2	0.37	0.18	0.12	0.14	0.11	0.11	0.02	0.02	0.09	0.04	0.51
Al_2O_3	8.94	6.57	6.92	7.07	3.31	5.74	1.38	0.19	7.46	0.16	2.93
Fe_2O_3	1.57	2.08	1.47	2.04	1.72	1.75	2.76	3.05	1.76	1.92	1.82
MnO	0.00	0.00	0.01	0.02	0.00	0.00	0.02	0.02	0.01	0.01	0.01
MgO	0.39	0.12	0.13	0.12	0.10	0.10	0.01	0.00	0.14	0.00	0.16
CaO	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.04	0.00	0.00
Na_2O	0.06	0.07	0.32	0.19	0.06	0.11	0.05	0.01	1.51	0.01	0.03
K_2O	2.89	2.47	1.89	2.18	1.25	2.28	0.44	0.06	2.74	0.02	0.98
P_2O_5	0.03	0.06	0.04	0.06	0.03	0.03	0.02	0.02	0.02	0.01	0.00
LOI	1.07	0.55	0.32	0.14	0.19	0.40	0.00	0.00	0.41	0.00	0.09
Total	98.53	100.10	97.77	100.93	100.83	100.12	100.48	102.24	100.61	99.48	98.58
Ba	355	501	383	2719	187	424	212	24	700	10	182
Rb	101	79	70	55	29	59	20	4	75	2	25
Sr	31	29	31	29	55	38	5	1	82	1	3
Y	15	6	7	10	5	7	2	1	8	0	4
Zr	105	118	56	60	112	86	33	35	41	27	277
Nb	6	2	1	2	1	1	0	0	3	0	5
Th	4.4	2.7	2.6	2.3	2.0	2.4	2.1	0.4	3.5	0.2	3.3
Pb	6	8	11	17	0	11	10	10	16	0	0
Ga	11	5	6	6	2	5	0	0	5	0	4
Zn	16	12	12	10	7	5	22	4	13	7	7
Cu	7	0	8	16	13	11	31	39	15	25	21
Ni	4	7	4	4	5	6	5	7	5	5	5
V	44	11	8	16	11	9	0	0	9	0	21
Cr	39.5	15.6	5.0	15.8	9.5	8.0	7.3	7.2	10.4	3.4	16.2
Hf	3.1	3.0	1.6	1.6	2.4	2.2	1.6	1.1	1.7	1.1	6.6
Cs	2.1	2.8	2.6	2.1	1.0	1.3	1.4	0.0	0.8	0.0	0.0
Sc	7.2	2.2	1.7	2.0	1.4	1.6	0.4	0.2	2.3	0.2	1.9
Ta	0.5	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Co	1.3	3.2	2.5	2.9	3.4	2.4	5.0	6.0	2.9	3.3	3.0
La	14.4	15.9	14.0	16.3	8.8	11.3	8.7	1.9	16.3	0.6	10.1
Ce	29.0	26.0	23.0	33.0	14.0	19.0	16.0	4.0	32.0	1.0	17.0
Nd	12.0	10.0	10.0	12.0	6.0	8.0	6.0	2.0	12.0	0.0	8.0
Sm	2.20	1.76	1.76	2.36	1.08	1.42	0.98	0.24	2.24	0.08	1.49
Eu	0.52	0.58	0.50	0.45	0.32	0.44	0.10	0.06	0.56	0.05	0.37
Tb	0.3	0.2	0.3	0.3	0.1	0.2	0.1	0.0	0.3	0.0	0.2
Yb	1.31	0.74	0.75	0.79	0.50	0.55	0.32	0.19	0.78	0.13	0.56
Lu	0.19	0.11	0.11	0.11	0.07	0.08	0.04	0.02	0.12	0.02	0.08
U	1.0	1.1	0.6	0.8	0.6	0.7	0.4	0.2	0.6	0.1	0.4

Major oxides in [wt%]; trace elements in [ppm]; LOI — loss on ignition; MS — metasandstones of the Jegłowa Beds; G — gneiss; 0.0 — element con-

Table 2

metasandstones and gneisses of the Strzelin Massif

J1A	N3	K2A	R10	R3	GE2 (3.6)	J3	J4	GE2 (183.6)	K13	N20
MS	MS	MS	MS	MS	MS	MS	MS	G	G	G
0.73	0.84	0.63	0.81	0.77	0.60	0.72	0.55	0.73	0.70	0.73
94.33	96.42	75.15	78.43	79.03	69.01	95.23	78.85	72.00	74.62	72.25
0.11	0.10	0.49	0.60	0.47	0.52	0.24	0.31	0.11	0.09	0.18
2.86	1.99	12.32	12.31	10.38	13.94	1.83	9.28	13.61	13.92	15.40
2.63	1.94	5.06	5.21	6.02	6.67	2.80	4.24	3.90	2.42	2.25
0.02	0.01	0.03	0.02	0.02	0.05	0.02	0.13	0.05	0.02	0.03
0.07	0.00	1.00	0.78	0.30	0.92	0.07	1.07	0.31	0.24	0.54
0.08	0.00	0.07	0.08	0.00	0.23	0.06	0.80	1.18	0.41	1.65
0.09	0.02	1.79	0.12	0.14	3.22	0.08	2.41	4.11	4.70	5.37
0.71	0.32	3.82	2.26	2.57	3.19	0.42	1.91	3.44	3.23	2.26
0.01	0.01	0.05	0.06	0.07	0.06	0.06	0.06	0.03	0.16	0.10
0.06	0.07	1.08	0.94	0.66	0.00	0.00	0.69	0.00	0.42	0.23
100.97	100.88	100.86	100.81	99.66	97.81	100.81	99.75	98.74	100.23	100.26
74	25	711	375	382	688	44	286	1088	628	482
30	14	160	111	102	120	14	56	79	94	116
6	3	61	29	61	104	17	98	422	154	399
3	4	20	28	16	36	10	19	8	10	11
12	45	135	258	245	192	227	88	62	42	93
0	0	11	9	9	13	3	4	6	8	14
1.2	1.8	7.0	10.1	8.3	6.8	2.9	3.0	3.8	3.7	5.2
0	0	7	0	13	9	0	7	15	16	15
4	3	15	16	14	19	0	8	20	17	22
7	6	53	27	25	45	5	49	37	86	32
33	24	16	20	19	58	35	20	31	21	11
10	4	17	34	30	18	5	15	6	4	2
26	23	50	66	49	32	11	28	0	0	20
33.8	15.9	36.8	62.2	56.6	30.7	52.1	16.3	0.0	2.2	2.4
0.4	1.2	3.5	6.1	7.0	5.0	6.1	2.6	2.1	1.4	2.8
1.0	0.6	8.1	4.1	17.3	4.5	0.4	1.1	0.8	0.5	2.9
3.9	1.8	8.0	10.1	9.3	7.9	2.1	5.6	1.5	2.1	4.2
0.0	0.0	0.9	0.6	0.6	0.8	0.5	0.4	0.0	1.1	1.0
5.4	2.9	10.8	10.7	9.6	10.8	4.0	10.2	4.5	3.8	2.8
5.0	9.3	30.5	49.6	40.9	46.5	11.4	20.6	18.0	9.9	20.3
9.0	14.0	82.0	97.0	79.0	87.0	24.0	33.0	29.0	21.0	35.0
4.0	5.0	32.0	40.0	32.0	34.0	12.0	14.0	10.0	8.0	14.0
0.71	0.97	4.81	7.55	5.57	6.96	2.33	3.01	1.87	1.26	1.97
0.21	0.12	1.26	1.30	1.18	1.52	0.54	0.85	0.35	0.33	0.54
0.1	0.1	0.7	0.8	0.6	0.9	0.3	0.6	0.2	0.3	0.2
0.45	0.45	1.83	2.96	1.91	2.21	0.95	1.67	0.55	0.89	0.85
0.06	0.06	0.24	0.39	0.28	0.30	0.14	0.24	0.08	0.13	0.12
0.2	0.4	1.3	1.7	1.1	1.9	0.7	0.6	0.4	0.4	1.2

centration below detection limit; CIA — chemical index of alteration

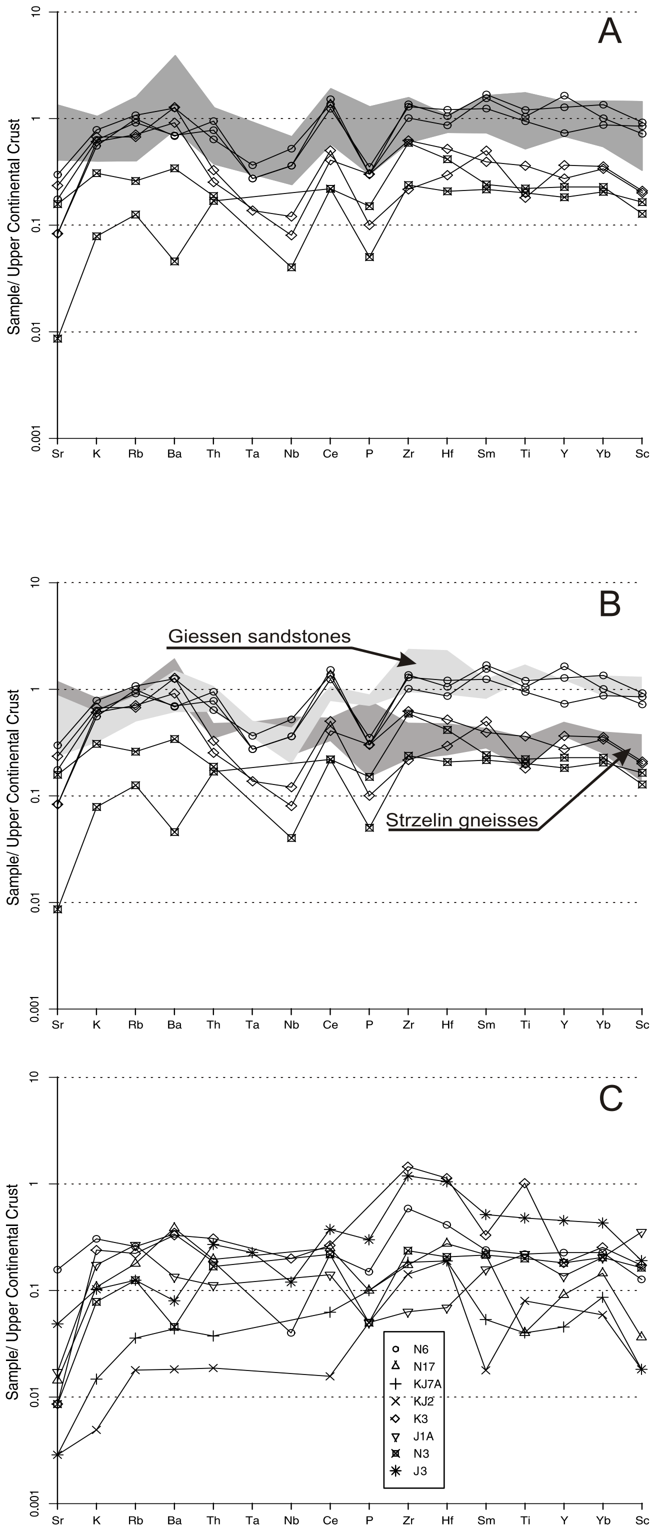

Fig. 6. Multielement plots normalised to the average upper continental crust composition (Taylor and McLennan, 1985)

A — diagram comparing the Jegłowa Beds metasandstones with island-arc granites; shaded area — island-arc granites from south-west Japan (Kutsukake, 2002); **B** — diagram showing the Jegłowa Beds metasandstones on a background of gneisses from the Strzelin Massif (dark shaded) and synorogenic sandstones (light shaded area) from the Giessen Nappe in the southeastern Rhenish Massif (Floyd *et al.*, 1990); metasandstone samples shown on diagrams 6A and B are the same as those in Figure 4; **C** — low-quartz group of metasandstones

DISCUSSION

SEDIMENTARY CYCLE

Chemical reactions during a sedimentary cycle usually result in changes in major-element abundances (e.g. Bhatia and Crook, 1986). Large ion lithophile element (LIL) concentrations can be also subjected to significant changes during weathering, transport and sedimentation (e.g. Wedepohl, 1991). In contrast, the lanthanides and HFS elements exhibit only minor changes during sedimentary processes (e.g. Bhatia, 1985; Bhatia and Crook, 1986).

The chemical index of alteration (CIA; Nesbitt and Young, 1982) allows the assessment of the weathering degree of source rocks supplying material to the protolith of the metasandstones studied. The Jegłowa Beds show CIA values between 0.55 and 0.84 (Table 2), with an average of 0.71, suggesting a moderately weathered source.

Syn- and post-depositional alteration caused by exchange reactions during deposition and diagenesis seem to be insignificant with regards to the abundance of HFS elemants and REE in the metasandstones studied. The petrography of the metasandstones suggests very low contents of clay in the primary sediments; thus a selective absorption of LREE on clay minerals (Fleet, 1984) should not have substantially influenced the REE distributions in the metasandstone precursors.

The missing or insignificant negative Eu anomalies, characteristic of most of the chondrite-normalized REE patterns (Fig. 5), point to quite oxidizing conditions both during sedimentation and even diagenesis. Highly reducing conditions necessary for the development of a negative Eu anomaly (MacRae *et al.*, 1992) cannot be expected during the sedimentation of the primary siliciclastics deposits, since black shale-type metapelites are absent from the metasandstone-bearing sequences (*cf.* Oberc, 1966; Chmura, 1967; Oberc-Dziedzic, 1995; Szczepański and Mazur, 2004).

Hydraulic sorting of zircon, leading to Zr, Hf and HREE enrichment in sands (Cullers *et al.*, 1987), was most probably not an important process as indicated by the trace-element distributions (Fig. 6). Only a few of the investigated samples are Zr- and Hf-rich (J3, KJ7A, KJ2, K3).

METAMORPHISM

Significant mobility of alkalis and alkaline earth elements has to be expected under low-grade metamorphic conditions (e.g. Wedepohl, 1991). The HFS elements remain almost immobile during regional metamorphism of sedimentary rocks (e.g. McLennan *et al.*, 1983), and should be the HREEs (Elderfield and Sholkovitz, 1987; Camiré *et al.*, 1993). However, concentrations of LREE and P, widely accepted as immobile elements, can be altered by secondary crystallization of some minerals (e.g. epidote, sphene and apatite) changing some trace-element abundances (e.g. Hellmann *et al.*, 1979; Altenberger, 1996).

The metasandstones display relatively uniform major-element compositions excluding the quartz-rich variety (Table 2). Consequently, the major-element abundances in the rocks studied can be considered as largely unchanged by regional metamorphism. The spider diagram (Fig. 6A) shows almost identical shapes of the trace-elements patterns for samples representing greenschist- and amphibolite-grade metasandstones. Thus, it is suggested that not only REE but also trace- and major-element concentrations (perhaps with the exception of K_2O, Na_2O, Ba, Rb and Sr) were not significantly altered during the Variscan regional metamorphism and in the majority of samples may correspond to the pre-metamorphic geochemical signature.

SOURCE ROCKS AND TECTONIC SETTING OF DEPOSITION

The metasandstones mostly display K/Rb values close to 230 and in the diagram of Rb *vs*. K_2O they follow the "main trend" of differentiated magmatic suites (Fig. 7; Shaw, 1968). This relationship seems to be evidence for derivation of primary sediments from a largely igneous source. The location of the mica-poor metasandstones in the field of source rocks showing a basic composition (Fig. 7) is at least partly caused by the dilution effect of the surplus quartz on the concentrations of K and Rb in these rocks.

The tectonic affinity of a magmatic source supplying material to the Jegłowa Beds may be discussed on the basis of the Th/Sc *vs*. La/Sc diagram (Fig. 8; Floyd *et al*., 1991). Data points are mostly distributed close to the line joining averages of intermediate and acid volcanic arc igneous rocks (Fig. 8). This is even clearer when the chemistry of the analysed metasandstones is compared with island-arc granites from southwestern Japan (Kutsukake, 2002). Lines representing the mica-rich metasandstones show an identical shape to the area of island arc granites (Fig. 6A). The mica-poor metasandstones, due to their high-quartz content, are shifted beneath the lines representing mica-rich samples and the field of island-arc granites.

Interestingly, the comparison of chemical composition of the Jegłowa Beds and gneisses from the Strzelin Massif shows essential differences between these rocks (Fig. 6B), most visible for the mica-rich metasandstones. The LIL and some HFS elements (represented by Th, Ta and Nb) show similar contents both in the Strzelin gneisses and in the metasandstones analysed. However, there are considerably lower amounts of other HFS elements (namely Zr, Hf, Ti, Y and Sc) and some REE (Ce, Sm and Yb) in the gneisses compared to the mica-rich metasandstones of the Jegłowa Beds. Consequently, the gneisses from the Strzelin Massif could have made only a minor contributed to the Jegłowa Beds. Obviously, there must have been another source supplying detritus to the protolith of the metasandstones. Within the Brunovistulian domain, Devonian acid and intermediate volcanic rocks with volcanic arc and back-arc affinity, which may have contributed to the Jegłowa Beds, are known from the Jeseníky Mts. (Jakeš and Patočka, 1982; Patočka and Valenta, 1996; Janoušek *et al*., 2006*a*).

The average of the majority of the trace element concentrations and their proportions in the low-quartz content metasandstones are typical of sediments deposited on a continental island arc or active continental margin setting (Table 3; *cf*. Bhatia and Crook, 1986). The trace-element composition of the medium-quartz content group seems to be typical of an oceanic island arc (Th, Zr, Hf, Nb, La, Ce, Nd, La/Th and Th/Sc)

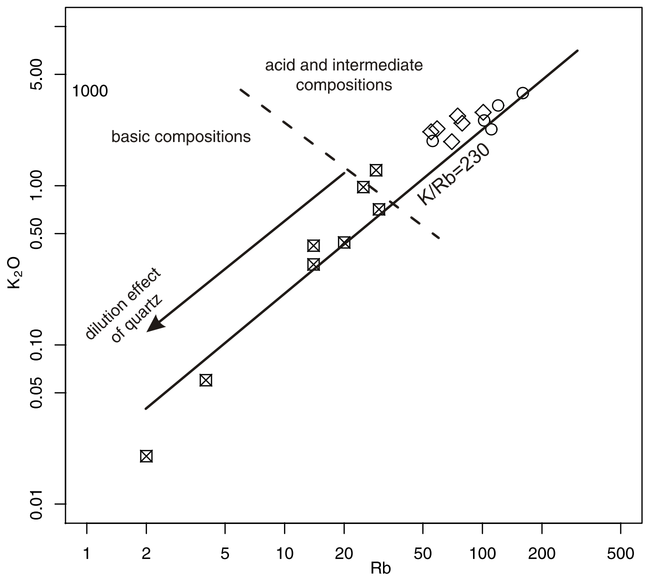

Fig. 7. Distribution of K and Rb in the Jegłowa Beds

The line equals the ratio of K/Rb = 230 and represents "main trend" of Shaw (1968); symbols as in Figure 4

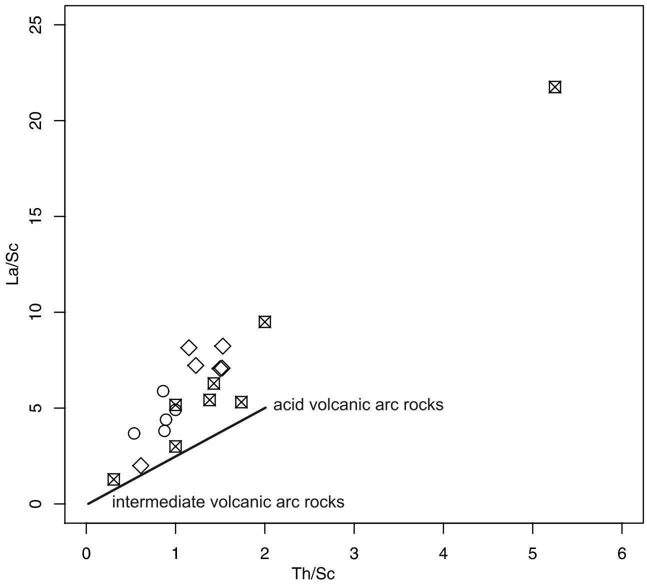

Fig. 8. The metasandstones of the Strzelin Massif (Jegłowa Beds) in Th/Sc *vs*. La/Sc diagram (Floyd *et al*., 1991)

Symbols as in Figure 4

or a passive margin (La/Y, Ti, Co, Zn and Sc/Cr). On the other hand, the high-quartz content group is chemically strongly varied as manifested e.g. by the wide range of Zr and Hf contents as well as by very low concentrations of some other elements such as Ti and Sc. Thus, the values shown in Table 3 for this group of metasandstones might be meaningless, although many of them are indicative of an oceanic island arc according to Bhatia and Crook (1986). Most probably the chemistry of these rocks was not controlled by the tectonic setting of the sedimentary basin but by sedimentary processes such as reworking of older deposits and sorting. Consequently, this group of samples might have formed by erosion and subsequent reworking of

Table 3

Contents (in ppm) and ratios of selected trace elements of the Jegłowa Beds metasandstones

Group	LQC					MQC					HQC				
Element/ Ratio	Min.	Max.	Aver.	Median	Tectonic setting	Min.	Max.	Aver.	Median	Tectonic setting	Min.	Max.	Aver.	Median	Tectonic setting
Pb	0.0	13.0	7.2	7.0	OIA	6.0	17.0	11.5	11.0	PM/CIA	0.0	10.0	2.5	0.0	OIA?
Th	3.0	10.1	7.0	7.0	CIA?	2.3	4.4	3.0	2.7	OIA	0.2	3.3	1.7	1.9	OIA
Zr	88.0	258.0	183.6	192.0	ACM	41.0	118.0	77.7	73.0	OIA	12.0	277.0	96.0	40.0	OIA
Hf	2.6	7.0	4.8	5.0	CIA	1.6	3.1	2.2	2.0	OIA	0.4	6.6	2.6	1.4	OIA
Nb	4.0	13.0	9.2	9.0	CIA/ACM	1.0	6.0	2.5	2.0	OIA	0.0	5.0	1.1	0.0	OIA?
Th/U	3.6	7.5	5.5	5.4	PM/ACM	2.5	5.8	3.9	3.9	CIA?	2.0	8.3	4.4	4.3	CIA/ACM
Zr/Hf	33.8	42.3	37.6	38.4	CIA	24.1	39.3	34.8	36.3	CIA?	20.6	46.7	33.8	34.5	CIA?
Zr/Th	19.3	29.5	26.4	28.2	CIA/PM	11.7	43.7	27.1	25.0	CIA/PM?	10.0	135.0	61.4	67.1	OIA
La	20.6	49.6	37.6	40.9	ACM/PM	11.3	16.3	14.7	15.2	OIA?	0.6	11.4	7.0	8.8	OIA
Ce	33.0	97.0	75.6	82.0	ACM/PM	19.0	33.0	27.0	27.5	OIA	1.0	24.0	12.4	14.0	OIA?
Nd	14.0	40.0	30.4	32.0	PM	8.0	12.0	10.7	11.0	OIA	0.0	12.0	5.4	5.5	
La/Y	1.1	2.6	1.6	1.5	PM	1.0	2.7	1.8	1.8	PM?	1.1	4.4	2.2	1.9	PM?
La/Th	4.4	6.9	5.6	4.9	OIA	3.3	7.1	5.2	5.0	OIA	3.0	5.2	4.1	4.2	OIA
La/Sc	3.7	5.9	4.5	4.4	ACM	2.0	8.2	6.6	7.2	PM	1.3	21.8	7.2	5.4	PM
Th/Sc	0.5	1.0	0.8	0.9	CIA	0.6	1.5	1.3	1.4	CIA?	0.3	5.3	1.8	1.4	ACM?
Ti/Zr	11.5	21.8	16.9	16.2	ACM	7.7	21.1	13.0	13.0	ACM	3.4	55.0	13.4	7.6	ACM
Ti	0.2	0.4	0.3	0.3	CIA/ACM	0.05	0.22	0.10	0.08	PM?	0.01	0.31	0.09	0.06	
Sc	5.6	10.1	8.2	8.0	ACM	1.6	7.2	2.8	2.1		0.2	3.9	1.5	1.6	
V	28.0	66.0	45.0	49.0	ACM	8.0	44.0	16.2	10.0		0.0	26.0	11.5	11.0	
Co	9.6	10.8	10.4	10.7	CIA/ACM	1.3	3.2	2.5	2.7	PM	2.9	6.0	4.1	3.7	PM
Zn	25.0	53.0	39.8	45.0	PM	5.0	16.0	11.3	12.0	PM	4.0	22.0	8.1	7.0	
Sc/Cr	0.2	0.4	0.3	0.3	CIA/ACM	0.1	0.3	0.2	0.2	PM	0.0	0.1	0.1	0.1	PM?

Tectonic settings according to the classification of Bhatia and Crook (1986); ACM — active continental margin; CIA — continental island arc; PM — passive margin; OIA — ocean island arc; LQC — low-quartz content group; MQC — mid-quartz content group; HQC — high-quartz content group

older crust. However, most of the significant element ratios in the low- and medium-quartz groups are representative of a subduction-related environment. Interestingly, the affinity revealed by the metasandstones studied to an oceanic island arc setting, specifically represented by back-arc and forearc basins (*cf.* Bhatia and Crook, 1986), is consistent with the provenance postulated for the Devonian mafic rocks from the nearby Jeseniký Mts. (Patočka, 1987; Patočka and Valenta, 1996; Janoušek *et al*., 2006*a*). The complexity of the trace element characteristics of the metasandstones investigated may well be explained by erosion of two crustal domains: passive margin and partly dissected magmatic arc formed on an attenuated continental crust. The active continental margin or continental island arc affinity of the Jegłowa Beds is supported by the comparison of their chemical composition to the sandstones from the Giessen Nappe in the SE Rhenish Massif. The latter rocks were described as synorogenic Late Devonian greywackes deposited in an arc-related environment (Floyd *et al*., 1990). The chemistry of these greywackes (light shaded area on Fig. 6B) is almost identical to the composition of the mica-rich metasandstones from the Jegłowa Beds (Fig. 6B).

The distribution patterns of the trace-element concentrations in the low- and medium-quartz content Jegłowa Beds, i.e. the depletion in Ta and Nb and in specific Th, Zr, Hf, Nb, Th/U, Zr/Hf, Zr/Th, La, Ce, La/Th, Th/Sc and Ti/Zr ratios resemble those in siliciclastic rocks deposited in a subduction-related tectonic setting (Table 3; *cf.* Bhatia and Crook, 1986). The metasandstone precursors probably inherited low Ta and Nb contents from acid and intermediate rocks generated as volcano-plutonic arc magmas (*cf.* Floyd *et al*., 1990; Foley and Wheller, 1990). In fact, the majority of the metasandstones display Hf concentrations mostly lower than the average sandstone value (3.9 ppm after Bowen, 1979). Furthermore, observed values of Hf and La/Th (Fig. 9) are intermediate between an andesitic and rhyolitic arc source (Floyd and Leveridge, 1987).

The metasandstones studied display the same lanthanide distribution patterns as in sediments derived largely from intermediate to acid calc-alkaline igneous rocks, namely the significant LREE-enrichment and negative Eu anomaly (*cf.* Bhatia, 1985; Taylor and McLennan, 1985; Bhatia and Crook, 1986). However, the mica-poor metasandstones usually have low total REE concentrations (Fig. 5). In the Sc-Th-Zr and Co-Th-Zr ternary diagrams (Fig. 10) the rocks analysed fall within the continental island arc field described by Bhatia and Crook (1986). Only mica-poor samples characterised by the highest SiO_2 content depart from this trend, being almost randomly scattered in the lower part of the diagrams.

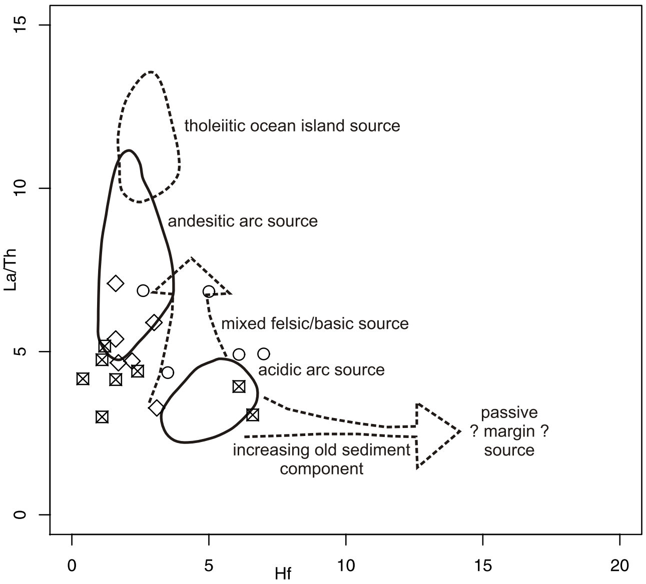

Fig. 9. Source and compositional discrimination of sandstones in terms of La/Th ratio and Hf abundance (after Floyd and Leveridge, 1987)

Symbols as in Figure 4

PALAEOTECTONIC MODEL

The Devonian volcano-sedimentary sequence of the Vrbno Group (Svoboda *et al*., 1966), approximately 1 600 m thick, is composed of a variety of metasedimentary rocks (pelitic schists, quartzites and minor marbles) and mafic to felsic metavolcanic rocks. The southern part of the Vrbno Group represents the major centre of Devonian volcanism in the Moravo-Silesian Zone (Barth, 1966). The Early Devonian (middle Pragian) fauna, a typical nearshore benthic assemblage (brachiopods, bivalves and ichnofossils), was found in abundance in the basal quartzites allowing dating of the onset of sedimentation (Chlupáč, 1989, 1993). The overlying Devonian tholeiitic to calc-alkaline volcanic-arc related volcanic rocks (Jakeš and Patočka, 1982; Patočka, 1987; Patočka and Valenta, 1996; Patočka and Hladil, 1997) associated with the extensive succession of siliceous deep-water sedimentary rocks provide evidence for the subsequent formation of a back-arc basin. Some of the basic metavolcanic rocks corresponding to tholeiitic to alkaline WPB-type rocks (Souček, 1981; Patočka, 1987) indicate contemporaneous crustal break-up related to the initiation of this basin.

The back-arc extension responsible for the deposition of the Vrbno Group and the Jegłowa Beds must have been induced by the ongoing Early to Mid-Devonian subduction beneath the Brunovistulian active margin. The eastward polarity of such subduction was recently postulated by Mazur *et al.* (2006) for the oceanic domain separating the Brunovistulian microplate from the Central Sudetic terrane(s) (Fig. 11). The oceanic crust of this domain must have been ultimately consumed in the Late Devonian when the collision between the Central Sudetes and the Brunovistulian microplate took place. The time of this collision, dated by the age of UHP granulite facies metamorphism in the Orlica–Śnieżnik unit at 386±2.6 Ma by Sm-Nd on garnet (Anczkiewicz *et al.,* 2007), is contemporaneous with the cessation of sedimentation and volcanism within the Vrbno Group (Hladil, 1986). Despite the growing amount of new data (Oberc-Dziedzic *et al.,* 2003, 2005), the exact present-day position of the Brunovistulian active margin remains largely unknown since it has been obscured by Late Devonian collisional tectonics. Further complication of tectonic structure is caused by the subsequent Early Carboniferous closure of the back-arc

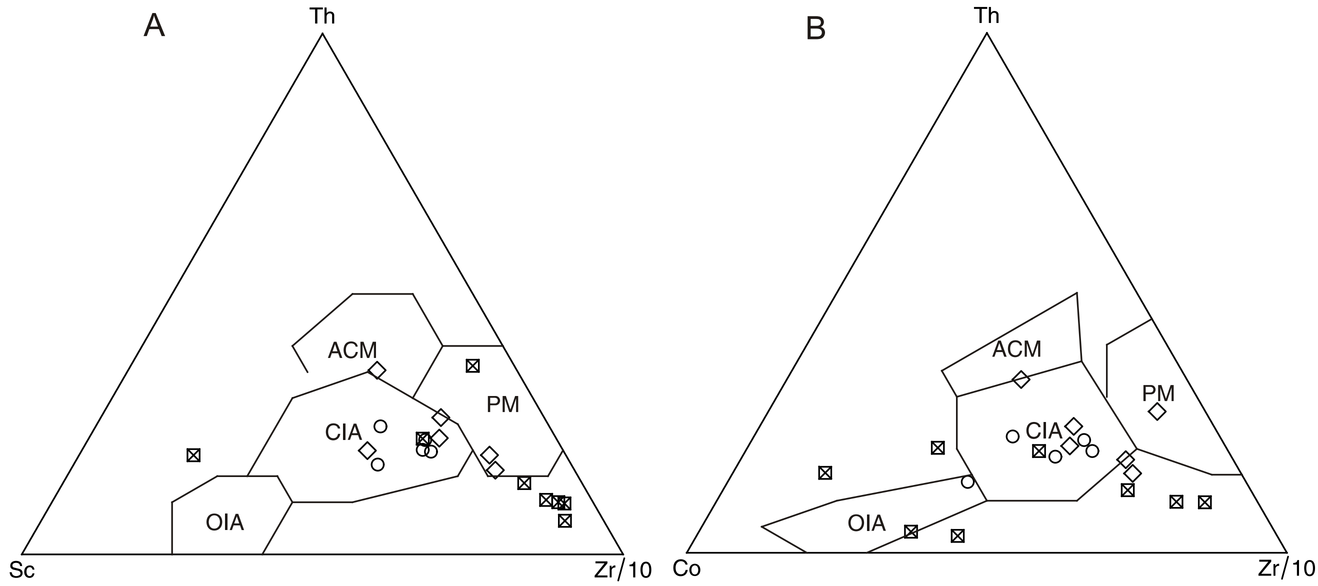

Fig. 10. Ternary diagram after Bhatia and Crook (1986)

Most of the data points are located in the field typical of continental arc sediments on discrimination diagrams Sc-Th-Zr/10 (A) and Co-Th-Zr/10 (B) of Bhatia and Crook (1986); only samples containing the highest amounts of quartz are almost randomly distributed over different fields marked in the diagram; other explanations as in Figure 4 and Table 3

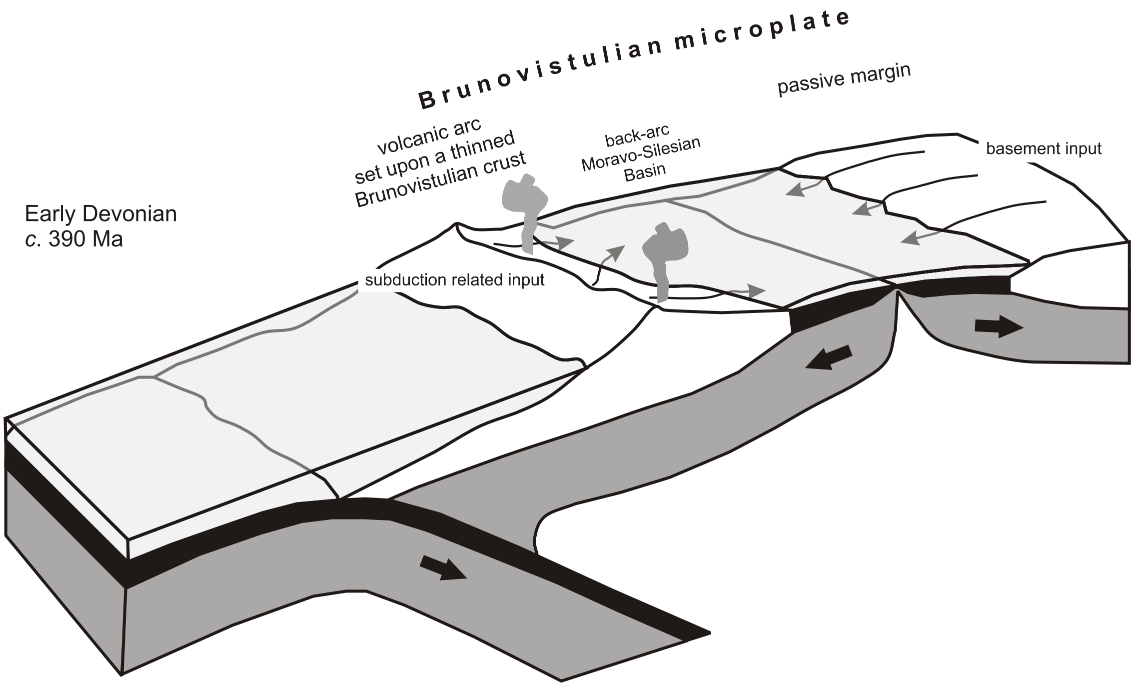

Fig. 11. Hypothetical geodynamic scenario explaining the tectonic setting for deposition of the Jegłowa Beds and Vrbno Group in the Late Palaeozoic

basin parental to the Vrbno Group (Schulmann and Gayer, 2000) with the volcano-sedimentary sequence being mostly included in the allochthonous thrust unit (Cháb *et al*., 1994).

CONCLUSIONS

1. The Devonian metasandstones of the Jegłowa Beds from the Strzelin Massif comprise mica-rich and mica-poor varieties.

2. The sources to the protolith of the metasandstones were:

— Devonian volcanic arc-type igneous rocks almost contemporaneous with the siliciclastic precursors of the metasandstones;

— gneisses of the Strzelin Massif.

3. The metasandstones experienced low- to medium-grade Variscan regional metamorphism and ductile deformation resulting in overall recrystallization of their protolith. The framework mineralogy, matrix composition and relative proportions between matrix and framework grains are mostly obscured.

4. The metasandstones analysed may be divided into three chemically different groups. The mica-rich metasandstones show the lowest silica abundances. The mica-poor metasandstones may be chemically subdivided into two subgroups (namely with medium- and high-silica contents) showing different silica concentrations. Although the relative element abundances are similar in both the metasandstone varieties, the mica-poor rocks are generally depleted in all major and trace elements in terms of absolute concentrations except for silica. This is probably related to the dilution effect of quartz.

5. The sedimentary precursors to the majority of the Jegłowa metasandstones possessed shared gochemical characteristics indicative of a subduction-related tectonic setting. Only a few of the samples analyzed resemble strongly reworked sediments. Thus, a back-arc basin seems to be the most realistic site of deposition for the Jegłowa Beds.

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APPENDIX

Samples location

Sample number	Location
K2A	North of Kuropatnik. West of the Kuropatnik–Strzelin road. Small exposure located 200 m to the W of the hill at 202.8 m
K3	North of Kuropatnik. West of the Kuropatnik–Strzelin road. Small abandoned quarry located 500 m to the E of the hill at 224.3 m
K13	North of Kuropatnik. West of the Kuropatnik–Strzelin road. Small exposure located 500 m NW of the hill at 202.8 m
K16	North of Kuropatnik. East of the Kuropatnik–Strzelin road. Abandoned quarry located 350 m to the SSW of the cemetery in Kuropatnik
GE2 (3.6) and GE2 (183.6)	Vicinity of Kuropatnik. West of the Kuropatnik–Strzelin road. Sample taken from a borehole. Depth (m) is indicated in the brackets
J1A, J3, J4, J8A	Jegłowa. Large, partly abandoned quartzite quarry located between Jegłowa and Krzywina. Excavation K-4
KJ2	Vicinity of Krzywina. Small abandoned quarry located near the blue footpath, *ca*. 200 m to the NW from Krzywina
KJ7A	Vicinity of Przeworno. Abandoned limestones quarry located to the N of the railway station in Przeworno
KJ10	Vicinity of Krzywina. Small abandoned quarry located *ca*. 2 km to the NE of Gromnik Hill (370.1 m). West slope of Szerzawa Hill (250 m) near the yellow footpath
R3	Vicinity of Romanów. Small natural exposure located near the red footpath *ca*. 600 m to the NW of Gromnik Hill (393.0 m)
R10	Vicinity of Romanów. Natural exposure located on the red footpath, 100 m to the N of Romanów
N1B	Vicinity of Nowolesie. Small natural exposure located on top of Nowoleska Kopa (193 m)
N3	Vicinity of Nowolesie. Small abandoned quarry located on top of the hill at 241.0 m; *ca*. 350 m to the N of the church in Nowolesie
N6	Vicinity of Skalice. Small abandoned quarry located near the red footpath *ca*. 200 m to the SW of the hill 312.2 m
N8	Vicinity of Skalice. Small abandoned quarry located near the red footpath *ca*. 800 m to the NNE of the hill 312.2 m
N12	Vicinity of Skalice. Small abandoned quarry located near the red footpath 1100 m to the NE of the hill 312.2 m
N17	Vicinity of Nowolesie. Small natural outcrop located *ca*. 350 m to the NNE of the hill 291.2 m
N20	Vicinity of Skalice. Natural outcrop located *ca*. 250 m away from Skalice