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Granitoids of the Odra Fault Zone: late- to post-orogenic Variscan intrusions in the Saxothuringian Zone, SW Poland

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Abstract There are 5 occurrences of granodioritic to monzogranitic rocks found subsurface along the Odra Fault Zone a Permo-Mesozoic horst defining the northeastern edge of the Bohemian Massif. These are generally unfoliated, I-type granitoids with low A/CNK and initial Sr/Sr ratios making them geochemically and petrographically akin to late- to post-kinematic Variscan granitoids of the West Sudetes, being closest to those of the eastern part of the Fore-Sudetic Block (Strzelin, Niemcza). They represent late/post-orogenic, collisional intrusives of Early-Late Carboniferous age which are widespread throughout the Saxothuringian and Moldanubian zones in the Bohemian Massif. The country rocks to the granitoids are mica schists and paragneisses attaining staurolite-grade. The granitoids lack evidence of ductile or brittle strike-slip movement of Late Carboniferous–Permian age along the Odra Fault Zone, which thus has to be taken as a dip-slip fault zone, rather than a late Variscan dextral strike-slip feature. Brittle to semi-brittle deformation of the Odra granitoids relates to the formation of the horst during Permo-Mesozoic times. A Silurian–Early Devonian magmatic arc of the Mid-German Crystalline Rise, identified further to the west in Germany, probably does not have an easterly prolongation into Poland because there is no evidence for arc-related magmatism of that age in the Sudetes and Fore-Sudetic Block.

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INTRODUCTION

In the northeastern part of the Bohemian Massif, the crystalline rocks exposed in the Sudetes continue under the Cenozoic cover across the Sudetic Marginal Fault into the Fore-Sudetic Block and reach the Odra Fault Zone, which defines the northeastern boundary of the massif (Don & Żelaźniewicz, 1990; Żelaźniewicz *et al.*, 1997). As elsewhere in the Bohemian Massif, they include here a large number of late to post-orogenic, generally fabricless, 340–300 Ma Variscan granitoid bodies. Of these only a few are characterized by the presence of pronounced magmatic (e.g. Niemcza granodiorite) or subsolidus foliations (e.g. Stare Mesto tonalite) due to syn- to post-intrusive shearing. Small granitoid bodies found subsurface within the NW-trending Odra Fault Zone and immediately to the south of it are particularly abundant (Fig. 1). Their relative abundance there allows them to be distinguished as 'the granitoids of the Odra Fault Zone' ('the Odra granitoids' in short). It is disputable whether they should be compared with the intrusives of the Saxothuringian Zone or specifically only with those of the Mid-German Crystalline Rise occurring further west. This paper, based on the petrologic and geochemical characteristics of the Odra granitoids and the first results of Rb-Sr isotopic datings, also addresses this dilemma.

THE ODRA FAULT ZONE

The Odra Fault Zone is a 10–20 km wide and 180–200? km long horst of basement rocks of unknown age, widening to the southeast, found by numerous drillings under the Cenozoic cover between Gubin and Olawa (Fig. 1). It came into being during the Late Carboniferous and Permian block movements in the region. On its northern side, the basement is discretely downthrown and deeply hidden under the Permo-Carboniferous and Mesozoic

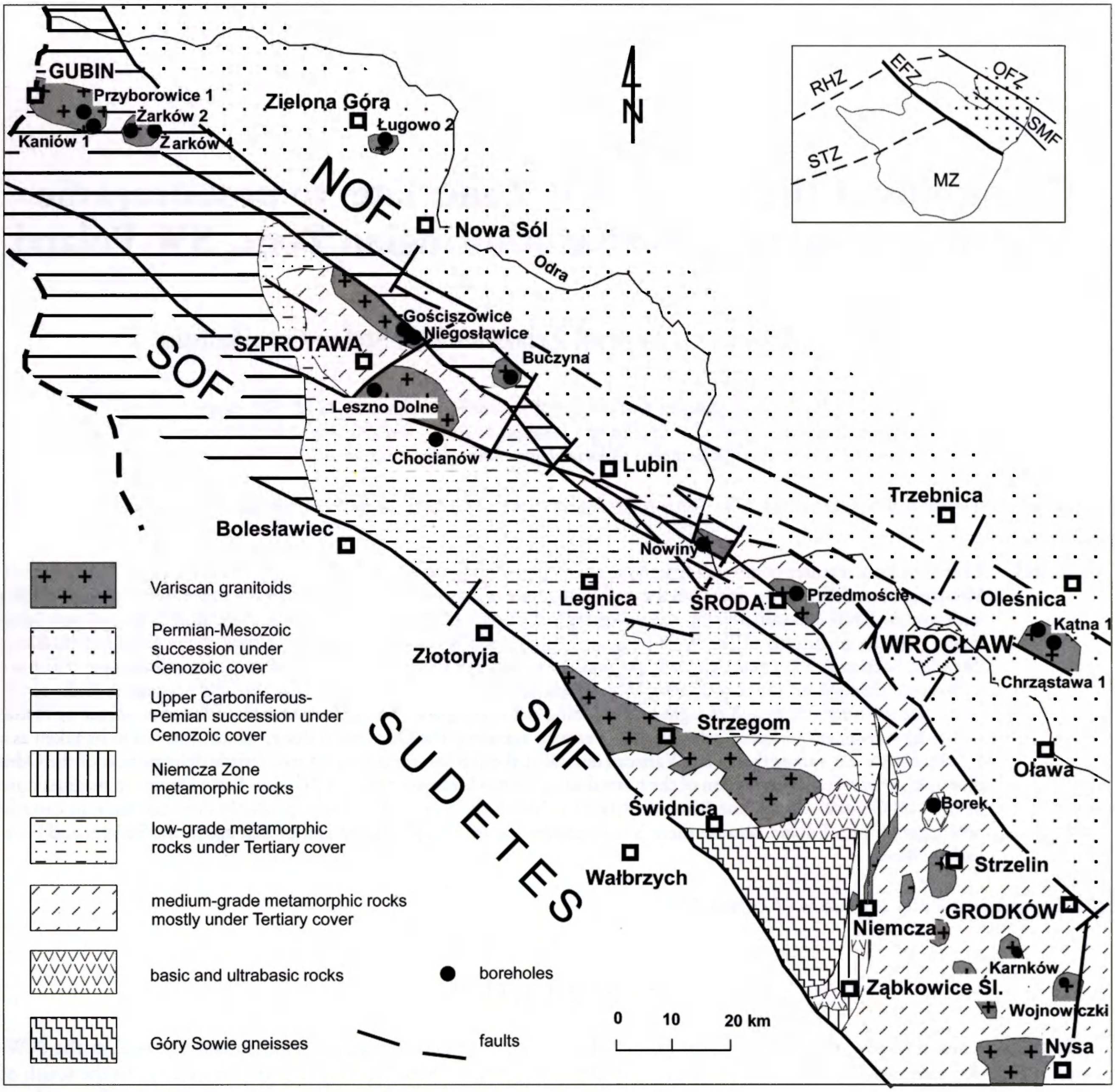

Fig. 1. Geologic sketch of the Fore-Sudetic Block to locate granitoids of the Odra Fault Zone.

strata of the Fore-Sudetic Monocline. The boundary fault which is marginal to the monocline is referred to as the northern Odra fault (Fig. 1; Żelaźniewicz & Cwojdziński, 1994). It is not equivalent to the poorly defined Silesian-Lubushian fault (Oberc, 1972) assumed to stretch from Nowa Sól to Oleśnica and to separate supposedly Proterozoic rocks from Lower Palaeozoic ones, all lacking any age determinations. The other border of the horst is defined by the southern Odra fault (Fig. 1; Żelaźniewicz & Cwojdziński, 1994), which is equivalent to the Middle Odra fault of Oberc (1972).

Most of the metamorphic rocks elevated in the horst of the Odra zone markedly differ by their higher metamorphic grade and type of lithologic associations from the adjacent low-grade metapelites and metabasites of the Kaczawa succession, which continue to the Fore-Sudetic Block from the Góry Kaczawskie (Jerzmański, 1975, 1991; see Cwojdziński & Żelaźniewicz, 1995). Such differences led Oberc (1972, 1978) to distinguish the rocks within this horst as the Middle Odra metamorphic unit. However, they are comparable with rocks outcropping in the eastern part of the Fore-Sudetic Block. A lack of more discriminating details allows all these medium to high grade rocks to be assigned to one lithostratigraphic unit referred to as the Fore-Sudetic complex (Cwojdziński & Żelaźniewicz, 1995; Fig. 1). The Fore-Sudetic complex forms along with other metamorphic complexes of the Sudetes and of the Fore-Sudetic Block form the eastern part of the Saxothuringian Zone (Franke *et al.*, 1993; Franke & Żelaźniewicz, 1997). Within this zone there are numerous late- to post-orogenic 340–300(280) Ma Variscan granitoids. The eastern outcrops of the Fore-Sudetic complex embrace a wide array of relatively small, post-orogenic granite bodies stretching from Strzelin in the north (Oberc-Dziedzic, 1988, 1991) to Žulova in the south and broadly marking the boundary between the Saxothuringian Zone and the Moravo-Silesian Zone (Cwojdziński & Żelaźniewicz, 1995). The Fore-Sudetic complex elevated in the horst of the Odra Fault Zone is particularly riddled with small granitoid bodies. Their relative abundance there justifies them being termed the granitoids of the Odra Fault Zone.

DISTRIBUTION AND PETROGRAPHY OF GRANITOIDS

The small granitoids bodies drilled in several places along the Odra Fault Zone were grouped into five occurrences, which are probably not linked with one another, at least within the uppermost crust. From the NW to SE these are: the Gubin, Szprotawa, Środa Śląska, Wroclaw and Grodków granitoids, each consisting of at least two subcropping bodies (Fig. 1; see Sachanbiński, 1980). The mineral composition of these rocks is shown in Table 1.

THE GUBIN GRANITOIDS

The northwesternmost Gubin granitoids, which may unite at greater depth into one body, occur at the NE tip of the Żary anticlinorium (Milewicz & Kornaś, 1971; Górecka *et al.*, 1977). They are known from 5 boreholes: Guben 2 (2497–2537 m; Möbus & Unger, 1967), Przyborowice 1 (1475.0–1477.7 m) and Kaniów 1 (1382.5–1393.0 m) some 10–12 km east of Gubin, and Żarków 2 (930.0–994.1 m) and Żarków 4 (1040.2–1059.7 m) located 28 km ESE of Gubin. The granite drilled in the Ługowo 2 borehole (2846.2–2847.3 m) 8 km S of Zielona Góra may either be-

Table 1

Mineral composition of the Odra Fault Zone granitoids (in volume percent)

Mineral	Granodiorite Guben 2[1]	Granodiorite Przyborowicce 1[2] 1476.0 m	Monzogranite Niegoslawice 1/II[3] 380.0 m	Granodiorite Niegoslawice 1/III[3] 399.3 m	Granodiorite Leszno Dolne 2/II[3] 267.5 m	Monzogranite Leszno Dolne 2/II[3] 280.0 m	Granodiorite Nowiny[4] ~300 m	Granodiorite Przedmoście 4/IV[5] 250.0-268.3 m
Quartz	27.5	20-25	24.8	21.0	14.7	16.7	15.0	12.8
K-feldspar	11.0	40-60	20.7	23.7	11.4	16.3	20.0	23.4
Plagioclase	46.0	20-30	36.4	27.5	37.7	27.2	30.0	35.9
Biotite	15.5	10.0	15.4	9.6	20.9	15.9	13.0	8.2
Hornblende				16.5	15.0	23.1	12.0	15.1
Chlorite							9.0	3.6
Calcite			2.4					
Others			0.4	1.6	1.0	0.9	0.8	1.0

	Granodiorite Przedmoście 4/IV[5] 280.6-300.8 m	Granodiorite Kątna 1[4] 660.0-1791.3m	Granodiorite Chrząstawa[4] 1470.0-1538.0 m	Granite Karnków[5] 265.5 m	Tonalite Wojnowiczki[5] 228.8 m	Quartz diorite Wojnowiczki[5] 274.0 m	Granodiorite Wojnowiczki[5] 308.4 m
Quartz	12.2	20.7	8.0	30.6	14.8	15.8	30.9
K-feldspar	23.0	22.6	17.8	31.2	0.2	6.8	18.2
Plagioclase	31.8	38.2	37.0	33.4	52.3	60.6	42.3
Biotite	11.2	10.7	15.8	4.8	17.6	16.3	8.6
Hornblende	18.6	6.5	17.6		12.1		
Chlorite	2.4	0.4	1.4				
Calcite		0.3	1.4				
Others	0.8	0.6	0.9		3.0	0.5	

[1] Möbus & Unger, 1967; [2] Juroszek in Górecka *et al.*, 1977; [3] Majerowicz, 1974; [4] Juroszek, 1977, vide Sachanbiński, 1980; [5] Morawski, 1974

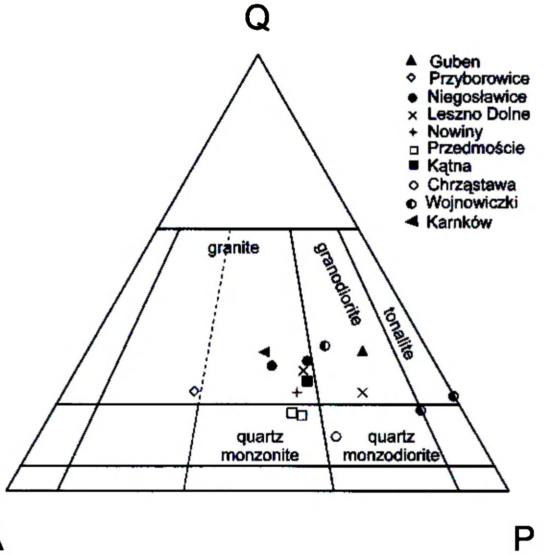

Fig. 2. Systematics of the Odra Fault Zone granitoids on QAP plot. Data from Möbus & Unger, (1967) for Guben 2; Cz. Juroszek in Górecka *et al.* (1977) for Przyborowice; Majerowicz (1974) for Niegosławice and Leszno Dolne; C. Juroszek in Kłapciński *et al.* (1975) for Nowiny, Kątna 1 and Chrząstawa 1; Morawski (1974) for Przedmoście, Karnków and Wojnowiczki.

long to the Gubin granitoids, or form an independent body off the Odra Fault Zone (Fig. 1).

The Guben 2 granodiorite (Fig. 2) is a dark grey, medium-grained rock composed of K-feldspar, plagioclase, quartz and biotite. A quartz-biotite hornfels occurs below the granodiorite at a depth of 2537–2550 m (end of drilling).

The Przyborowice granite (Fig. 2) is a pinkish, medium-grained (up to 3 mm) rock, occasionally porphyritic, with no preferred mineral orientation. It consits of plagioclase (An_{8-12}); Milewicz & Kornaś, 1971), sericitized K-feldspar, chloritized biotite and amphibole, with minor epidote, apatite and zircon (Fig. 3).

The Kaniów 1 granite (C. Juroszek in Górecka *et al.*, 1977) is a medium-grained rock composed of K-feldspar, plagioclase, quartz and biotite. Xenomorphic K-feldspar

Fig. 3. The Przyborowice granite. Black area in the middle between K-feldspar and zoned plagioclase crystals is hornblende replaced by an aggreagte of chlorite and calcite. Scale bar 1 mm.

grains, up to 6 mm across, include biotite, quartz and plagioclase. Less common and smaller oligoclase (to albite) crystals are often automorphic. The rock is cataclased, with strongly fractured and altered K-feldspar, and biotite wholly replaced by chlorite and Fe-oxides.

The Żarków granite is porphyritic, with dark pink perthitic phenocrysts of K-feldspar 8–12 mm long, riddled with plagioclase inclusions and surrounded by white plagioclase rims. The groundmass is composed of small K-feldspar grains, zonal plagioclase (cores of 25% An; see C. Juroszek in Górecka *et al.*, 1977) and quartz. Dark minerals are represented by biotite and hornblende, whereas zircon, apatite and rutile are accessory minerals.

The Lugowo granite is a grey-pinkish, fine-grained, cataclased rock (see Cz. Juroszek in Kłapciński *et al.*, 1975). Phenocrysts of xenomorphic microcline are rare and up to 1 mm across. Plagioclase (An_{18}) occurs as automorphic, often albitized crystals. Albite also forms independent grains dominating over the oligoclase. Biotite is strongly chloritized.

The drilled samples of the Gubin granitoids are often intensely altered. K-feldspar and plagioclase are sprinkled with a hematite pigment and often incrusted by calcite and plagioclase also contains secondary epidote. Biotite and hornblende are usually completely altered into chlorite or aggregates of iron hydrated oxides. Fracture surfaces are covered with Fe-compounds and calcite.

THE SZPROTAWA GRANITOIDS

The granitoids of the Szprotawa occurrence were drilled in 4 boreholes: Gościszowice (333.5–346.0 m; some 10 km NE of Szprotawa), 1/II Niegoslawice (341.0–399.3 m; 14 km ENE of Szprotawa), 2/II Leszno Dolne (261.2–300.0 m; 8 km SE of Szprotawa) and Buczyna S-74 (816.0–817.3 m, 28 km E of Szprotawa). They probably form two or even three small bodies (Grocholski, 1976). The granodiorites at Gościszowice, Niegoslawice and Leszno Dolne come to the Tertiary surface, while those in the Buczyna S-74 borehole occur below schistose hornfelses (806.0–816.0 m; Klapciński *et al.*, 1975) which are in turn covered with Rotliegendes deposits.

The granites from Gościszowice and Niegoslawice are fabricless rocks, grey or dark grey, and pinkish due to weathering. They are composed of plagioclase, poorly perthitic microcline, quartz, hornblende ($z/\gamma = 19–21$), biotite and accessory titanite, apatite and zircon (Fig. 4, 5).

The Niegoslawice granite (Fig. 2) is dark grey at the top, with 0.6–0.8 cm whitish feldspar phenocrysts passing into even-grained pinkish granite with depth. The latter resembles a finer-grained variant of the quartz monzonites drilled at Przedmoście (the Środa Śląska occurrence).

The Gościszowice granite contains pink K-feldspar phenocrysts up to 2.5 cm long, which are set in a medium-grained matrix mainly composed of plagioclase, K-feldspar, quartz, biotite and hornblende (Klapciński *et al.*, 1975; Oberc & Oberc-Dziedzic, 1978). Plagioclase grains are subhedral, sometimes zonal (27–35% An) with pericline and albite twinning. Their inner parts are strongly

Fig. 4. The Niegoslawice granite. K-feldspar contains inclusions of plagioclase, biotite and pale green hornblende. Note late brittle shear and faulting. Scale bar 1 mm.

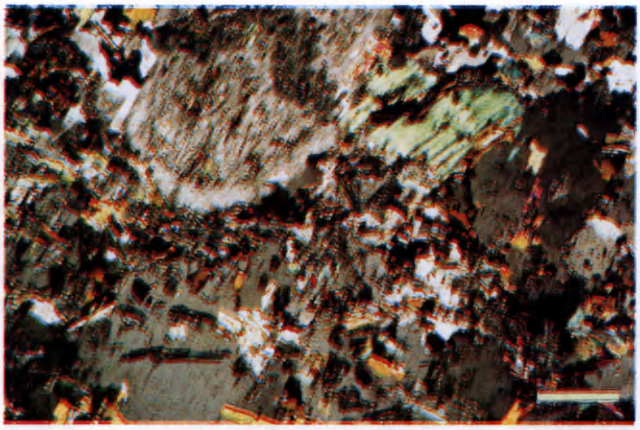

Fig. 6. The Leszno Dolne granite. Zoned plagioclase and poikilitic K-feldspar including biotite and hornblende. Scale bar 1 mm.

Fig. 5. The Gościszowice granite. Plagioclase, hornblende and biotite form inclusions in K-feldspar. Scale bar 1 mm.

sericitized. K-feldspars grains are xenomorphic and contain inclusions of all the other minerals mentioned (Fig. 5). Sometimes K-feldspar forms micrographic intergrowths with quartz. Biotite is found in two varieties: brown and green. The latter forms pseudomorphs after hornblende. Biotite flakes are, occasionally, bent. Hornblende is not as common as biotite. It forms grains of up to 2.5 mm in length and shows yellow-green pleochroism. Both dark minerals are often strongly chloritized. Zircon, ilmenite and apatite occur as accessory minerals.

The granites and granodiorites from the 2/II Leszno Dolne borehole (Fig. 2) are dark grey, fine- to medium-grained rocks, with very local indistinct subvertical magmatic foliation. Feldspars, occasionally phenocrystic (up to 1 cm), and dark minerals are generally randomly oriented and almost unaffected by subsolidus deformation. Automorphic plagioclase grains are 3–10 mm long. They can have more albitic rims in direct contact with poikilitic microcline phenocrysts (Fig. 6). The phenocrysts grow against the fine-grained groundmass (0.11 mm) which is characteristically squeezed between large feldspar grains without any sign of deformation having developed in the latter. Microcline phenocrysts in some cases include the groundmass minerals. This testifies to the regime of this deformatin having been magmatic and texturally isotropic. K-feldspar forms xenomorphic grains with all other mineral constituents as inclusions. Zoned plagioclase with strongly altered inner parts has andesine composition. Dark minerals are represented by brown biotite and pale green hornblende (z/γ = 16–17; Majerowicz, 1974), both having been only slightly altered. The Leszno Dolne granodiorite is a few tens of times richer in Ni, Co, V and Cr (Grocholski *ed*, 1975) than the other granitoids of the Szprotawa occurrence.

In the Buczyna S-74 borehole quite a similar dark gray pinkish granodiorite of 0.5–0.8 mm grainsize is rimmed by a hornfelsed two feldspar-quartz-biotite unfoliated rock with large biotite porphyroblasts interpreted as having arisen from the thermal influence of the granitoid on its country rock.

The Szprotawa granitoids have granitic to granodioritic composition, with randomly arranged minerals, and contain 'pre-microcline' myrmekite and poorly perthitic microcline that embraces all other minerals as inclusions (Majerowicz, 1974). They generally have neither magmatic, nor subsolidus ductile fabric. Quartz grains show only weak undulatory extinction without reaching the stage of deformation bands. Thin, occasional cataclastic zones with chloritized dark minerals are veined with hematite, calcite, and quartz-carbonate minerals. These veining testifies to brittle deformation, with common steep fracturing.

THE ŚRODA ŚLĄSKA GRANITOIDS

The granitoids of the Środa Śląska occurrence are known from two boreholes: Nowiny (263.0–300.3 m) some 15 km NW of Środa Śląska and 4/VI Przedmoście (211.5–300.8 m) 4 km NE of Środa Śląska. They may represent two different bodies.

In the Nowiny borehole, the granite (Fig. 2) is covered with Lower Permian (215.0–263.0 m) and Tertiary sediments. The Nowiny granite is a fine to medium-grained, dark grey rock with a pinkish tint. It consists of plagioclase, quartz, K-feldspar, biotite and hornblende. Plagio-

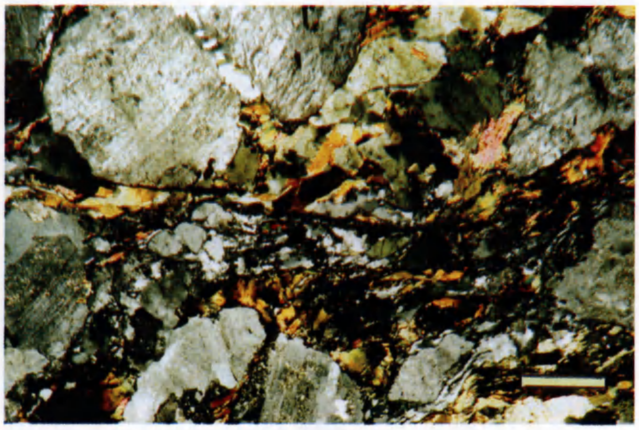

Fig. 7. The Przedmoście granite. Shearing under temperature equivalent to lower amphibolite facies conditions: plagioclase is kinked and faulted, biotite and hornblende are stable, quartz dynamically recrystallizes. Note c. 1 mm displacement along the shear zone. Scale bar 1 mm.

clase grains (25–33% An; see C. Juroszek in Klapciński *et al.*, 1975) are arranged into triangles with quartz grains inside, all having been overgrown with microcline. Microcline is the youngest mineral in the rock, which resembles the Szprotawa granites. Quartz forms xenomorphic grains with occasional merely undulose extinction. Dark brown biotite slightly dominates over intensive green hornblende and both minerals are strongly chloritized. With depth (between 263 m and 303 m) the grainsize increases from 1 to 3 mm, which may reflect the outer and more inner portions of the granitoid body, respectively (Górecka *et al.*, 1977).

In the 4/VI Przedmoście borehole, quartz monzonite (Fig. 2) is only covered with Tertiary deposits. It is composed of plagioclase (35–37% An), K-feldspar, hornblende (z/γ = 18–20), biotite and quartz, with accessory titanite and zircon (Morawski, 1974; Grocholski *ed.*, 1975). The dark minerals are retrogressively chloritized. The rock looks like a deformed variant of the Niegoslawice or Leszno Dolne granitoids. This monzonite (increased Ni, Cr, V, Co contents as in Leszno Dolne) with pink K-feldspar phenocrysts (up to 3 cm), uniquely possesses a magmatic fabric expressed by a roughly subparallel arrangement of pink K-feldspar phenocrysts up to 3 cm across, set in a fine-grained groundmass (0.1–0.5 cm). The primary foliation is folded, changing its attitude from vertical to horizontal. Microscopic examination reveals subsolidus ductile shear zones (0.55 mm thick) in which quartz, feldspar and pale green hornblende grains are dynamically recrystallized, with grainsize reduction, producing asymmetric microstructures accompanied by occasional biotite fishes or biotite tails (Fig. 7). This high-temperature subsolidus deformational overprint gives a somewhat gneissic appearance to the rock. Pull-apart structures in plagioclase grains are filled with chlorite and quartz. The brittle-ductile deformation in drill cores is localized in steeply dipping 70–80° cataclastic zones with marked hematite and carbonate mineralization. The monzonite was also cut by aplitic veins which were subjected to strong cataclasis as well.

THE WROCŁAW GRANITOIDS

The granitoids of the Wroclaw occurrence are known from two boreholes: Kątna 1 (1660.0–1791.3 m) some 15 km E of the centre of Wroclaw and Chrząstawa 1 (1470.0–1538.7 m) 3 km further east (Fig. 1). Subcrops of these crystalline rocks are c. 1.5 km downthrown relative to those of the Odra horst from the Środa Śląska and Szprotawa areas.

In the Kątna borehole, the granite (Fig. 2) is overlain by locally laminated two-feldspar-quartz-biotite gneisses (1357.0–1660.0 m) and Lower Permian sediments. The Kątna granite is a medium- to coarse-grained, porphyritic, dark grey to greenish rock, which turns pink with increasing amount of K-feldspar. It is composed of plagioclase, K-feldspar, quartz, biotite and hornblende, and accessory rutile, ilmenite, apatite and zircon. Mineral grains may show some preferred orientation, with up to 15 mm long K-feldspar phenocrysts and 2–5 mm long euhedral plagioclase grains (32–33% An; see C. Juroszek in Klapciński *et al.*, 1975). Myrmekite is observed at the interface of these two feldspars. The amount of quartz differs from place to place. Dark minerals are represented by brown biotite and green hornblende, often in automorphic crystals.

The granite is altered due to sericitization of plagioclase and chloritization of biotite and hornblende, especially widespread in cataclastic zones. Moreover the feldspars are sprinkled with a hematite pigment. Plagioclase and hornblende alteration allowed for the growth of calcite.

Some granitic veins penetrate into the overlying dark, fine-grained, partly migmatitic gneissees. They contain cordierite relics and pinnite pseudomorphs after cordierite. Textural evidence suggests that cordierite growth and the migmatitization of the gneisses preceded the intrusion of the granite into the already brittlely folded rocks (Oberc & Oberc-Dziedzic, 1978). Both were later cataclased.

In the Chrząstawa borehole, the quartz monzodiorite (Fig. 2) is directly overlain by Lower Permian sediments. It also consists of a plagioclase-K-feldspar-quartz-biotite-hornblende assemblage with late microcline overgrowing all other minerals (Fig. 8). The rock is strongly altered (chloritization, secondary carbonates) in cataclastic zones.

Fig. 8. The Chrząstawa monzodiorite with aggreagtes of dark minerals (biotite and hornblende). Scale bar 1 mm.

THE GRODKÓW GRANITOIDS

The southeasternmost granitoid occurrence is located near Grodków in the eastern part of the Fore-Sudetic Block, actually to the southwest of the SE continuation of the Odra Fault Zone proper, at least 15 km away from it (Fig. 1). These granitoids were drilled under Tertiary deposits in the 1/X Karnków borehole (12 km SW of Grodków) and in the 2/X Wojnowiczki borehole (12 km S of Grodków), both southeast/east of the outcrops of the c. 347 Ma Strzelin granite (Grocholski *ed.*, 1975; Puziewicz & Oberc-Dziedzic, 1995; Oberc-Dziedzic *et al.*, 1996). The Grodków granitoids, which strongly resemble the Strzelin granite, appear as several to tens of metres thick dykes or bodies within metamorphic rocks of unknown, probably Neoproterozoic age, belonging either to the Strzelin metamorphic unit, or to the northern continuation of the Moravo-Silesian basement (see Cwojdziński & Żelaźniewicz, 1995). Thus the Grodków granitoids seem somewhat less tightly linked with the GubenWrocław belt of granitoids described above.

In the 1/X Karnków borehole, a quartz-oligoclase-biotite paragneiss at a depth of 260.4 m is intruded by a 4.3 m thick granite vein (Grocholski *ed.*, 1975). No more granite occurs within the lower 80 m long interval drilled in plagioclase gneisses alternating with amphibolites. The granite from Karnków (Fig. 2) is a light grey, fine-grained rock (0.5–1 mm) composed of xenomorphic grains of plagioclase with more albitic rims, quartz, microcline, and tiny sparse biotite (strongly chloritized). It resembles two mica granites from the Strzelin massif (Biały Kościół) except for the lack of muscovite. Locally strong alterations are connected with cataclastic zones (Morawski, 1974).

In the 2/X Wojnowiczki borehole, under a 9 m thick amhibolite appearing at the Tertiary surface, at a depth of 228.0 m, a diversified granitoid body of unknown thickness occurs. Its drilled part consists of a 44 m thick tonalite portion overlying quartz diorite-granodiorite alternations to a depth of 315.8 m (end of the well), crosscut by a 2.5 m thick microtonalite dyke and numerous aplite veinlets (Fig. 2; Grocholski *ed.*, 1975). The tonalites are fine-grained rocks, with zoned plagioclase (cores of 46–44% An and rims of 28–22% An; Morawski, 1974), quartz, biotite and hornblende (Fig. 9). The quartz diorites differ from tonalites by their medium- to coarse-grained texture and larger amount of dark minerals. The granodiorites are fine-grained rocks composed of plagioclase (38–42% An in cores and 17–19% An in rims), microcline, quartz and biotite. The granitoids from the 2/X Wojnowiczki borehole are only slightly altered. At the bottom of the well, the granodiorite is slightly sheared in a c. 2 m thick zone dipping at an angle of 35, with unknown kinematics.

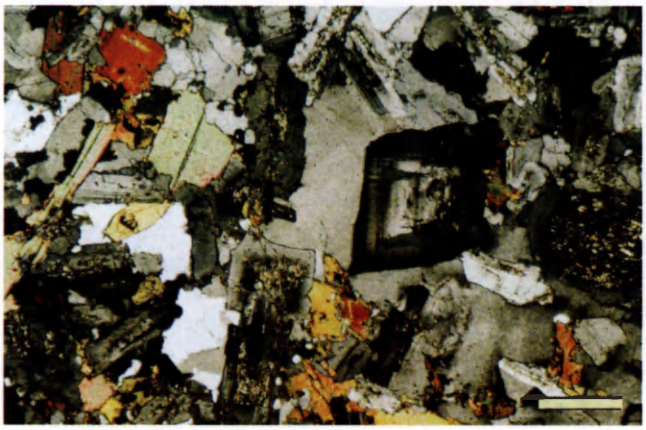

Fig. 9. The Wojnowiczki tonalite. Zoned plagioclase surrounded by quartz; subordinate biotite and hornblende. Scale bar 0.5 mm.

GEOCHEMICAL CHARACTERISTICS

The geochemical characteristics of the Odra granitoids are based on 33 analyses of major and some trace elements, including 23 major element analyses published by Sachanbiński (1980). Using the classification of Debon & Le Fort (1983), these rocks are classified mostly as adamellites, granites and quartz monzonites (Fig. 10), with mainly biotite and horblende as mafic minerals (Fig. 11). They are generally high-potassic (Fig. 12). The low-potassic tonalites found in the Lugowo 2 borehole are fairly exceptional, however, they are located outside the Odra Fault Zone (Fig. 1). Most of the Odra granitoids are metaluminous, or less commonly, peraluminous rocks (Fig. 11, 13a), being either calcic, calc-alkalic or alkali-calcic (Fig. 14a, 15a). In general, the Odra granitoids are characterized by high variations in aluminousity and calc-alkalinity and a lack of discrete trends in REE and trace element patterns. Such a chemical diversity probably stems from the small dimensions of the individual, yet internally diversified, bodies set in the zone.

Higher contents of Cr, Co Ni, V, recognized in case of the Leszno Dolne and Przedmoście granitoids, well correspond with amounts typical of mafic rocks and thus suggest their relation with basic magmas (Grocholski *ed.*, 1975). In this respect they are similar to granodiorites of the Niemcza Zone in the Fore-Sudetic Block (Grocholski *ed.*, 1975).

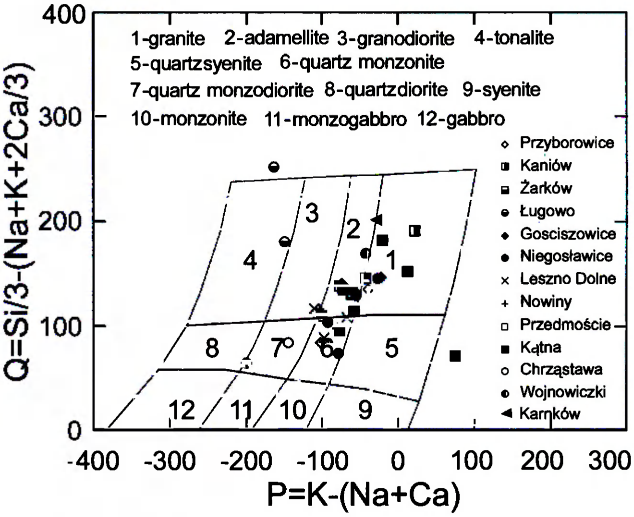

Fig. 10. Systematics of the Odra Fault Zone granitoids on Debon & Le Fort (1983) plot.

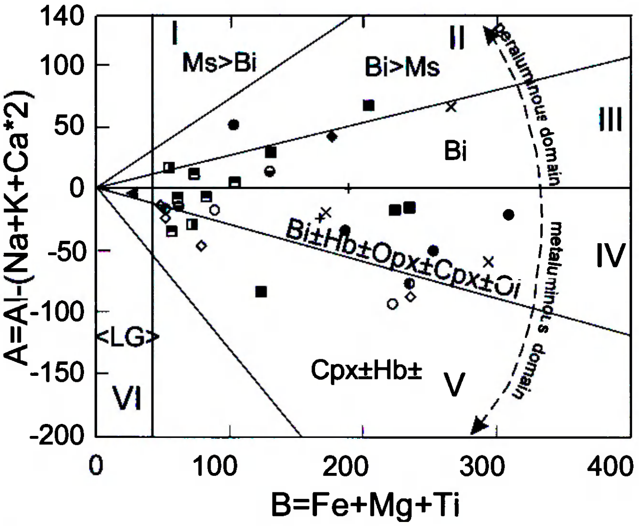

Fig. 11. The Odra granitoids on the "characteristic minerals" diagram (Debon & Le Fort, 1983). Bi – biotite; Cpx – clinopyroxene; Hb – hornblende; LG – leucogranite; Mu – muscovite; Ol – olivine; Opx – orthopyroxene. Legend as on Fig. 2.

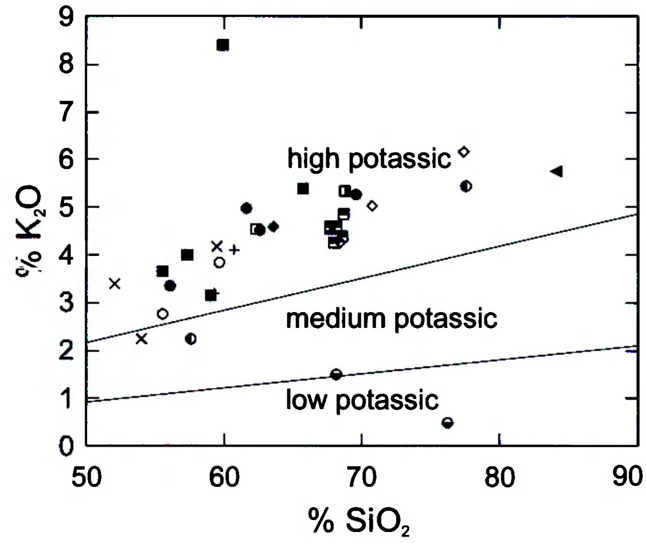

Fig. 12. Variation of K_2O vs. SiO_2 for the Odra granitoids. Legend as on Figure 10.

On the R1-R2 plot (Bachelor & Bowden, 1985), the Odra granitoids occupy a vast area from pre-collisional to late orogenic granites (Fig. 17a). Parts of the Gubin granitoids (Przyborowice, Żarków), the Szprotawa granitoids (Niegoslawice), the Wroclaw granitoids (Kątna) and the Grodków granitoids (Wojnowiczki) fall in the field of post-orogenic granites. Other parts of the Wroclaw granitoids (Chrząstawa), the Środa Śląska granitoids and the tonalites of Ługowo appear as pre-collisional granites, whereas points for some of the Gubin granitoids (Kaniów) appear in the poorly defined field of syn-collisional granites. Double representation of rocks from the same borehole in two fields of the diagram (e.g. Kątna and Nowiny both fall in fields 2 and 4) is likely due to alterations caused by pre-Permian weathering. However, plots representing rocks which come from different boreholes belonging to the same granitoid occurrence (e. g. Kątna and Crząstawa of the Wroclaw occurrence, or Niegoslawice and Leszno of the Szprotawa occurrence seem to indicate the presence of either different, small intrusive bodies, or composite intrusions.

Further information on geochemistry of the Odra granitoids will be given in in the chapter "Comparison with other Variscan granitoids of the West Sudetes".

DEFORMATION

Only in one case (Przedmoście of the Środa Śląska occurrence) does a steeply dipping primary foliation expressed by a roughly subparallel arrangement of pink K-feldspar phenocrysts testify to subvertical magmatic flow, presumably in a strike-slip shear zone. Some ductile deformation accomplished at least at c. 500 °C, found uniquely in the Przedmoście monzonite, overprinted the magmatic fabric and produced anastomosing mylonitic foliation but no identifiable lineation. The ductile shear zones (0.55 mm thick) are associated with grainsize reduction and asymmetric microstructures (Fig. 7), but concomittant myrmekite usually suggestive of solid-state shearing is not observed. The subvertically oriented mylonitic foliation in the Przedmoście monzonite accommodated ductile dextral wrench faulting at temperatures retaining hornblende stability under amphibolite facies conditions. Further deformation of the Przedmoście monzonite took place in a more brittle regime of the greenschist facies. Pull-apart structures in plagioclase grains are filled with chlorite and quartz, while biotite and hornblende become chloritized. The sense of movement during the brittle, cataclastic overprint remains undeciphered.

Some directional arrangement of biotite aggregates and hornblende crystals is also observed in granitoids of the Kątna and Chrząstawa boreholes (Fig. 8) and, apparently, increases up the log sections. In view of the lack of evidence for dynamic recrystallization such a fabric is interpreted as due to primary magmatic flow.

Scarce evidence of the preferred orientation of feldspar phenocrysts and small dark enclaves found in the Szprotawa and Wroclaw granitoids also point to the steeply dipping fabric that may be consistent with their emplacement into a wrench zone. Generally, however, the Odra Zone granitoids are fabricless, which gives them the status of postorogenic granites similar to that of other Variscan granites in the Sudetes, Fore-Sudetic Block and elsewhere in the Bohemian Massif. In view of the unknown geometries of the granitoid bodies at the Odra Zone the problem of their emplacement settings cannot be solved unequivocally.

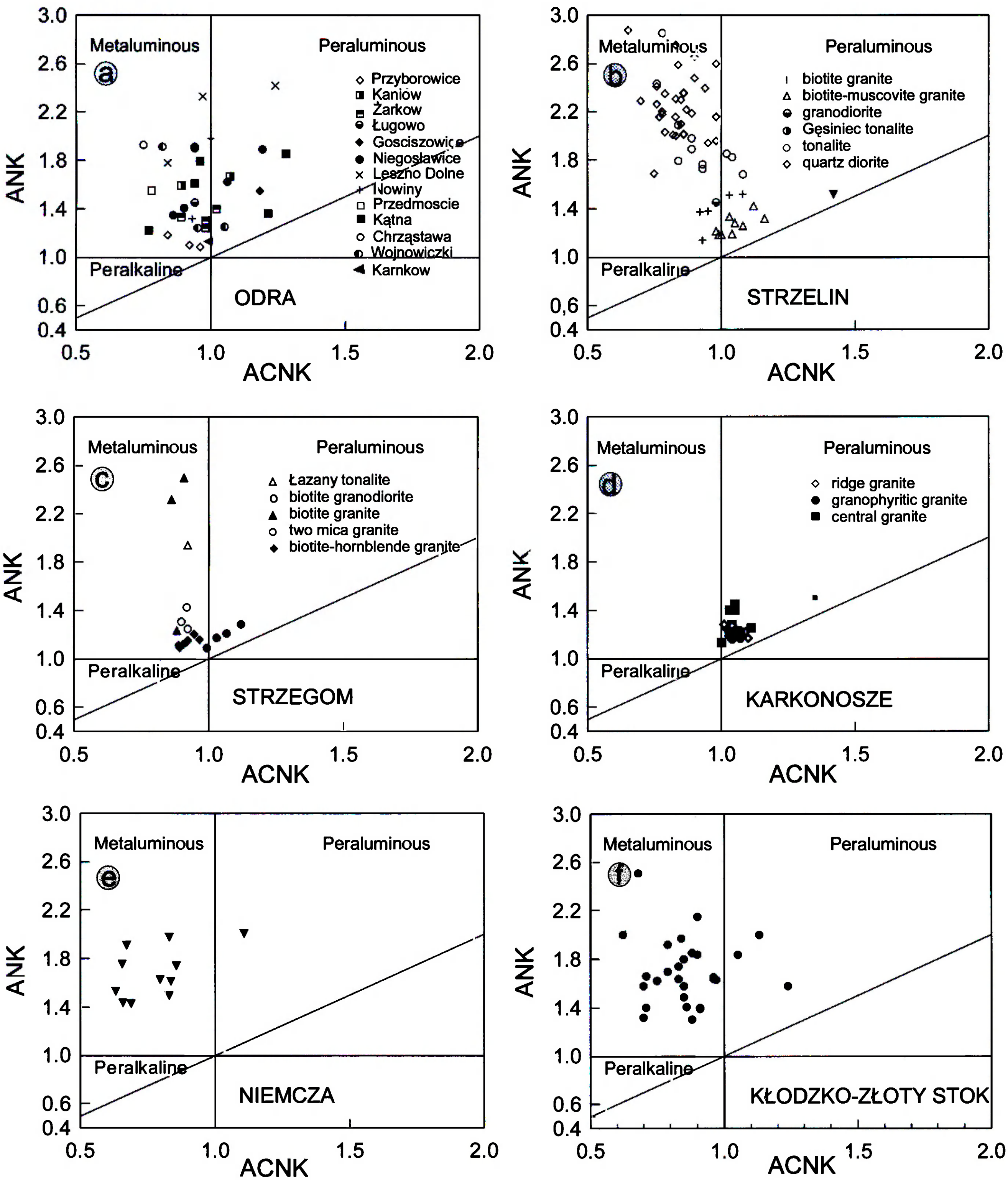

Fig. 13. Aluminousity of the Odra granitoids as compared to other Variscan granitoids from the Sudetes (Karkonosze, Kłodzko–Złoty Stok) and the Fore-Sudetic Block (Strzelin, Strzegom, Niemcza).

On the other hand, most granitoids from the Odra Fault Zone show more or less pronouced brittle deformation (Fig. 4; Majerowicz, 1974; Górecka *et al.*, 1977). Fracture surfaces are covered with Fe-oxides and rarely chlorite, or followed by thin calcite and quartz veining. The dominantly steep small-scale fault planes or zones are accompanied by variously oriented slickensides, pointing to predominantly dip-slip or less often strike-slip displacements in a brittle regime. Such a deformation, characteristic for the Odra Zone granitoids and uncommon in other granitic rocks of the Sudetes, can be related to Permian and younger faultings discretely confined to rocks at the Odra Fault Zone at the time when this complex horst was being formed.

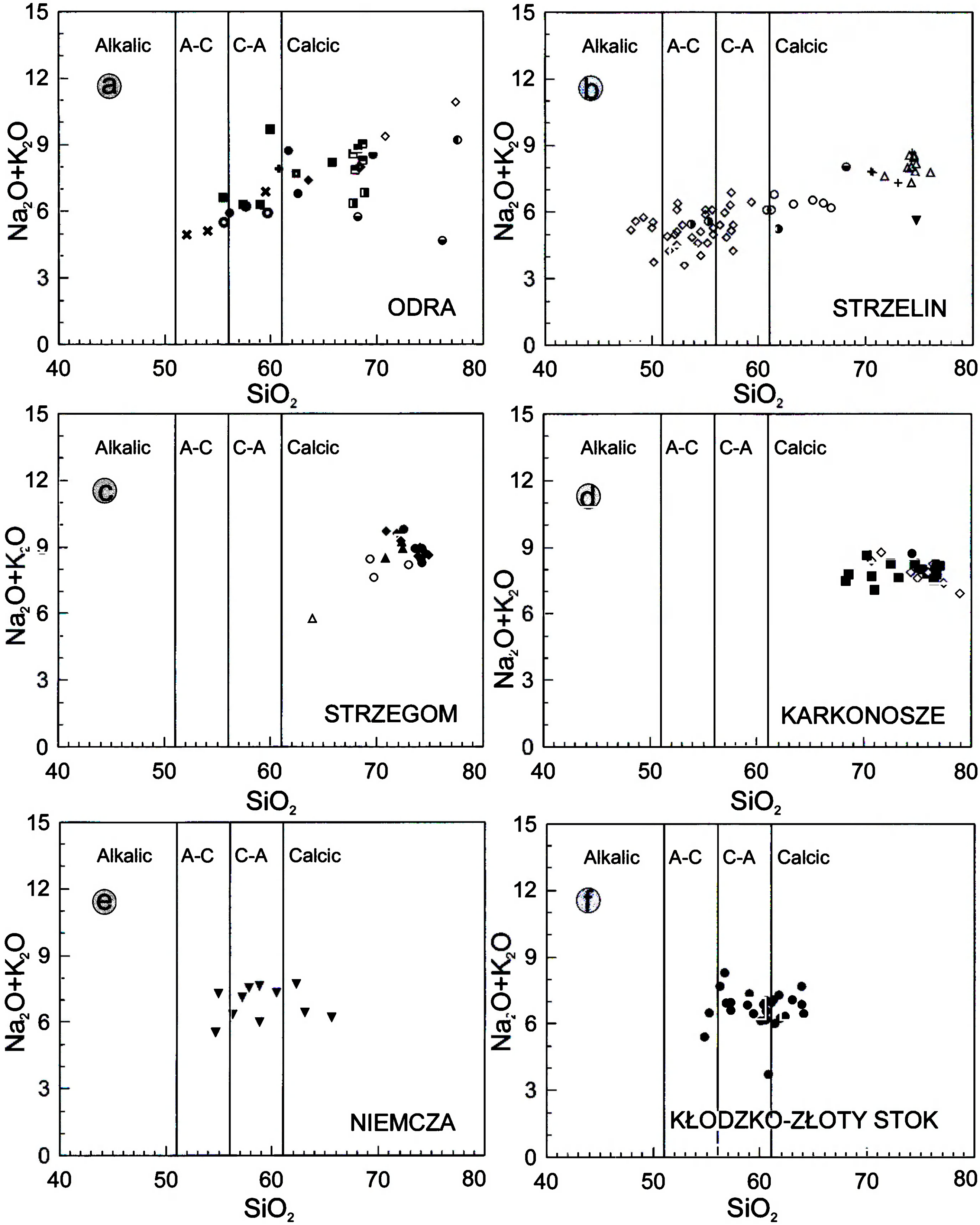

Fig. 14. Calc-alkalinity of the Odra granitoids and other Variscan granitoids of the Sudetes and Fore-Sudetic Block on the simplified diagram of Peacock (1931). Legend as on Figure 13.

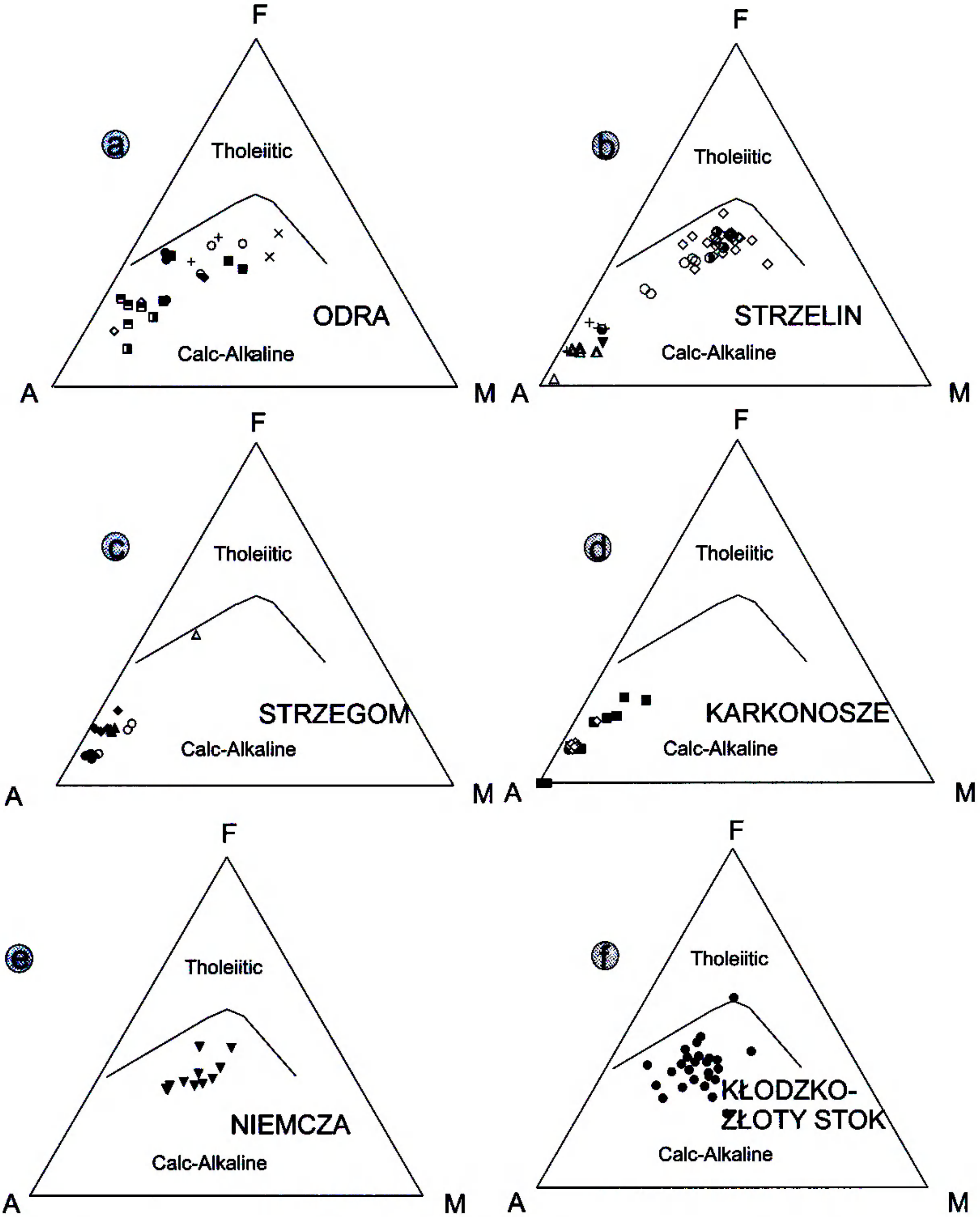

Fig. 15. Comparison of the Odra granitoids with other Variscan granitoids of the Sudetes and Fore-Sudetic Block on AFM plot. Field boundary from Irvine & Baragar (1971). Legend as on Figure 13.

AGE OF GRANITOIDS

Attempts at Rb-Sr whole rock and mineral datings of the Odra zone granitoids failed in all cases except for the Grodków occurrence. Either secondary alterations of minerals in the sampled drill cores and the unfortunate presence of some secondary carbonates, or infavourably low spread of the Rb-Sr ratios measured exclude most of them from the Rb-Sr studies. However, successful dating of granites from Karnków and Wojnowiczki from the Grodków area (Fig. 1) boreholes yielded Rb-Sr whole rock ages of c. 332 Ma and c. 338 Ma, respectively (A. Pieńkowski, 1998, oral comm.). The Leszno Dolne granite yielded the U-Pb zircon age of 344±1 (W. Dörr and P. Bylina, oral comm.). Accordingly, Visean has been confirmed as the age for the Odra granitoids, at least for their easternmost occurrence.

Stratigraphic evidence coming from the Chocianów IG3 borehole, located in the Fore-Sudetic Block very close to the Szprotawa granitoids (Fig. 1) shows that the graptolite-bearing Silurian pelites of the Kaczawa succession subjected to greenschist metamorphism during the Early Carboniferous were later affected by a contact oveprint (andalusite-cordierite hornfelses) within the thermal aureole caused by a younger granite (Jerzmański, 1975). This granite, although not drilled in the Chocianów borehole itself, undoubtedly belong to the Szprotąwa occurrence (Fig. 1), and it is most likely of the Early Carboniferous in age as well. The unfoliated country rocks to the Środa Śląska granitoids (Buczyna) also became hornfelsed. The Odra Fault Zone granitoids thermally influenced their surroundings in a way similar to other granitoid bodies in the Sudetes and Fore-Sudetic Block. Accordingly, it is very probable that the unfoliated granitoids of the 5 occurrences at the Odra Fault Zone are of the same Early to Late Carboniferous age.

Further to the west, in Germany, some 50 km west of Gubin, porphyritic biotite-hornblende granitoids were drilled and considered to represent the eastern continuation of the Mid-German Crystalline Rise (Kopp *et al.*, 1999). They are most similar to the Przedmoście granitoids of the Środa Śląska occurrence. Those coming from the Luckau and Luckenwalde boreholes yielded single zircon evaporation Pb-Pb ages of 337+8 and 350±5 Ma, respectively (Kopp *et al.*, 1999). Such data point to an extensive presence here of late orogenic Variscan granitoids. Speculations about the presence of arc-related Silurian intrusives remain unsupported.

COMPARISON WITH OTHER VARISCAN GRANITOIDS OF THE WEST SUDETES

Besides the five occurrences located at the Odra Fault Zone, Variscan granitoids are also ubiquitous in the entire Sudetic and Fore-Sudetic parts of the Saxothuringian Zone (Fig. 16). These are the Karkonosze massif (Borkowska, 1966; Wilamowski, 1998), Kudowa-Olešnice massif (Borkowska, 1959; Żelaźniewicz, 1977), Klodzko-Złoty Stok massif (Wierzcholowski, 1976; Lorenc, 1991) in the Sudetes and the Strzegom massif (Majerowicz, 1966; Puziewicz, 1990), Strzelin granitoids (Oberc-Dziedzic, 1998) and Niemcza granitoids (Dziedzicowa, 1963; Puziewicz, 1992 Lorenc, 1998) in the Fore-Sudetic Block. Except for the latter, all of them are generally late to post-kinematic intrusive rocks, ranging in their Rb-Sr ages within more than 60 m.y., from 347 Ma (the biotite granite of Strzelin, Oberc-Dziedzic *et al.*, 1966) to 280 Ma (the granodiorite of Strzegom, Pin *et al.*, 1989), with most data clustering the age of c. 330 Ma.

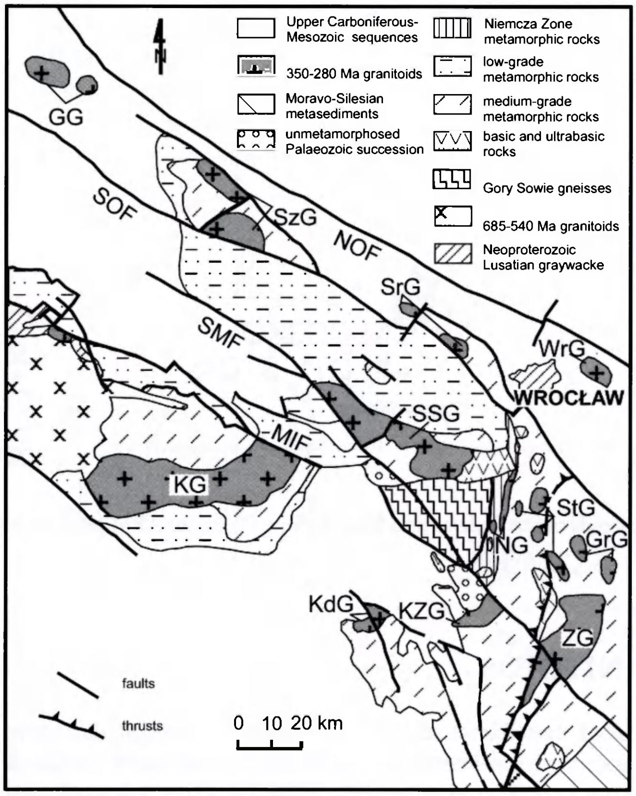

Fig. 16. Location of the Odra granitoids and other Variscan granitoids in the Saxothuringian Zone of the Sudetes and Fore-Sudetic Block.

CHEMISTRY

The chemistry of the Odra granitoids was compared with the chemistry of late to post-kinematic Variscan granitoids from the Sudetes and Fore-Sudetic Block, using analyses published by Majerowicz (1966), Wierzcholowski (1976), Puziewicz (1990, 1992), Wilamowski (1998) and unpublished data of the present authors. Although all these rocks are remarkably chemically diversified, three groups can be distinguished on the Na_2O+K_2O vs SiO_2 (Fig. 14) and AFM (Fig. 15) plots. These are: (1) calcic to alkalic granitoids of the Odra zone and Strzelin areas, characteristically occurring as small bodies, (2) calcic and calc-alkalic granitoids of the Niemcza and Klodzko–Zloty Stok massifs, and (3) calcic granitoids of the Karkonosze and Strzegom massifs.

Most of the Sudetic and Fore-Sudetic granitoids are metaluminous. The Odra granitoids, Strzelin granitoids and Strzegom granitoids comprise peraluminous components, whereas the Karkonosze granites are distinctly peraluminous (Fig. 13).

Taking into account the generally low A/CNK (commonly less than 1.1) and the presence of more mafic members (quartz diortites, monzodiorites), the Strzelin granites, Niemcza granodiorites and Klodzko–Zloty Stok granitoids may be classified as the I-type granitoids of Chappel & White (1974). In the case of the Strzelin granitoids this assignment is consistent with a low Sr/Sr initial ratio

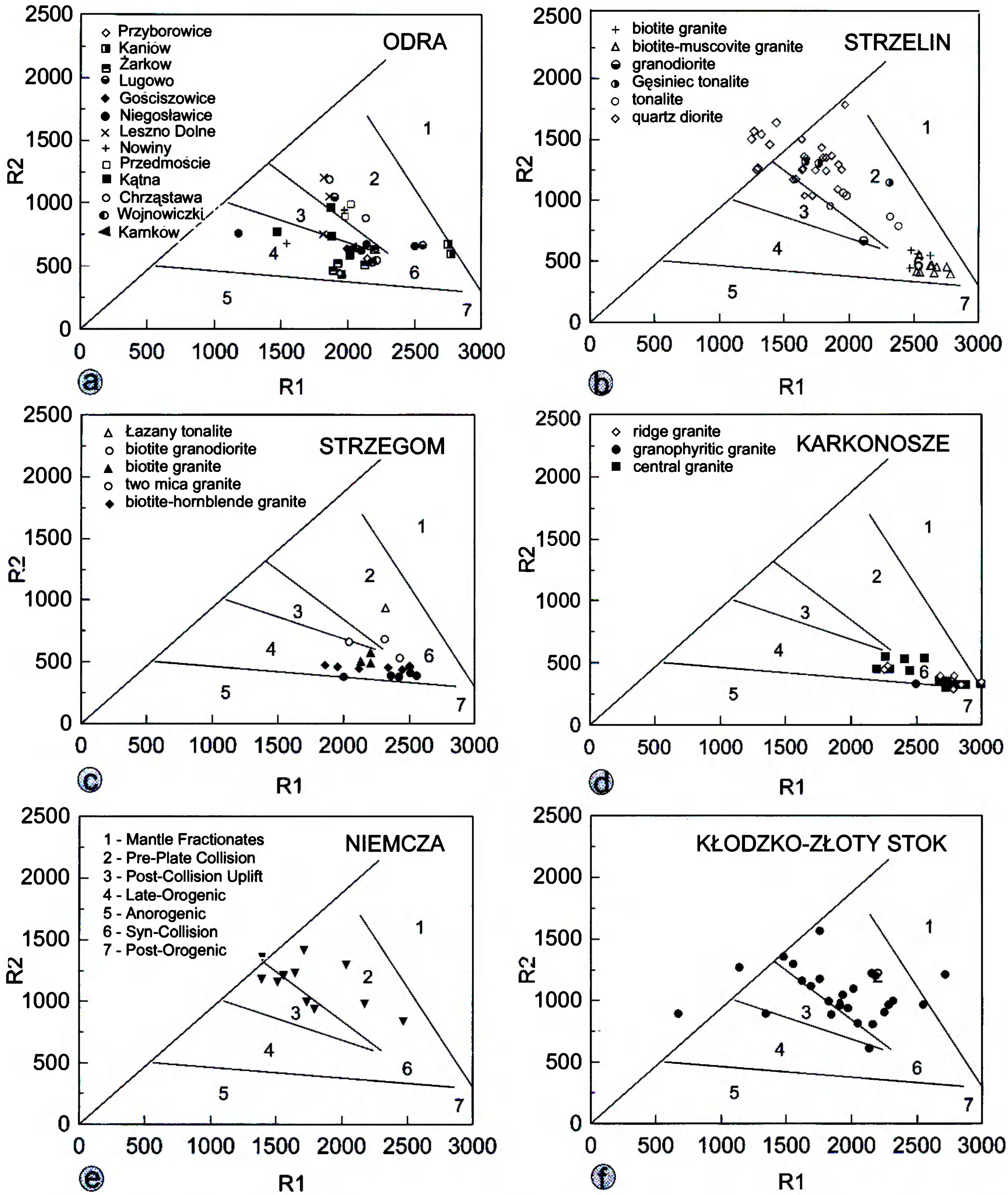

Fig. 17. Geotectonic discriminant R1-R2 multicationic plot (Bachelor & Bowden, 1986) to compare the Odra granitoids with other Variscan granitoids of the Sudetes and Fore-Sudetic Block. R1 = 4Si - 11(Na + K) - 2(Fe + Ti); R2 = 6Ca + 2Mg + Al.. Legend as on Figure 13.

of 0.7053 (Oberc-Dziedzic *et al.*, 1996). I-type affiliation is also suggested for the Karkonosze granite by Wilamowski (1998), although its Sr^{87}/Sr^{86} initial ratio slightly exceeds 0.706 (Duthou *et al.*, 1991) and most of them contain normative corundum (Borkowska, 1966). The Strzegom granitoids may also be assigned to the I-type, based on their generally low A/CNK ratio, but Sr^{87}/Sr^{86} initial ratio for some of their variants is as high as 0.7082–0.7098 (Pin *et al.*, 1989), probably due to contamination. The Sr^{87}/Sr^{86} initial ratio for the Grodków occurrence of the Odra Zone

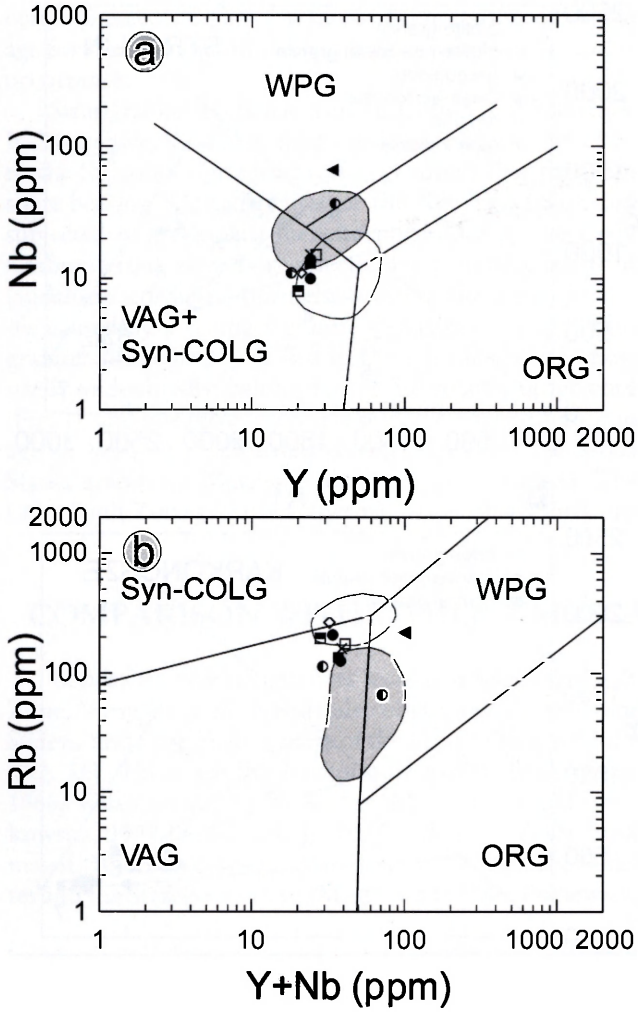

Fig. 18. Geotectonic discriminant diagrams (Pearce *et al.*, 1984) for the Odra granitoids, compared to fields for the Karkonosze granitoids (shaded) and Strzelin granitoids (contoured). a – Nb-Y plot; b – Rb-(Y+Nb) plot. Legend as on Figure 10.

granitoids is 0.7061 (A. Pieńkowski, 1998, oral comm.), which classifies them as I-type too. This is consistent with the low A/CNK ratio for these and other granitoids of the Odra Fault Zone. Accordingly, the Odra granitoids conform to other late to post-tectonic granites in the Sudetes and Fore-Sudetic Block, all representing relatively primitive magmas derived from a source with an overall low Sr^{87}/Sr^{86} initial ratio pattern (Kennan *et al.*, 1999).

GEOTECTONIC SETTING BASED ON DISCRIMINATION DIAGRAMS

Having compared the plots of the Odra granitoids (Fig. 17a) on the R1-R2 diagram (Bachelor & Bowden, 1985) with those of other Sudetic and Fore-Sudetic granitoids (Fig. 17b–f), three groups can be distinguished, corresponding to (1) pre-collisional, (2) late orogenic and (3) syn-collisional granites. Group (1) comprises part of the Odra granitoids, the Niemcza granitoids, and the tonalites and diorites of the Strzelin Hills (Oberc-Dziedzic, 1998) of the Fore-Sudetic Block as well as the adjacent Kłodzko-Złoty Stok granitoids (Lorenc, 1991) of the Sudetes. Some points representing the latter 3 massifs also occur in the field of post-collisional uplift granites. Group (2) comprises the other part of the Odra granitoids and the Strzegom granitoids and Karkonosze granitoids (Wilamowski, 1998). The Odra granitoids are absent from group (3) which includes biotite-muscovite variants of the Strzelin granites, part of the Karkonosze granites and a two-mica variant of the Strzegom granites.

On the other hand, the Odra granitoids are also similar to the Moldanubian I-type granites characterized by quartz monzonite to granite composition, intermediate A/CNK ratios and high K_2O contents (Finger & Steyrer, 1990)

On the Y-Nb diagram (Pearce et al., 1984) the Odra granitoids plot mostly in the island arc (VAG) and syn-collisional (syn-COLG) granite fields (Fig. 18a) with only the two-mica granites of the Grodków occurrence falling in the field of within-plate granites (WPG). They partly coincide with the area occupied by the Strzelin tonalites and diorites (Oberc-Dziedzic, 1998). The Y+Nb vs Rb plot (Pearce et al., 1984) shows that the analysed samples can be located in the VAG field, close to a triple boundary point for syn-COLG, VAG and WPG (Fig. 18b). On this plot they poorly correspond with the area of the Strzelin granitoids and slightly better with the area of the Karkonosze granites (Wilamowski, 1998). On both diagrams of Figure 18, those granitoids that spread between syncollisional and late orogenic granites occur close to each other (Fig. 17a). According to Pearce *et al.* (1985), a distribution of points similar to that on Fig. 18b is characteristic for post-collisional granites, presumably comparable with the late orogenic granites of Bachelor & Bowden (1985).

It is notorious that geotectonic classifications based on element ratios are often dubious, although discriminations utilizing trace and rare elements rather than major elements can be used with more confidence. It seems that differences in chemistry are a function of variable source chemistry and accommodation of particular mineral phases (e. g. ferromagnesian or plagioclase), rather than of differences in tectonic environment (see Rollinson, 1993).

DISCUSSION

The Rb-Sr age of c. 332–338 Ma of the Grodków granitoids from the eastern termination of the Odra Fault Zone and the Pb-Pb age of c. 350 Ma and 337 Ma of the granitoids to the west of this zone give likely time brackets to granitoids from the middle and western part of the Odra Fault Zone that are still undated (U-Pb zircon determinations are currently being done in Giessen). This notion is consistent with the evidence coming from the contact overprint produced by the Szprotawa granitoid on the graptolite-bearing Silurian pelites of the Kaczawa succession which were subjected to greenschist metamorphism during the Early Carboniferous.

Accordingly, it is extremely likely that the granitoids drilled at the Odra Fault Zone are of Early to Late Carboniferous age and represent the same magmatic event which gave rise to all the other, geochemically similar, late to post-kinematic granitic intrusions spread throughout the Saxothuringian Zone of the Sudetes and of the Fore-Sudetic Block (Fig. 16). The remarkable geochemical similarities of the Odra granitoids and Strzelin granitoids (Fig. 13, 14, 15) suggest a common derivation from the same type of crust and emphasize a direct compatibility, also geologically inferred, of metamorphic rocks exposed in the horst of the Odra Fault Zone and in the eastern part of the Fore-Sudetic Block, jointly assigned to the Fore-Sudetic complex (Cwojdziński & Żelaźniewicz, 1995). Variscan granitoids piercing this complex in the form of small stocks and dykes (Odra, Strzelin, Niemcza) caused a discrete thermal metamorphism accomplished in an extensional regime of uprising magmas, manifested by a syn- to late-kinematic growth of anadalusite during the last recognizable ductile deformational event (Nowak, 1998). It is roughly the same tectonothermal relationship that characterizes the 300 Ma Žulova granite further south, and its bearing on the Devonian cover of the Neoproterozoic Keprnik dome in the Jesenik Mts. of the Moravo-Silesian Zone (Schulmann & Ulrich, 1996).

Neither the high variations in aluminousity and calc-alkalinity, nor the lack of discrete trends in characteristic trace and REE elements for the Odra granitoids allow them to be assigned to an arc-related setting. They are broadly collisional intrusives. Accordingly, the Odra granitoids cannot be taken as equivalent to rocks of the Silurian magmatic arc recognized between Kreichgau and Erfurt (Zeh, 1996; Zeh *et al.*, 1997) at the northwestern rim of the Saxothuringian Zone, known as the Mid-German Crystalline Rise. This magmatic arc developed due to the southward subduction of East Avalonia below the Saxothuringian/Armorican terrane. The Mid-German Rise was produced by the Avalonian-Saxothuringian plate intercation. Avalonia did not enter Poland (Cocks *et al.*, 1997), terminating at the Dolsk Fault Zone (Kraków–Hamburg Line), thus there is a faint possibility of cylindrically continuing the Silurian magmatic arc of the Mid-German Crystalline Rise to Poland (Cwojdziński & Żelaźniewicz, 1999). Neither the metamorphic rocks of the eastern part of the Fore-Sudetic Block, nor their direct continuation into the Odra Fault Zone on one side and into the Orlica–Śnieżnik dome on the other can be taken as equivalent of such an arc. Consequently Lower and Upper Carboniferous siltstones, sandstones and subordinate greywackes occurring to the north of the Odra Fault Zone do not represent any straightforward continuation of the Rhenohercynian belt, which characteristically comprises Devonian–Carboniferous flysch deposited in a foreland basin in front of the Saxothuringian terrane overriding Avalonia. More detailed comparisons are, however, beyond the scope of this paper. The MP-MT metamorphic rocks exposed in the Odra fault Zone do not differ lithologically and in their tectonothermal history from those in the eastern Fore-Sudetic Block and all of them represent the eastern part of the Saxothuringian belt, with its characteristic HP eclogite relicts (Achramowicz *et al.*, 1997).

Unfoliated granitoids were also found subsurface to the north of the Odra Fault Zone. One such occurrence is the already mentioned Lugowo 2 granite (Fig. 1), the other is the location of Chrzypsko NW of Poznań, where granitic rocks were drilled below Permian rocks (A. Żelichowski, unpublished data).

Except for the Przedmoście monzonite of the Środa Śląska occurrence, the granitoids of the Odra Fault Zone do not show magmatic fabric and do not provide convincing evidence of having intruded into an active shear zone. Neither do they show evidence for a solid-state ductile mylonitization (again excepting Przedmoście). Semi-brittle or brittle shearing and fracturing are late phenomena, likely related to the formation of the Odra Zone horst in Permo-Mesozoic times. Thus the common notion derived from a general model of Arthaud & Matte (1977), assuming large-scale wrench displacements among others on the Odra Fault Zone during the Late Carboniferous and Permian remains unsupported here.

CONCLUSIONS

1) The granitoids of the 5 occurrences located at the Odra Fault Zone are geochemically and petrographically akin to the late- to post-kinematic Variscan granitoids of the Sudetes and they are closest to those of the eastern part of the Fore-Sudetic Block (Strzelin, Niemcza).

2) They represent late orogenic, collisional intrusives of Early-Late Carboniferous age.

3) The brittle to semi-brittle deformation of the Odra granitoids relates to the formation of the horst of the Odra Fault Zone in Permo-Mesozoic times.

4) The granitoids lack evidence of ductile or brittle strike-slip movement of Late Carboniferous–Permian age along the Odra Fault Zone, which thus has to be taken as a dip-slip fault zone, rather than a late Variscan dextral strike-slip feature.

5) The Silurian–Devonian magmatic arc of the Mid-German Crystalline Rise, identified in Thuringia and further to the southwest, probably does not have an easterly cylindrical prolongation via the mostly MP-MT metamorphic rocks of the Odra Fault Zone into the eastern part of the Fore-Sudetic Block (and consequently into the Orlica–Śnieżnik dome further south) because evidence for Silurian–Early Devonian arc-related granitoid magmatism is lacking there.

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