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ORIGINAL PAPER

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Neoproterozoic and Cambro-Ordovician magmatism in the Variscan Kłodzko Metamorphic Complex (West Sudetes, Poland): new insights from U/Pb zircon dating

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Abstract The Kłodzko Metamorphic Complex (KMC) in the Central Sudetes consists of meta-sedimentary and meta-igneous rocks metamorphosed under greenschist to amphibolite facies conditions. They are comprised in a number of separate tectonic units interpreted as thrust sheets. In contrast to other Lower Palaeozoic volcano-sedimentary successions in the Sudetes, the two uppermost units (the Orla-Gołogłowy unit and the Kłodzko Fortress unit) of the KMC contain meta-igneous rocks with supra-subduction zone affinities. The age of the KMC was previously assumed to be Early Palaeozoic–Devonian, based on biostratigraphic findings in the lowermost tectonic unit. Our geochronological study focused on the magmatic rocks from the two uppermost tectonic units, exposed in the SW part of the KMC. Two orthogneiss samples from the Orla-Gołogłowy unit yielded ages of 500.4±3.1 and 500.2±4.9 Ma, interpreted to indicate the crystallization age of the granitic precursors. A plagioclase gneiss from the same tectonic unit, intimately interlayered with metagabbro, provided an upper intercept age of 590.1±7.2 Ma, which is interpreted as the time of igneous crystallization. From the topmost Kłodzko Fortress unit, a metatuffite was studied, which contains a mixture of genetically different zircon grains. The youngest ^{207}Pb/^{206}Pb ages, which cluster at ca. 590-600 Ma, are interpreted to indicate the maximum depositional age for this metasediment. The results of this study are in accord with a model that suggests a nappe structure for the KMC, with a Middle Devonian succession at the base and Upper Proterozoic units at structurally higher levels. It is suggested here that the KMC represents a composite tectonic suture that juxtaposes elements of pre-Variscan basement, intruded by the Lower Ordovician granite, against a Middle Palaeozoic passive margin succession. The new ages, combined with the overall geochemical variation in the KMC, indicate the existence of rock assemblages representing a Gondwana active margin. The recognition of Neoproterozoic subduction-related magmatism provides additional arguments for the hypothesis that equivalents of the Teplá-Barrandian domain are exposed in the Central Sudetes.

Keywords Bohemian Massif · Neoproterozoic crust · Pre-Variscan basement · Variscan belt · Zircon geochronology

Introduction

Most of the metamorphosed volcano-sedimentary successions exposed in the West Sudetes show geochemical signatures indicating an origin in an initial rift or mature oceanic setting (Kryza and Pin 1997; Floyd et al. 2000). These magmatic suites represent the record of Early Palaeozoic rifting that led to the break-up of the northern Gondwana margin (Pin and Marini 1993) and the development of terranes now assembled in the Variscan belt (Tait et al. 2000). Magmatic complexes with such characteristics are widespread throughout the European Variscides (Pin and Marini 1993; Floyd et al. 2000). In the Sudetes, they are mainly represented by the volcano-sedimentary successions of the Kaczawa and South Karkonosze metamorphic units (Furnes et al. 1994; Patočka et al. 1997), and by the Sudetic ophiolites (Pin et al. 1988). These occurrences are interpreted to represent Ordovician continental rifts, as well as Silurian and Devonian successions of oceanic basins.

Interpretations that suggest the formation of these successions in an extensional setting were recently challenged by Kryza et al. (2003), based on geochemical results from the Kłodzko Metamorphic Complex (KMC). The new data indicate that the majority of meta-igneous rocks in this area originated in a supra-subduction setting. Hence, the development of the KMC is apparently in

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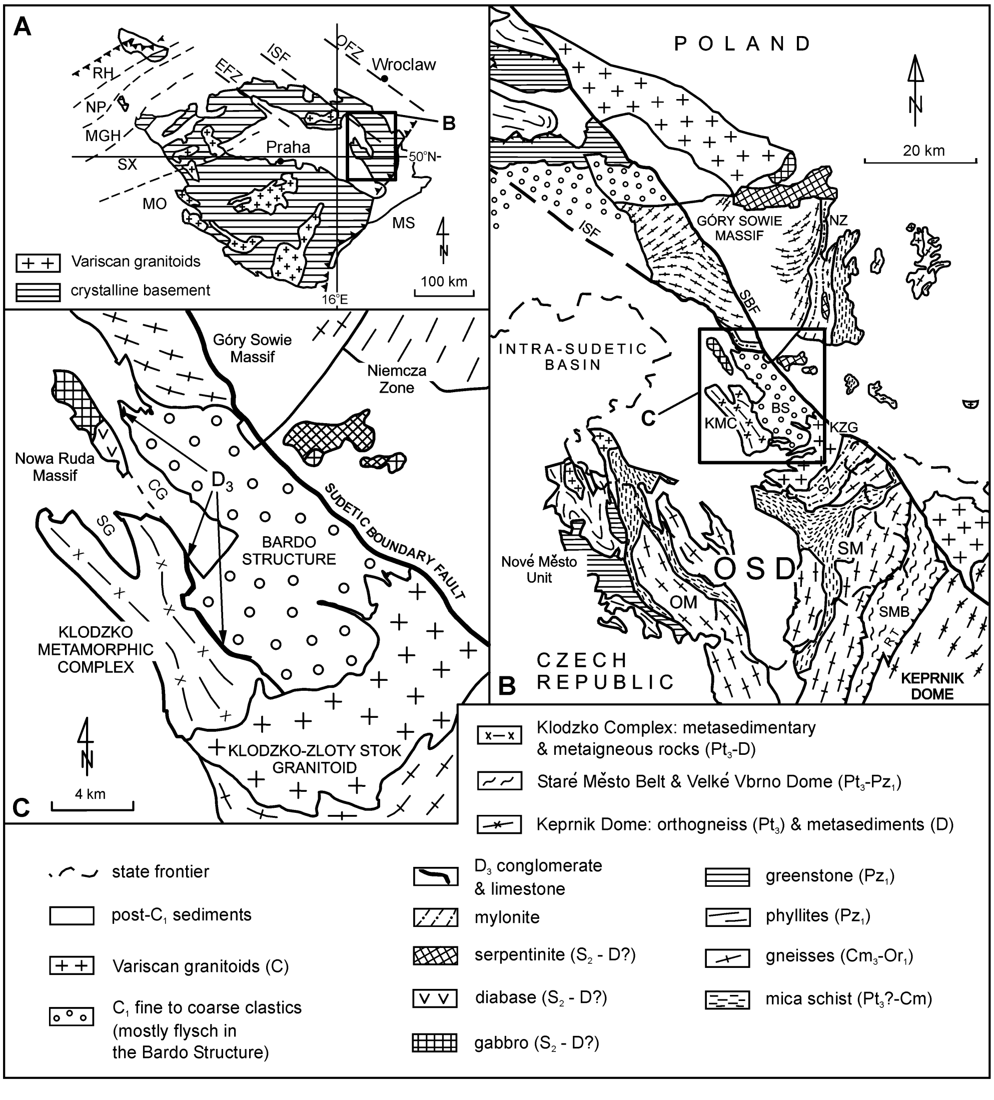
conflict with models assuming a relationship between the Early Palaeozoic magmatism and the overall extension across the pre-Variscan terranes (Crowley et al. 2000). This inconsistency is only a real problem if the assumed Early Palaeozoic–Devonian age of the KMC is correct (Gunia and Wojciechowska 1971; Wojciechowska 1990). To solve this issue, we have dated various meta-igneous and meta-tuffaceous rock types by means of the ID-TIMS U–Pb zircon method. The results indicate that the fossil-based ages (Gunia and Wojciechowska 1971) are not representative for the complete succession of the KMC and thus substantiate models suggesting a nappe structure for the study area.

Geological setting

The Kłodzko Metamorphic Complex (KMC) is exposed in an area of ca. 100 km^2 in the eastern part of the West Sudetes (Fig. 1). It is mostly surrounded by Upper Carboniferous and Permian sedimentary and volcanic rocks, which fill the eastern part of the Intra-Sudetic Basin. In the east, the KMC is bounded by an intrusive contact against the Kłodzko–Złoty Stok granitoid pluton. Towards the NE, the KMC is unconformably overlain by Upper Devonian conglomerates and limestones, which pass upwards into the Carboniferous clastic sediments of the Bardo Basin (Haydukiewicz 1990).

The KMC is generally divided into two parts with different lithology and metamorphic grade. The NE part mostly comprises meta-sedimentary and meta-volcanic rocks, which were metamorphosed under greenschist to epidote–amphibolite facies conditions. In contrast, the SW part is mainly composed of metagabbros, amphibolites and gneisses, which were subjected to amphibolite-facies metamorphism (Fig. 2). Subdivision of the KMC into several tectonic units is based on variations in metamorphic grade and history, differences in lithological composition and the occurrence of tectonic contacts (Aleksandrowski and Mazur 2002; Mazur 2003). By use of these criteria six tectonic units can be distinguished (Fig. 3). From base to top, these are:

Fig. 1 Tectonic setting of the Kłodzko Metamorphic Complex (**C**) in the Sudetes (**B**) and Bohemian Massif (**A**). *Inset map*: *A* EFZ: Elbe Fault Zone; *ISF* Intra-Sudetic Fault; *MGH* Mid-German Crystalline High; *MO* Moldanubian Zone; *MS* Moravo–Silesian Zone; *NP* Northern Phyllite Zone; *OFZ* Odra Fault Zone; *RH* Rhenohercynian Zone; *SX* Saxothuringian Zone. *B BS* Bardo Structure; *KMC* Kłodzko Metamorphic Complex; *KZG* Kłodzko–Złoty Stok Granitoid; *NZ* Niemcza Shear Zone; *OM* Orlica Massif; *OSD* Orlica-Śnieżnik Dome; *RT* Ramzová Thrust; *SBF* Sudetic Boundary Fault; *SMB* Staré Město Belt; *SZ* Skrzynka Shear Zone; *ŚM* Śnieżnik Massif. *C CG* Czerwieńczyce graben; *SG* Święcko graben. Age assignments: *Pt* Proterozoic; *Pz* Palaeozoic; *Cm* Cambrian; *Or* Ordovician; *D* Devonian; *C* Carboniferous; $_1$ early; $_2$ middle; $_3$ late



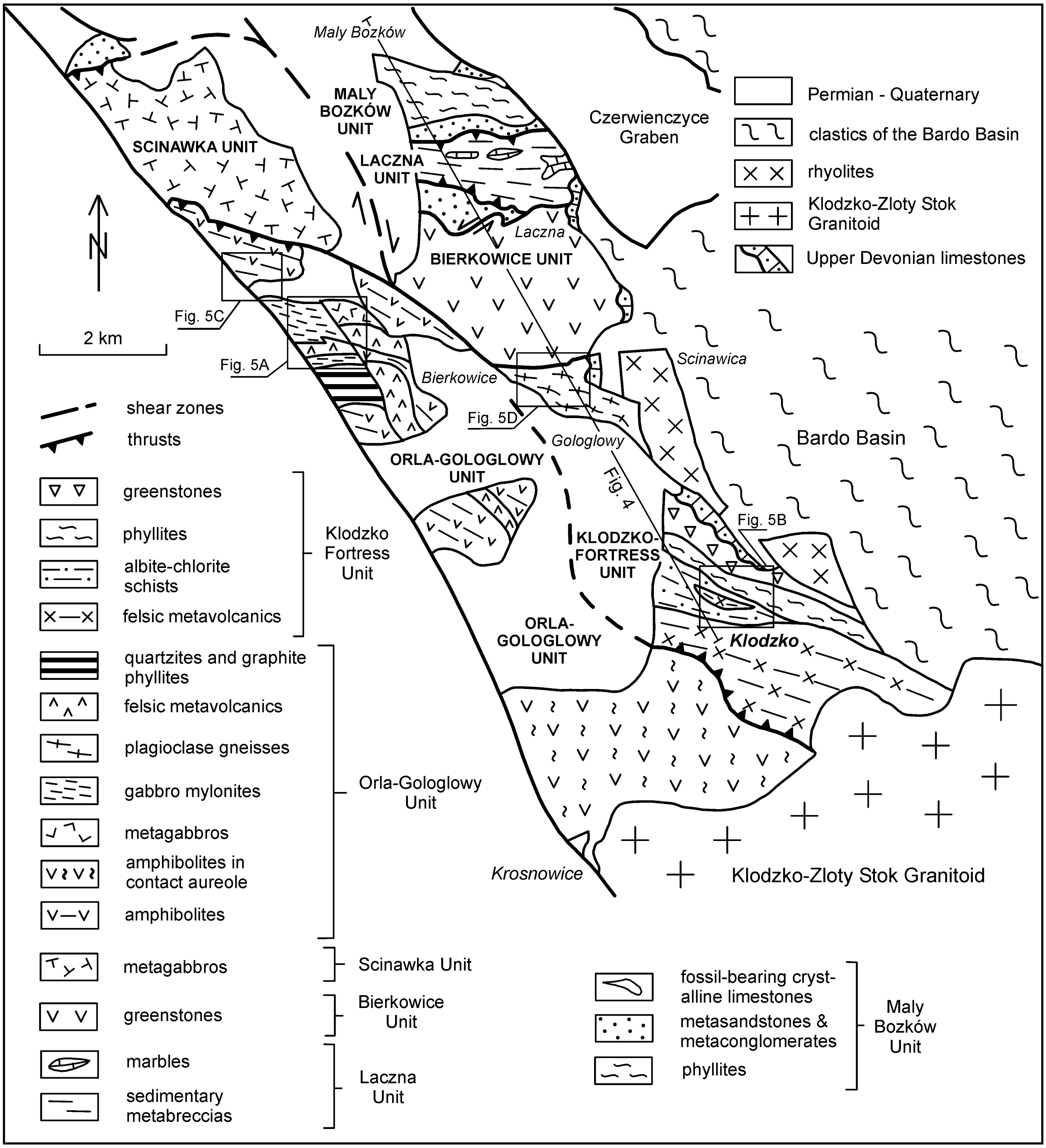


Fig. 2 Generalised geological map of the Kłodzko Metamorphic Complex showing its division into tectonic units

1. The Mały Bożków unit, which consists of a Middle Devonian (Givetian) progradational shelf sequence (Hladil et al. 1999).
2. A mélange body defining the Łączna unit (Mazur and Kryza 1999).
3. The Bierkowice unit, which is built up by mafic volcanic rocks with an intraplate geochemical signature (Narębski et al. 1988; Kryza et al. 2003).
4. The Ścinawka unit, which comprises a MORB-type gabbro (Kryza et al. 2003)
5. The Orla-Gołogłowy unit, which consists of MORB-type gabbros and mafic volcanics (Kryza et al. 2003), deep marine sediments, felsic volcanics and granitoid intrusions.
6. The Kłodzko Fortress unit, which is composed of a distal flysch with basaltic lavas, partly volcaniclastic sandstones and dacitic/andesitic tuffs.

The increasingly higher tectonic units are consecutively exposed from the NW to SE (Fig. 4). Their metamorphic grade increases upwards from the greenschist facies in the Mały Bożków unit, through the epidote–amphibolite facies in the Łączna and Bierkowice units, to the upper amphibolite facies in the Ścinawka and Orla-

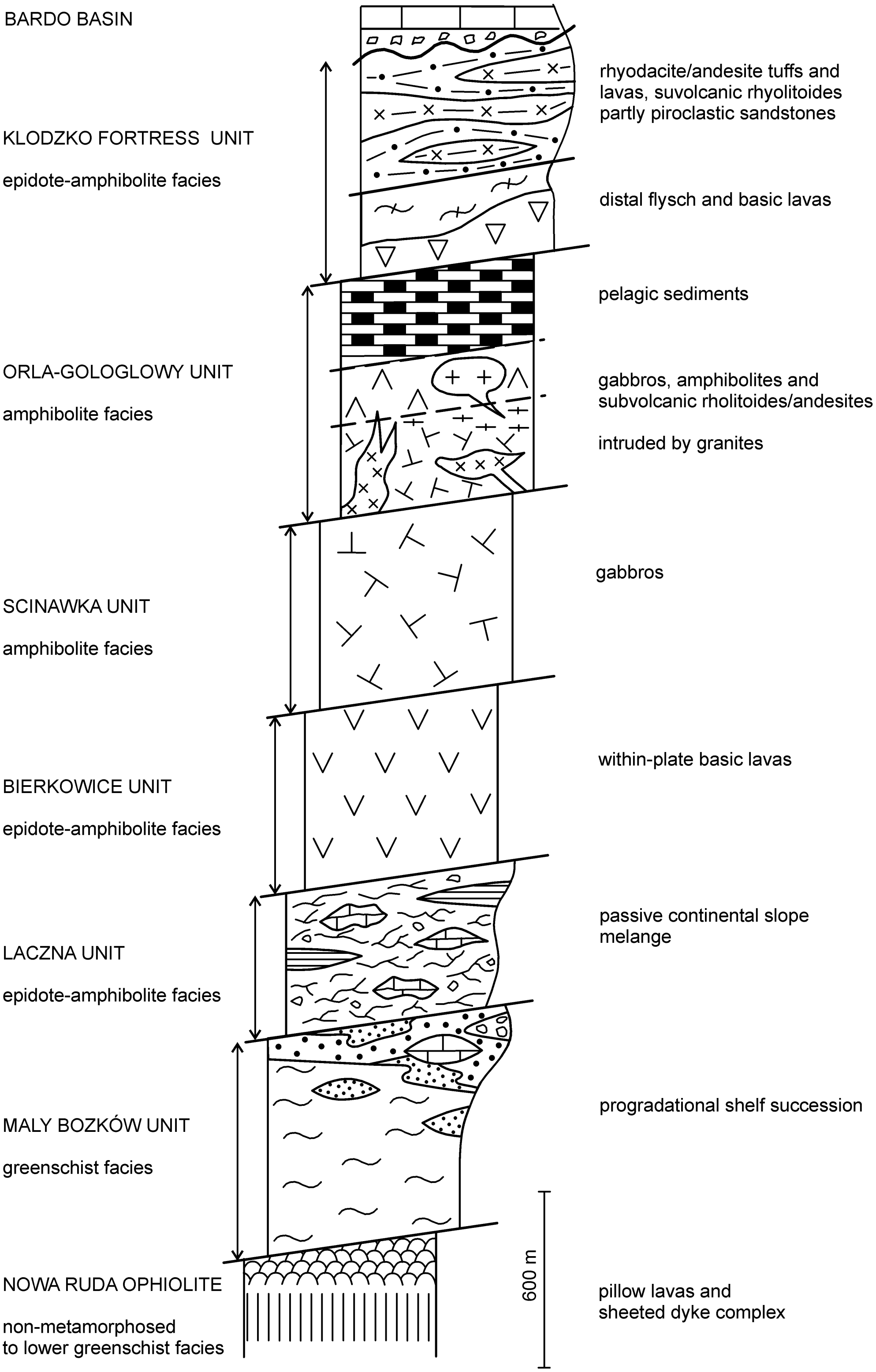
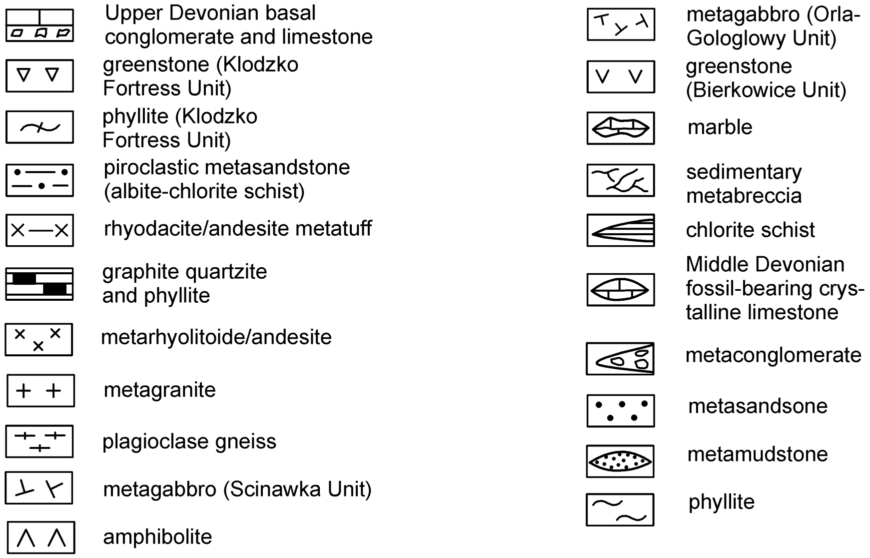


Fig. 3 Lithotectonic profile of the Kłodzko Metamorphic Complex

Gołogłowy units. Only the Kłodzko Fortress unit deviates from this trend, indicating a tectonic inversion of the metamorphic P–T conditions. The latter unit was metamorphosed under transitional conditions between the epidote–amphibolite and amphibolite facies. The deformation history of the KMC comprises six distinct events (D_1–D_6, Mazur 2003). The earliest D_1 event involved a top-to-the WNW-thrusting and resulted in uplift and juxtaposition of tectonic units. This stage was followed by the D_2 folding into E–W-trending folds, the D_3 dextral strike-slip shearing along a WNW direction under a transpressive regime and the D_4 sinistral to dip-slip shear,

Fig. 3 (continued)



which is associated with the final exhumation of the complete metamorphic successions in the Late Devonian. The next two events took place after a considerable time gap and also affected the Carboniferous sedimentary succession of the Bardo Basin. The D_5 event included sinistral strike-slip shearing along a WNW direction, synchronous with the emplacement of the Kłodzko–Złoty Stok granitoid pluton. Subsequently, the Bardo Basin and adjacent parts of the KMC experienced intense folding (D_6) due to N–S compression. The D_1 event (top-to-WNW thrusting) has caused the formation of several nappes in the KMC. The entire tectonic stack rests on top of the essentially unmetamorphosed Nowa Ruda Ophiolite and is unconformably covered by the younger sedimentary sequence of the Bardo Basin (Fig. 4).

Previous work

The protoliths of the KMC were assumed to be of Early Palaeozoic age since the discovery of a coralline and stromatoporoid fauna (Gunia and Wojciechowska 1964, 1971) in the crystalline limestone near Mały Bożków (Figs. 2, 3). This fauna, originally interpreted as Upper Silurian (Gunia and Wojciechowska 1964, 1971), was considered to document an Early Palaeozoic age for the whole KMC, based on the assumption that the entire

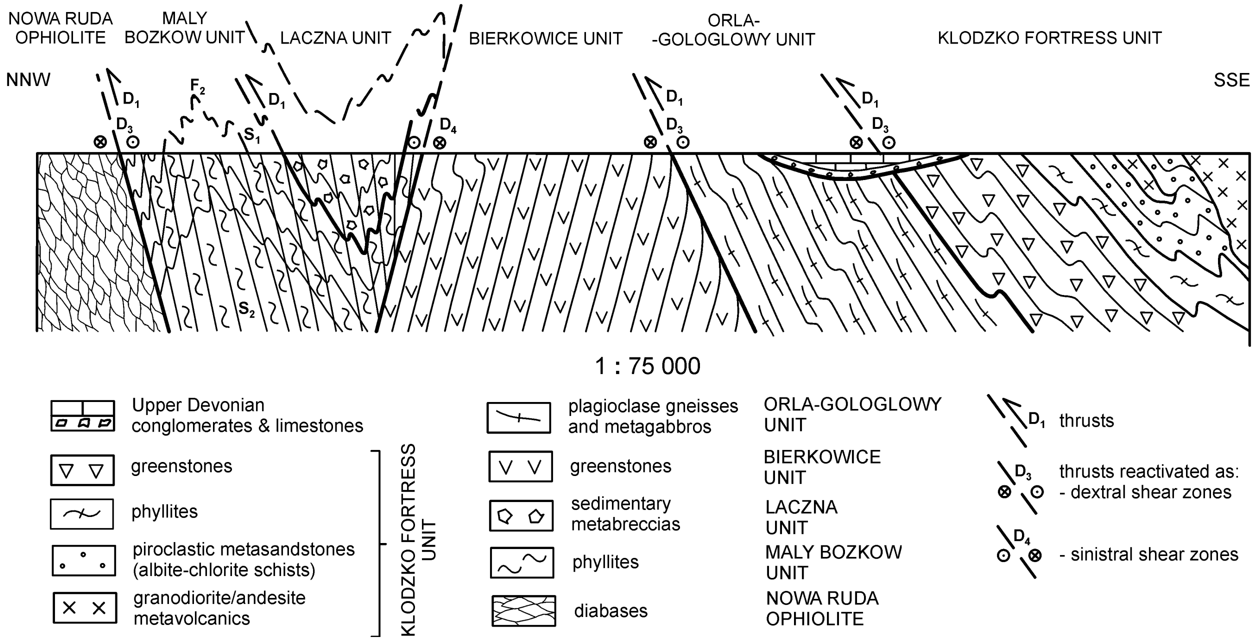


Fig. 4 Schematic NNW–SSE-oriented section across the Kłodzko Metamorphic Complex

KMC represents a continuous volcano-sedimentary succession (Narębski et al. 1988; Wojciechowska 1990). Subsequent re-interpretation of the Mały Bożków fauna as early Givetian (Middle Devonian) by Hladil et al. (1999) did not cause a significant modification of the interpretation that the KMC is built up by a structural coherent metamorphic succession. Due to the fact that the fossil-bearing limestone occurs near the base of the whole succession (Fig. 3), the entire KMC was considered as a condensed Middle–Upper Devonian sequence. However, recent work has clearly shown, that the KMC is built up by a stack of separate thrust units (Mazur and Kryza 1999; Mazur 2001, 2003; Aleksandrowski and Mazur 2002) and geochemical results (Kryza et al. 2003) also indicated derivation of particular tectonic units from contrasting tectonic settings.

The folded and metamorphosed rocks of the KMC are unconformably overlain by a non-metamorphosed, mostly calcareous sedimentary succession. Its late Frasnian–Fammenian age provides the upper time limit for the deformation of the KMC. For this reason, the folding of the KMC was believed to have occurred in Early Devonian times, as long as the Late Silurian age for the Mały Bożków limestone was presumed to be correct. Consequently, as already suggested by Bederke (1924, 1929), the KMC was considered to be a type locality for the influence of Caledonian tectonism on the structure of the Sudetes (Oliver et al. 1993; Johnston et al. 1994). In contrast, Hladil et al. (1999) claimed that deformation and metamorphism of the KMC took place in a narrow time window of ca. 10 Ma between the early Givetian and late Frasnian. These authors interpreted the time relationship in favour of an Early Variscan tectonic event, which preceded the Early Carboniferous final accretion of the Sudetic collage (cf. Aleksandrowski and Mazur 2002).

Field relationships and petrography of the studied rocks

Four representative samples were collected for geochronological studies from the two uppermost tectonic units of the KMC (Fig. 5). Three samples (SCI, GPL and K-163) were collected from the Orla-Gołogłowy Unit, whereas one sample (TKT) was derived from the Kłodzko Fortress Unit.

The GPL sample represents a typical variety of fine-grained, pale plagioclase gneiss, which forms thin intercalations within metagabbros. The studied sample was collected at the abandoned quarry on the northern slope of the Orla Hill (Fig. 5A) and is mainly composed of plagioclase, epidote, quartz, minor chlorite and calcite. Zircon and apatite occur as typical accessories. The plagioclase gneiss grades continuously into the neighbouring metagabbro.

The Ścinawka gneisses (samples SCI and K-163) form dykes (tens of centimetres to tens of metres in width), which cross cut amphibolites. They comprise various textural and mineralogical varieties. Depending on the amount of strain, a range from almost undeformed rocks of granitic texture, through augen gneisses, to highly deformed, streaky varieties and mylonites, were recognised. In some cases, the mineralogy is similar to that of an ordinary granite, but often these rocks contain calcic amphibole and garnet. The SCI sample represents a typical variety of the medium-grained Ścinawka gneiss exposed at the scarp of the river next to the water mill (Fig. 5C). It is composed of quartz, plagioclase, K-feldspar, epidote, biotite and minor amphibole, garnet, chlorite and opaque minerals. Zircon and monazite occur as accessories. Sample K-163 was collected from an outcrop in a small ravine north of Gołogłowy (Fig. 5D). It consists of quartz, plagioclase, epidote, garnet, chlorite and minor biotite, K-feldspar, white mica and opaque minerals (± zircon, tourmaline and titanite).

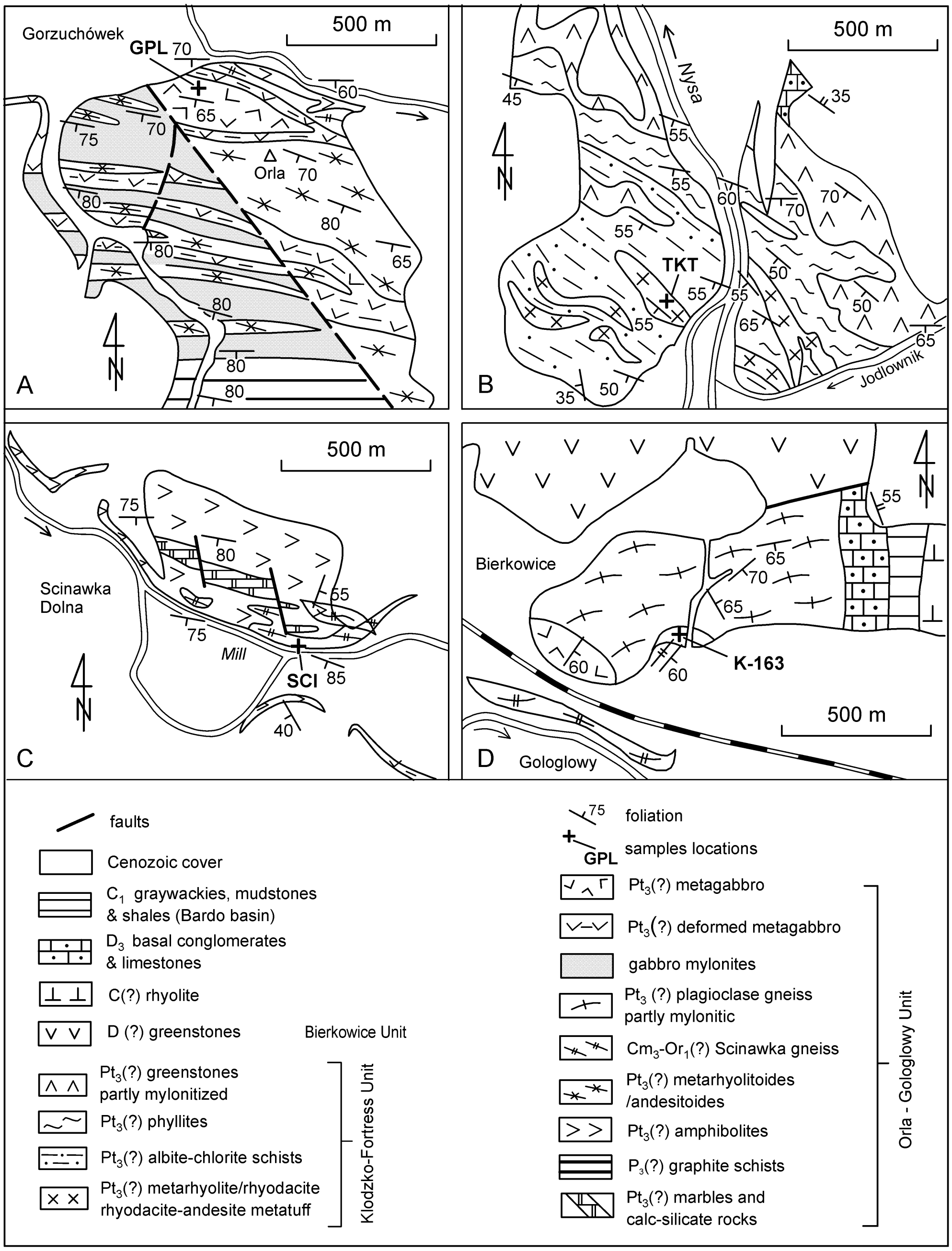
The Kłodzko Fortress Unit crops out on both sides of the Nysa river near Kłodzko (Fig. 2). It consists of a differentiated volcano-sedimentary succession with greenstones, phyllites, albite–chlorite schists and intermediate to acidic meta-volcanics. The geochemistry of the latter rocks indicates derivation from a subduction-related setting, as also observed for the meta-volcanic rocks from the Orla-Gołogłowy unit (Kryza et al. 2003). The middle section of the Kłodzko Fortress Unit is dominated by albite–chlorite schists with several intercalations of rhyodacites/dacites and andesites (Fig. 5B). These rocks form regular layers (tens of centimetres to several metres in thickness), which locally show continuous transitions into the surrounding schists. The volcaniclastic sedimentary rocks representing sample TKT are pale to pinkish rocks with porphyric texture and regular lamination. They are composed of quartz, plagioclase, K-feldspar, white mica and minor iron oxides. Common accessories are zircon and apatite.

Analytical procedures

Zircon concentrates were prepared at the Institute of Geological Sciences, Wrocław University. Rock samples were crushed using a jaw-crusher and disk mill, then sieved into different grain-size fractions. Heavy mineral concentrates were obtained using heavy liquids and a magnetic separator. Representative zircons from each rock were investigated by transmitted light microscopy. Secondary electron, cathodoluminescence and back-scattered electron images were made at the Polish Geological Institute (Warsaw) by use of a LEO 1430 Scanning Electron Microscope fitted with appropriate detectors. Identification of mineral inclusions were carried out with the aid of an EDS ISIS Oxford Instruments detector.

Final subdivision of zircon grains into fractions for U–Pb analyses was performed under a binocular microscope. Grains with cracks, visible cores, inclusions and turbid appearance were rejected. Some zircon fractions of samples SCI and K163 were air-abraded (Krogh 1982). The isotope analyses were performed at the Zentrallaboratorium für Geochronologie, Universität Münster. Zircon

Fig. 5 Geological sketch maps of the selected parts of the Kłodzko Metamorphic Complex (see Fig. 2 for their setting) to show location of analysed samples



fractions were loaded into Savillex containers, washed in 4 N HNO_3 in an ultrasonic bath and repeatedly rinsed with ultrapure water. Subsequent dissolution in steel-coated Teflon bombs and chemical extraction of U and Pb on anion exchange columns were carried out by procedures similar to those described by Krogh (1973). A ^{233}U–^{205}Pb-mixed spike was added to all samples for isotope dilution. For chemical separation of U a HCl–HNO_3 technique was applied. Purification of Pb is based on HBr–HCl chemistry. U and Pb were loaded with phosphoric acid and silica gel on single Re filaments and measured on a VG Sector 54 multicollector mass spectrometer in static mode, using Faraday cups and a Daly detector for ^{204}Pb. Total procedural blanks were less than 150 pg for Pb and 6 pg for U. Isotopic ratios of U and Pb were corrected for mass discrimination with a factor of 0.11% per a.m.u., based on analyses of standards NBS-SRM U-500 and NBS-SRM 982. For initial lead correction, isotopic compositions were calculated according to the model of Stacey and Kramers (1975). All ages and error ellipses were calculated using the Isoplot program, version 2.49 (Ludwig 1991), which uses the IUGS recommended decay constants (Steiger and Jäger 1977).

Zircon geochronology

SCI

The Ścinawka metagranite contains predominantly euhedral, transparent, colourless and normal-prismatic (mean elongation 2.56) crystals. In most zircons the {100} prism is better developed than the {110}, with the {101} bipyramid dominating over the {211} form. Some grains additionally have {301} bipyramids (Fig. 6a, b). BSE and CL imaging revealed oscillatory zonation that is characteristic of magmatic growth (Fig. 6). The rounded cores embedded in some zircons (ca. 17% of the population) represent an inherited component. Some of these cores display considerably weaker CL intensity than their mantle (Fig. 6e, f). The majority of zircons have inclusions that either occur as separate grains or as mineral aggregates, consisting of different phases. By use of EDS analyses apatite, quartz, K-feldspar, albite, biotite and Fe-oxide were identified as inclusions. Inclusion-rich grains as well as those with cores were avoided during grain selection for the isotopic analysis; however, it is possible that some of these grains have gone unnoticed during screening under the binocular.

The U–Pb results obtained for non-abraded (A-E) and abraded (ABR) grain fractions from the sample SCI all are discordant (Table 1). The most discordant fraction, also characterised by the lowest concentration of U, mainly consisted of yellowish crystals. Six fractions of this sample define a discordia line (MSWD=1.6) with an upper intercept at 500.4±3.1 Ma (Fig. 7a) This age is interpreted to reflect the timing of crystallization from a melt and indicates the protolith age for the Ścinawka metagranite. The ^{207}Pb/^{206}Pb ages range between 503 and 513 Ma (Table 1); the weighted average is 505.8±3.1 Ma and overlaps within error with the upper intercept age. Two explanations may account for the negative value of the lower intercept (–62±37 Ma; not shown in Fig. 7a). (1) The six data points provided a relatively small spread in isotopic ratios and cluster at the higher end of the discordia line. As a consequence, the upper intercept is well anchored and of geological significance, whereas the lower intercept only is vaguely defined. (2) The studied zircon fractions may comprise some grains with an inherited component, which caused different concordant and nearly concordant starting points before the lead loss event. Different degrees of subsequent lead loss may have caused a negative lower intercept without significantly influencing the geological relevance of the upper intercept.

K-163

In contrast to the SCI concentrate, the zircon population of sample K-163 comprises a larger number of coloured, yellowish or brownish, subhedral grains, often with cloudy appearance. Zoned crystals with inherited cores are much less abundant (ca. 4% of population) than in the SCI sample. Most grains are short prismatic (mean elongation 1.85) and are dominated by high proportions of the P-subtype, with only one bipyramid {101} and with the prism{100} better developed than {110} (Fig. 8a, b). Zircons with the {211} form are rare. Crystals show primary oscillatory (magmatic) zoning and superimposed secondary structures due to incipient recrystallisation (Fig. 8c–f). A characteristic feature is a generally weak cathodoluminescence. The zircons may contain inclusions of apatite, quartz and albite. Ten fractions were prepared and all of them yielded discordant results. A corresponding regression line provided an upper intercept at 500.2±4.9 Ma (MSWD=2.6; Fig. 7b) and a lower intercept at present (–2±54 Ma), indicating the protolith age and recent lead loss. The abundant occurrence of recrystallised zircons in the concentrate apparently has not greatly influenced the age, which overlaps within error with the result for sample SCI.

GPL

Zircons are mainly euhedral, clear, colourless to light yellow, short prismatic with magmatic oscillatory zoning. Most crystal morphologies are combinations of the {100}, {110}, {101} forms. Some prismatic zircons possess well-developed pyramids {211}. Such grains were grouped separately (fraction C). All studied zircon fractions are discordant (Table 1). Four data points cluster close to the upper intercept. One data point (GPL-D) was affected by severe lead loss. All fractions define a regression line (MSWD=0.53) with an upper intercept age of 587.1±2.4 Ma (Fig. 9a). This discordia line provides a negative lower intercept (–44±2.6 Ma, not shown in Fig. 9a). For regression without GPL-D, an upper intercept age of 590.1±7.2 Ma (MSWD 0.31) was obtained (Fig. 9b). In this case, the lower intercept age is 46±170 Ma. Within error, the upper intercept ages can not be distinguished and are considered to be geologically meaningful, indicating the crystallisation age of the magmatic precursor. Both the negative intercept (with GPL-D) and the very high uncertainty on the positive intercept (without GPL-D) are related to the fact that the regression line is mainly anchored around the upper intercept (four fractions with ^{207}Pb/^{206}Pb ages between 586 and 590 Ma) and is poorly defined towards the lower end by a highly discordant zircon fraction with a significantly different ^{207}Pb/^{206}Pb age (722 Ma), possibly affected by inheritance.

TKT

This meta-volcaniclastic rock contains a mixture of genetically distinct zircon grains. Seven fractions of zircon were selected according to colour and morphology (Table 1). Three fractions consisted of colourless, euhedral crystals with magmatic zonation. The zircons were prismatic with the {100} form better developed than {110}

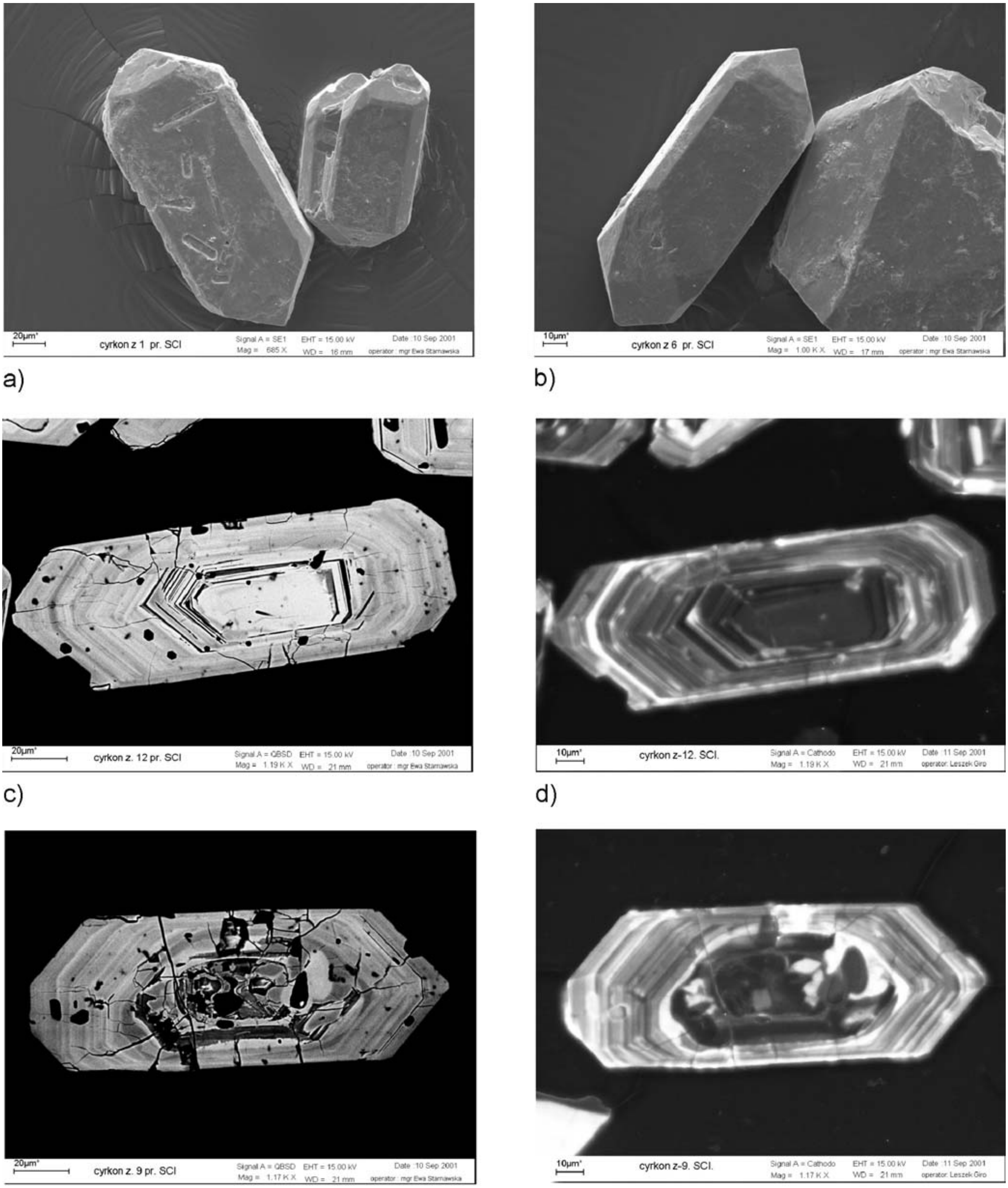


Fig. 6 SEM images of representative zircon crystals from the SCI sample: **a, b** typical morphologies of crystals with {100} dominating over {110} and {101} better developed than {211}. Note presence of the{301} bipyramid in some crystals; **c, d** BSE and CL images of zircon with typical magmatic oscillatory zoning; **e, f** BSE and CL images of crystal with rounded core showing low CL intensity, mantled by oscillatory zoned zircon

Table 1 U–Pb analytical results for zircons from Ścinawka metagranite (SCI, K163), plagioclase gneiss (GPL) and volcaniclastic metasediment (TKT). *c* Colourless; *y* yellow; *p* pink; *lp* long-prismatic; *np* normal-prismatic; *sp* short-prismatic; *a* air-abraded; *w* width in μm

Sample name	Description	Concentrations[a]		Measured isotope ratios				Corrected isotope ratios				Apparent age (Ma)			rho
		U (ppm)	Pb (ppm)	206/204	208/206	207/206	±2σ	207/235	±2σ	206/238	±2σ	^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb	
SCI-A 3923	c,np,w:30–45	851	60	1,581	0.0815	0.05742	0.00008	0.5633	0.0020	0.07115	0.00022	443.1	453.7	507.7	0.91
SCI-D 3924	c,np+lp,w:50–75	409	29	3,684	0.0767	0.05731	0.00007	0.5711	0.0020	0.07227	0.00023	449.8	458.7	503.5	0.92
SCI-B 3925	c,np+lp,w:60–100	436	31	3,626	0.0774	0.05742	0.00007	0.5644	0.0019	0.07128	0.00023	443.9	454.4	507.8	0.93
SCI-C 3926	c,np,w:110–140	217	16	2,007	0.0738	0.05736	0.00007	0.5741	0.0020	0.07259	0.00023	451.8	460.7	505.4	0.92
SCI-E 3927	y,np+sp,w:110–160	40	3	556	0.0681	0.05756	0.00013	0.5390	0.0022	0.06791	0.00022	423.5	437.7	513.2	0.82
SCI-B2 3962	c,np,a,w:80–120	106	8	2,830	0.0783	0.05730	0.00007	0.6196	0.0021	0.07843	0.00025	486.8	489.6	503.0	0.93
K163-A 3880	y,sp+np,w:120–130	1,113	89	475	0.0718	0.05705	0.00015	0.5712	0.0029	0.07261	0.00030	451.9	458.8	493.6	0.85
K163-B 3881	c,np+sp,w:90–110	1,089	84	1,612	0.0747	0.05715	0.00008	0.6046	0.0018	0.07673	0.00020	476.6	480.2	497.4	0.87
K163-E 3883	c,np+sp,w:70–90	979	80	1,068	0.0766	0.05730	0.00009	0.6365	0.0033	0.08056	0.00040	499.5	500.1	503.1	0.95
K163-D 3884	c,np+lp,w:20–40	1,400	100	702	0.0824	0.05737	0.00012	0.5535	0.0022	0.06997	0.00023	436.0	447.3	505.7	0.84
K163-A2 3918	y,sp+np,w:120–130	159	11	472	0.0734	0.05727	0.00015	0.5187	0.0022	0.06568	0.00021	410.1	424.3	502.1	0.79
K163-B2 3919	c,np+sp,w:100–130	225	17	1,236	0.0748	0.05723	0.00009	0.5740	0.0020	0.07275	0.00023	452.7	460.6	500.4	0.90
K163-E2 3920	c,np,w:70–90	357	27	842	0.0751	0.05725	0.00010	0.5818	0.0021	0.07370	0.00023	458.4	465.6	501.2	0.87
K163-C2 3921	c,np+sp,w:60–80	720	54	1,182	0.0773	0.05715	0.00009	0.5792	0.0021	0.07350	0.00024	457.2	463.9	497.5	0.90
K163-D2 3922	c,np+lp,w:20–40	1,921	149	600	0.0825	0.05724	0.00012	0.5766	0.0023	0.07307	0.00023	454.6	462.3	500.6	0.83
K163-S2 3958	c,np+sp,a,w:50–80	3,140	244	1,605	0.0784	0.05727	0.00008	0.6163	0.0021	0.07804	0.00025	484.4	487.5	502.0	0.91
GPL-A 3905	clrs,sp,w:100–130	439	39	549	0.0518	0.05951	0.00017	0.7323	0.0033	0.08924	0.00029	551.1	557.9	586.0	0.76
GPL-B 3906	c,sp,w:80–100	78	7	1,427	0.0419	0.05958	0.00010	0.7573	0.0028	0.09219	0.00029	568.5	572.5	588.5	0.88
GPL-C 3907	c,np,w:60–100	131	12	670	0.0431	0.05960	0.00013	0.7685	0.0031	0.09351	0.00030	576.3	578.9	589.2	0.83
GPL-D 3908	c,np,w:50–70	3,841	65	1,369	0.0437	0.06340	0.00021	0.1654	0.0010	0.01892	0.00009	120.8	155.4	721.7	0.85
GPL-E 3909	c,np+lp,w:20–50	357	32	382	0.0423	0.05963	0.00021	0.7382	0.0039	0.08979	0.00030	554.3	561.3	590.1	0.74
TKT-A 3897	c,np,w:100–140	41	4	546	0.0974	0.05979	0.00015	0.7148	0.0030	0.08672	0.00028	536.1	547.6	595.9	0.81
TKT-C 3899	c,sp+np,w:90–120	113	10	960	0.1066	0.05966	0.00011	0.7118	0.0026	0.08653	0.00027	535.0	545.8	591.3	0.87
TKT-D 3900	c,sp+eq,w:120–150	33	3	500	0.0852	0.05994	0.00016	0.7333	0.0032	0.08872	0.00029	548.0	558.5	601.6	0.78
TKT-E 3901	p,np,w:50–60	565	182	2,443	0.0425	0.12620	0.00014	5.5074	0.0185	0.31652	0.00100	1,772.7	1,901.7	2,045.6	0.94
TKT-F 3902	p,np+sp,w:90–110	96	33	3,709	0.0495	0.12715	0.00014	5.9604	0.0199	0.33998	0.00107	1,886.6	1,970.1	2,058.9	0.94
TKT-G 3903	p,np+sp,w:60–80	27	7	2,438	0.0466	0.12261	0.00014	4.5459	0.0160	0.26890	0.00089	1,535.2	1,739.4	1,994.6	0.94
TKT-H 3904	y,np+sp,w:120–160	192	20	681	0.0814	0.07567	0.00013	1.0321	0.0038	0.09892	0.00032	608.1	720.0	1,086.3	0.88

[a] Concentrations are approximate values with a high degree of uncertainty, because exact sample weights were not determined but roughly estimated from size, morphology and number of grains

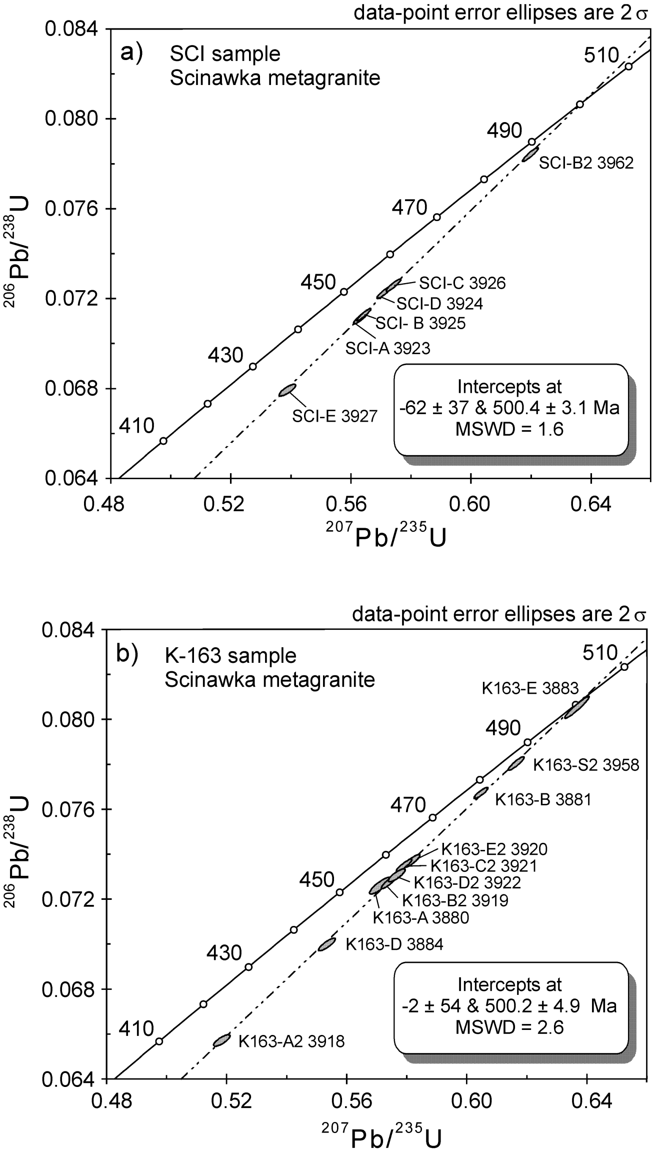


Fig. 7 Concordia diagrams showing U–Pb data for **a** SCI and **b** K-163 samples from the Orla-Gołogłowy Unit

and {101} was at least equal to the steep pyramid{211}. One fraction TKT-H 3904 contained yellow euhedral grains and three fractions comprise pink grains with rounding related to transport. The morphology of the pink grains was dominated by {110} prism and {211} pyramid.

All fractions yielded discordant results (Fig. 10a). Application of zircon multigrain dating for detrital zircons can at best only provide broad time constraints. The pink detritic zircons yielded ages exceeding 2 Ga (Fig. 10b). In case of a heterogeneous mixture, this result indicates a minimum age for the oldest component. The fraction consisting of yellow euhedral grains gave a ^{207}Pb/^{206}Pb date of ca. 1,100 Ma with unknown geological significance. The colourless euhedral zircon fractions provided fairly consistent ^{207}Pb/^{206}Pb ages around 590–600 Ma (Table 1) defining a likely maximum age of protolith deposition, probably corresponding to the time of volcanic activity.

Summary of results

The SW part of the Kłodzko Metamorphic Complex comprises Neoproterozoic crust included into two separate thrust sheets: the Orla-Gołogłowy and Kłodzko Fortress units occupying the uppermost structural position in the nappe pile. The Orla-Gołogłowy Unit consists mostly of a meta-igneous plutonic suite, including metagabbros, amphibolites, felsic subvolcanic dykes and plagioclase gneisses probably derived from the basement of a back-arc basin. The magmatic protolith of the plagioclase gneiss intimately associated with metagabbros is dated at 590.1±7.2 Ma. The Kłodzko Fortress Unit comprises a volcano-sedimentary succession probably developed in a basin bordering a volcanic arc. Syn-sedimentary inliers of volcaniclastic rocks of rhyodacite/andesite composition suggest an age of approximately 590–600 Ma. The Orla-Gołogłowy Unit was intruded by granitic dykes subsequently transformed into the Ścinawka gneiss. Two samples collected at different locations yielded similar ages of 500.4±3.1 and 500.2±4.9 Ma.

Discussion and conclusions

The results of this study indicate the occurrence of Neoproterozoic successions in the SW part of the KMC. According to Kryza et al. (2003) these occurrences have a supra-subduction zone origin. Rock complexes of similar age and provenance have previously not been recognised in the Sudetes, but are known from the Saxothuringian and Tepla-Barrandian zones of the Bohemian Massif (Fiala 1977; Linnemann et al. 2000), as well as from the Brno Massif (Finger et al. 2000). The origin of these occurrences, including the KMC, is in accord with models, which suggest Neoproterozoic subduction of an oceanic domain beneath the active Gondwana margin (Nance and Murphy 1996).

The Neoproterozoic age of meta-igneous and volcano-sedimentary successions from the SW part of the KMC explains their divergent geochemical characteristics compared with the other volcano-sedimentary successions of the Sudetes. The latter developed between the Cambrian and the Devonian in extensional tectonic settings on the outer edges of terranes rifted away from the northern Gondwana margin (Winchester et al. 2002).

Our data confirm the influence of Early Ordovician magmatic activity on the evolution of the KMC. Granitoid magmatism of this age is widespread in the Sudetes (Oliver et al. 1993) and the entire Variscan belt (cf. Aleksandrowski et al. 2000). No consensus has been reached so far concerning the origin of this magmatic activity, which has been related either to subduction zone processes (Oliver et al. 1993; Kröner and Hegner 1998) or to rift-related settings (Kryza and Pin 1997). The new

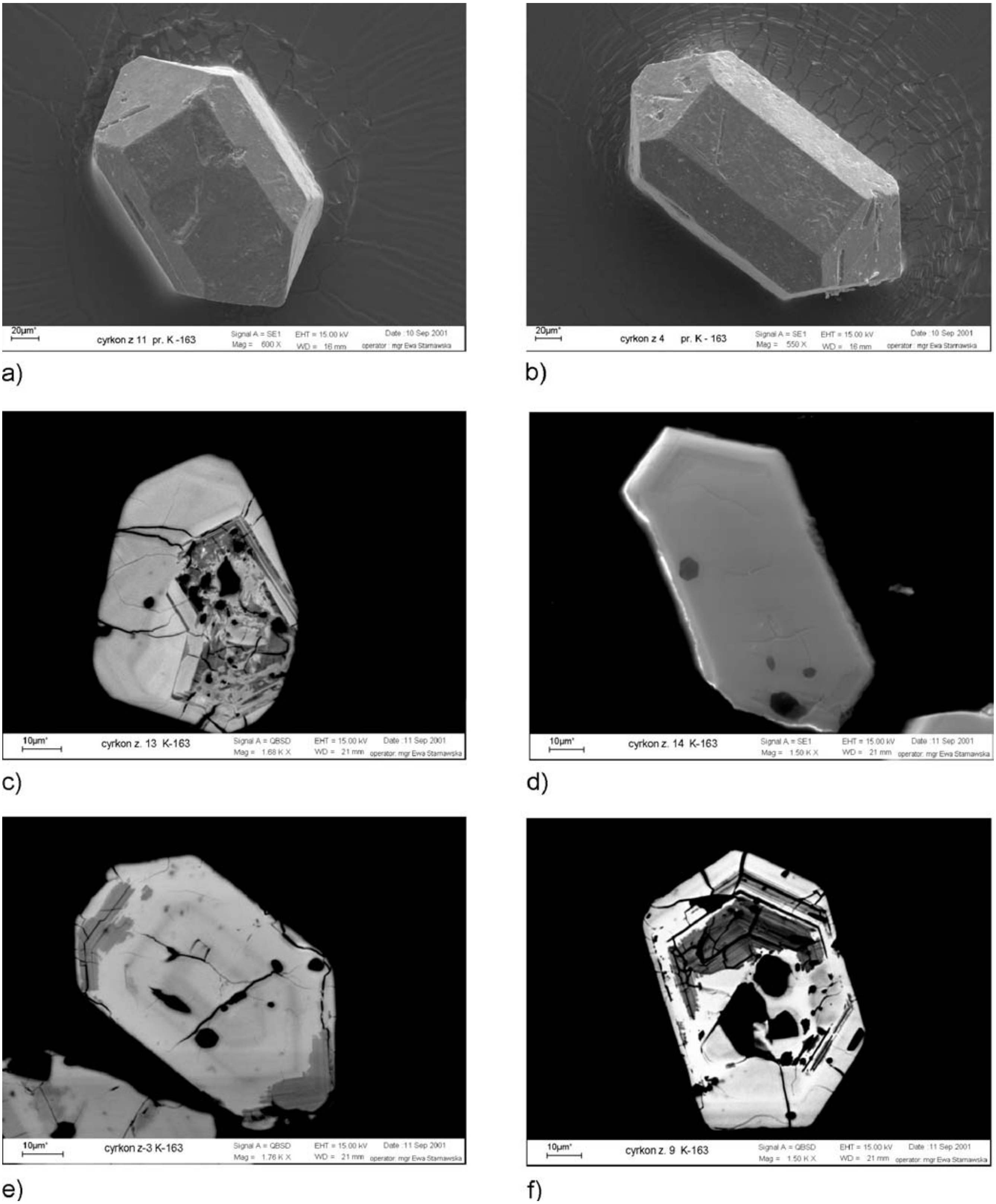


Fig. 8 SEM images of representative zircons from the GPL sample: **a, b** typical prismatic zircons with dominating {100} terminated by {101} bipyramid; **c–f** BSE images of zircons with recrystallised crystal domains

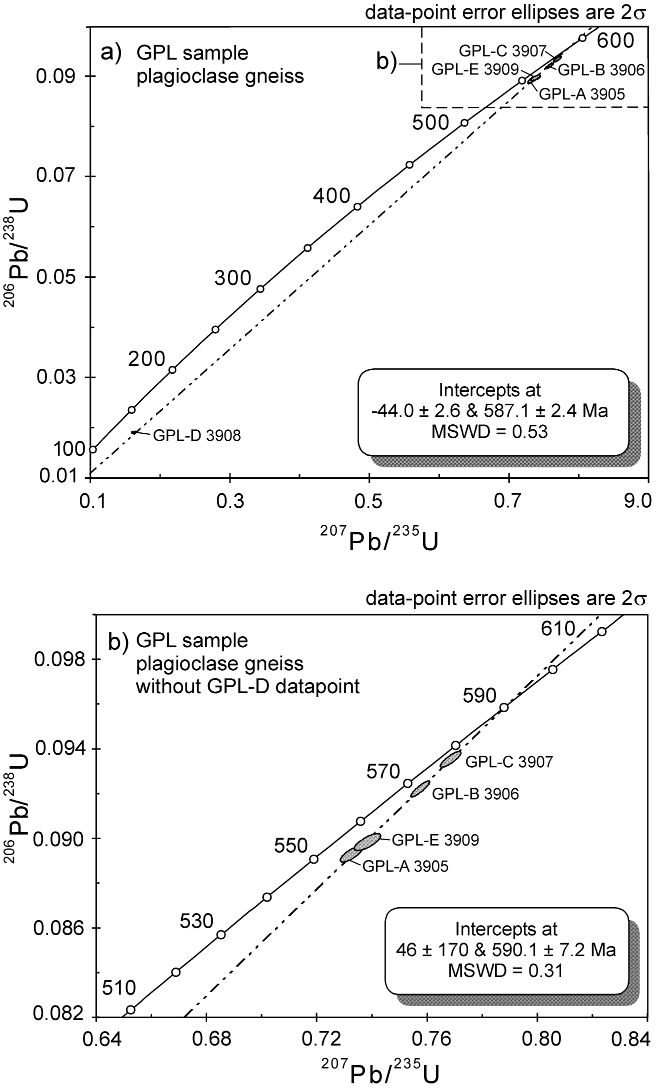


Fig. 9 Concordia diagrams showing U–Pb data for GPL sample from the Orla-Gołogłowy Unit: **a** all data points, **b** regression without GPL-D data point affected by severe lead loss

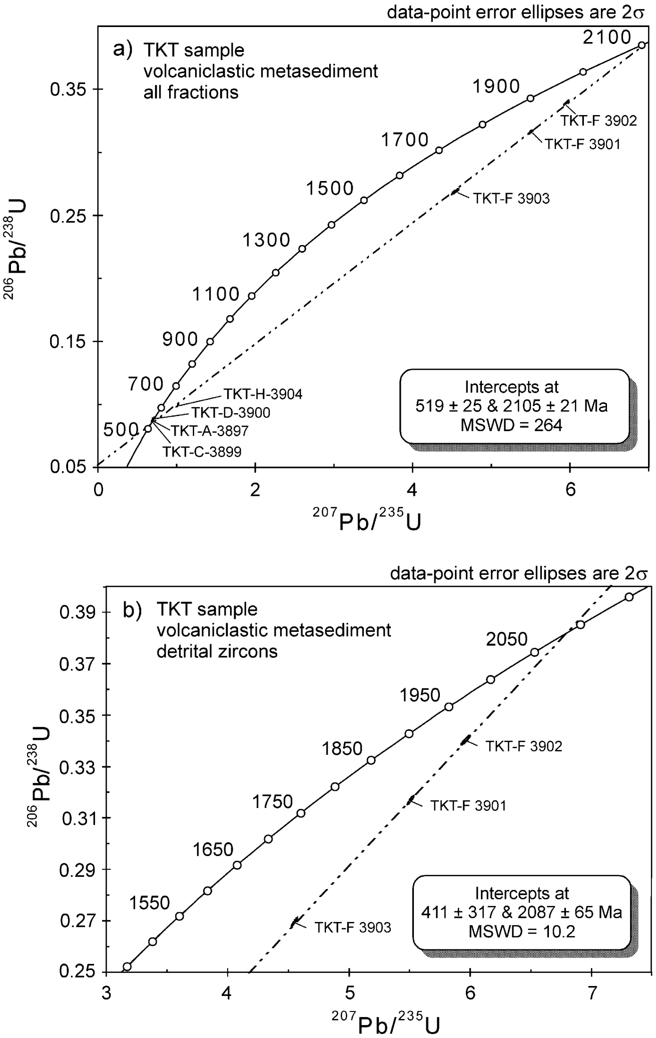


Fig. 10 Concordia diagrams showing U–Pb data for TKT sample from the Kłodzko Fortress Unit: **a** all data points, **b** three zircon fractions interpreted as detrital grains. The *lower intercepts in both diagrams* are considered as geologically meaningless

results from the KMC justify the conclusion that the Early Palaeozoic plutonism, despite its setting, is a common feature of the Sudetic pre-Variscan basement.

The documentation of Neoproterozoic protoliths for the SW part of the KMC, combined with the Late Devonian age of their exhumation, suggests affinities to the Teplá-Barrandian, as already postulated in the terrane model of Matte et al. (1990). Continuation of the Teplá-Barrandian terrane into the West Sudetes, originally suggested by Malkovský (1979) and Chaloupský et al. (1995), is supported by results of this study which put new constraints on the terrane reconstructions in the Bohemian Massif (e.g. Aleksandrowski and Mazur 2002).

The KMC exemplifies the complex magmatic evolution of the different terranes presently comprised in the Variscan belt. Its Neoproterozoic succession was originally developed by Cadomian subduction beneath the northern Gondwana margin. The Neoproterozoic crust was subsequently intruded by granitoid bodies at the turn of the Cambrian and Ordovician. This magmatic event was probably related to the ongoing Early Palaeozoic terrane dispersion. The crystalline basement of the KMC was subsequently onlapped by the Early Palaeozoic to Devonian volcano-sedimentary succession, which developed on a passive continental margin (Fig. 11). The latter is probably represented by tectonic units comprised in the NE part of the KMC, despite the fact that their Palaeozoic age is only partly documented. At the turn of Middle and Late Devonian times, the protoliths of the KMC, including both the Neoproterozoic, mostly igneous suites and their Palaeozoic volcano-sedimentary cover, must have been tectonically juxtaposed (Fig. 11). By the end of the Late Devonian, the tectonic units were exhumed as a nappe pile and, finally, thrust over the adjacent Nowa Ruda ophiolite.

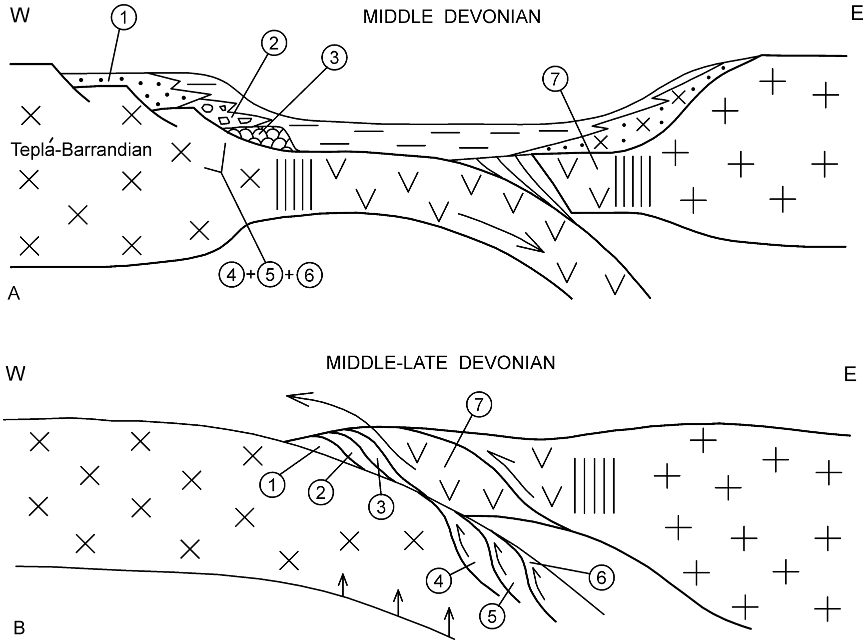


Fig. 11 Evolution of the Kłodzko Metamorphic Complex in Devonian. *1* Mały Bożków Unit; *2* Łączna Unit; *3* Bierkowice Unit; *4* Ścinawka Unit; *5* Orla-Gołogłowy Unit; *6* Kłodzko Fortress Unit; *7* Nowa Ruda Ophiolite. **A** Pre-collisional stage: protoliths of the Mały Bożków, Łączna and Bierkowice units are comprised in the volcano-sedimentary succession of the passive continental margin; **B** collisional stage: obduction of the ophiolite and subsequent nappe stacking are induced by uplift of the earlier subducted continental crust

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