Miner Petrol (2014) 108:681–694
DOI 10.1007/s00710-014-0326-6

ORIGINAL PAPER

Plagioclase transfer from a host granodiorite to mafic microgranular enclaves: diverse records of magma mixing

Anna Pietranik · Jurgen Koepke

Received: 5 June 2013 / Accepted: 28 March 2014 / Published online: 17 April 2014

Abstract Chemical and structural zoning in plagioclase can develop in response to a number of different magmatic processes. We examine plagioclase zonation formed during the transfer of plagioclase from a granodioritic host to a monzodioritic enclave to understand the development of different zonation patterns caused by this relatively simple magma mixing process. The transferred plagioclase records two stages of evolution: crystallization of oscillatory plagioclase in the host granodioritic magma and crystallization of high An zones and low An rims in the hybrid enclave magma. High An zones (up to An_{72}) are formed only in the hybrid enclaves after plagioclase transfer. Plagioclase from a primitive enclave, showing no or only minimal interaction with the host, is $An_{30–43}$. The implication is that high An zones crystallize only from the hybrid magma and not from the primitive one, probably because of an increase in water content in the hybrid magma. Complex interactions between the two magmas are also recorded in Sr content in plagioclase, which indicates an initial increase in Sr concentration in the melt upon transfer. This is contrary to what is expected from the mixing of low Sr enclave magma with a high Sr granodiorite one. Such Sr distribution in the plagioclase implies that the transfer of the plagioclase took place before the onset of plagioclase crystallization in the enclave magma. Therefore, the mixing between high Sr granodiorite magma and low Sr enclave magma was recorded only in plagioclase rims and not in the high An zones.

Introduction

Resorption surfaces in plagioclase are common in both volcanic and plutonic rocks and resorption is commonly followed by crystallization of plagioclase with higher anorthite content. Major resorption surfaces and the following increase in An content are attributed to changes in conditions of crystallization such as increase in temperature, increase of water concentration in the melt, decrease in pressure, or changes in magma composition. Such changes are commonly induced by injection of more mafic magma into the magma chamber in which plagioclase crystallizes (Ginibre et al. 2002; Ginibre and Wörner 2007; Kocak et al. 2011; Shcherbakov et al. 2011; Viccaro et al. 2010). If minerals crystallize in an open magmatic system, the response of the crystals to magma mixing is complex and controlled by the coexistence of compositionally distinct magma domains that can contribute material to growing crystals (Perugini et al. 2006; Słaby et al. 2011).

Plagioclase structure and composition are commonly used to reconstruct conditions of crystallization. In volcanic rocks, the task is difficult owing to the physical mixing of grains crystallized in different environments (e.g. Viccaro et al. 2010). In plutonic rocks, resorption structures in plagioclase are commonly observed in mafic microgranular enclaves because plagioclase crystals are transferred from more silicic host rocks to more mafic, and usually hotter, enclave magma (e.g. Adamuszek et al. 2009; Kocak et al. 2011; Xiong et al. 2012). Contrary to the volcanic regime, mafic microgranular enclaves provide a relatively simple environment for illustrating plagioclase response to changing magma conditions. The

---

Editorial handling: M. Okrusch

Electronic supplementary material The online version of this article (doi:10.1007/s00710-014-0326-6) contains supplementary material, which is available to authorized users.

A. Pietranik (✉)
Institute of Geological Sciences, University of Wrocław, Maksa Borna 9, 50-204 Wrocław, Poland
e-mail: anna.pietranik@ing.uni.wroc.pl

A. Pietranik
e-mail: apietranik@gmail.com

J. Koepke
Institute of Mineralogy, Leibniz University of Hannover, Callinstr. 3, D-30167 Hannover, Germany

enclaves are chemically distinct from the host magma and usually plagioclase is transferred only once from the host to the enclave magma. In this study we examine late resorption structures in plagioclase from mafic microgranular enclaves in the Kośmin intrusion in the Niemcza Zone, Sudetes, SW Poland (Fig. 1). Our aim is to characterize in detail the chemical response of plagioclase to the change of surrounding magma composition from granodioritic host to monzodioritic magma and then again to more silicic magma as the two magmas mix. We hope to define the structural and chemical variability that may occur in different grains and different enclaves during the transfer from the host to the enclave. That, in turn, will illustrate changes in plagioclase composition that might be induced by relatively simple magma mixing processes.

Study area

In this study we analyzed samples from a granodiorite intrusion containing mafic microgranular enclaves located in Kośmin in the Niemcza Zone, Sudetes (or Sudeten Mountains), SW Poland (Fig. 1). The intrusion crops out in an active quarry 400 by 300 m wide and 50 m high. This quarry is the largest outcrop of granodioritic rocks in the Niemcza Zone and the type locality for this group of rocks.

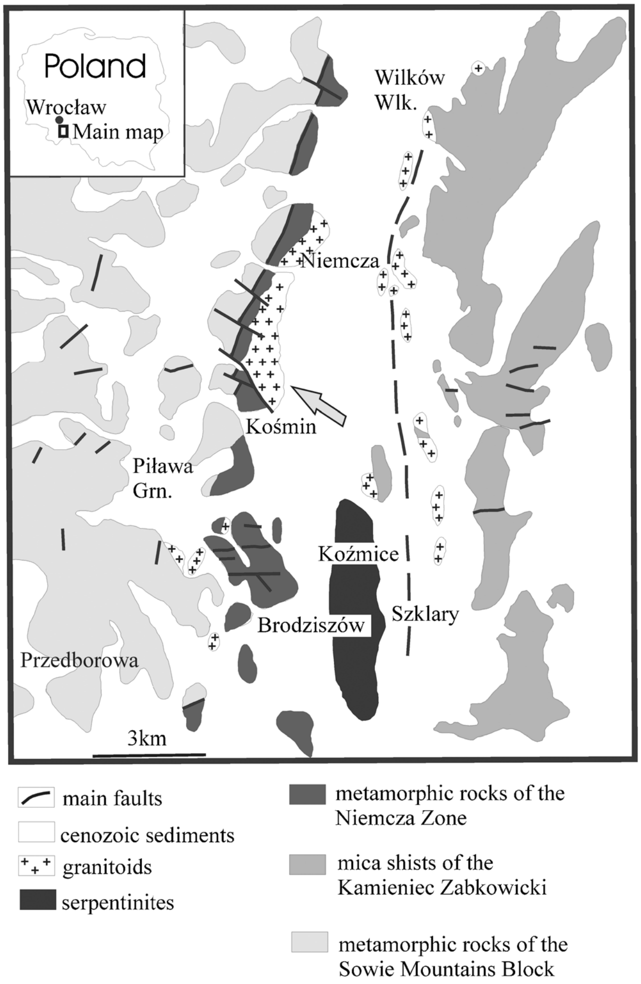


Fig. 1 Simplified geologic map of the Niemcza Zone, Sudetes (or Sudeten Mountains), southwestern Poland showing the location of the Kośmin Intrusion. Map modified after Lorenc and Kennan 2007)

Intrusive rocks occur in several places in the Niemcza Zone (Fig. 1) and they belong to two groups: dioritic and granodioritic (Dziedzicowa 1963). Both groups intruded contemporaneously during the Variscan orogeny (336–342 Ma, Oliver et al. 1993; Pietranik et al. 2013).

The rocks belonging to the granodioritic group (Kośmin type) are generally lineated and foliated and the fabric is subparallel to the penetrative fabrics in the surrounding rocks (Dziedzicowa 1963). They include granodiorites, quartz monzonites, quartz monzodiorites, and rare granites. The largest intrusions are at Kośmin and Koźmice (Fig. 1). The granodiorites are composed of different proportions of quartz, feldspars, biotite, and amphibole (Puziewicz 1992; Oberc-Dziedzic and Puziewicz 1995). Fine-grained dioritic enclaves are common in the granodioritic rocks. The temperature of granodioritic magma crystallization for the Koźmice granodiorite is estimated to be 730–850 °C and the pressure of emplacement 0.4 ± 0.1 GPa (Puziewicz and Radkowska 1990; Puziewicz 1992). The initial ^{87}Sr/^{86}Sr$_{338}$ was analyzed for Kośmin granodiorite and was determined to be 0.7077–0.7079 (Lorenc 1998; Lorenc and Kennan 2007).

The dioritic rocks (Przedborowa type) are undeformed and form fine-grained veins as separate intrusions or occur as enclaves in granodioritic rocks. They comprise monzodiorites, quartz diorites, and quartz syenites and belong to a high-K to ultrapotassic series (Dziedzicowa 1963; Pietranik et al. 2013). The largest occurrences are in Przedborowa (Fig. 1) and Kłosnik Hill. They are composed predominately of plagioclase, amphibole, and biotite with minor clinopyroxene and K-feldspar (Dziedzicowa 1963; Puziewicz 1987, 1988, 1990). For diorites from Przedborowa, the initial ^{87}Sr/^{86}Sr$_{338}$ is 0.70598 (Lorenc 1998; Lorenc and Kennan 2007).

Analytical procedures

Thirteen samples of microgranular enclaves and nine of granodiorite host were collected for this study. Thin sections from the samples were characterized by optical microscopy.

Whole rock geochemical analyses for five enclave samples and three granodiorites were done in the ACME Analytical Laboratory. Four of those enclave analyses were presented in Pietranik et al. (2013); the remaining data are presented in this study. The analytical procedures and uncertainties are also described in Pietranik et al. (2013).

For this detailed study of plagioclase, five enclave samples were selected. Four enclaves JG001, 002, 003, and 005 contained plagioclase phenocrysts and they are called porphyritic enclaves in the following text. In the fifth enclave, JG004, plagioclase phenocrysts are absent; it is hereafter called the primitive enclave.

Mineral compositions were analyzed by electron microprobe (a CAMECA SX-100, CAMECA, Gennevilliers, France) at the Institute for Mineralogy at Leibniz University Hannover, Germany, following methods described by Pietranik and Koepke (2009). Analytical conditions were 20 kV accelerating voltage, 40 nA sample current. The beam was defocused to 2 μm for Sr analyses, focused for other elements. Counting time was 10 s for major elements (both peak and background) and 180 s/90 s for peak and background for Sr. Detection limit for Sr was 200 ppm.

Three to six plagioclase phenocrysts and numerous smaller plagioclase grains were analyzed from each enclave sample (see Table S1 in Supplementary Material). Representative examples of other minerals were also analyzed (Table S1). Anorthite content in plagioclase grains were first assessed by core to rim or rim to rim traverses. Based on these preliminary analyses, the least altered grains were chosen for detailed analyses of major elements and Sr. The points within plagioclase grains to be analyzed for Sr were carefully selected to target and define all compositional variations within plagioclase and to avoid inclusions and areas of sericitization.

Granodioritic host and enclaves: petrography and geochemistry

The granodiorite is porphyritic with plagioclase forming most of the larger crystals (up to 1.5 cm along the c-axis, Fig. 2a). Rare K-feldspar forms larger grains up to 2.5 cm in length (Fig. 2c). The c-axes of plagioclase and K-feldspar crystals are commonly parallel to each other and the grains are surrounded by a fine- to medium-grained matrix composed of quartz, K-feldspar, biotite, and amphibole (Fig. 2c, e). Amphibole is mainly magnesio-hornblende (Fig. 3a). Accessories are predominately apatite and zircon. Light minerals (plagioclase, K-feldspar, quartz) comprise around 70 vol.% of the rock and dark minerals (amphibole and biotite) around 30 vol.%. The three samples of granodiorite collected for this study show similar concentrations of SiO2, MgO, CaO and Sr (Table 1). SiO2 content is around 58 wt.%, MgO ranges from 4.7 to 5.2 wt.% and CaO from 5.6 to 5.9 wt.%; Sr is between 460

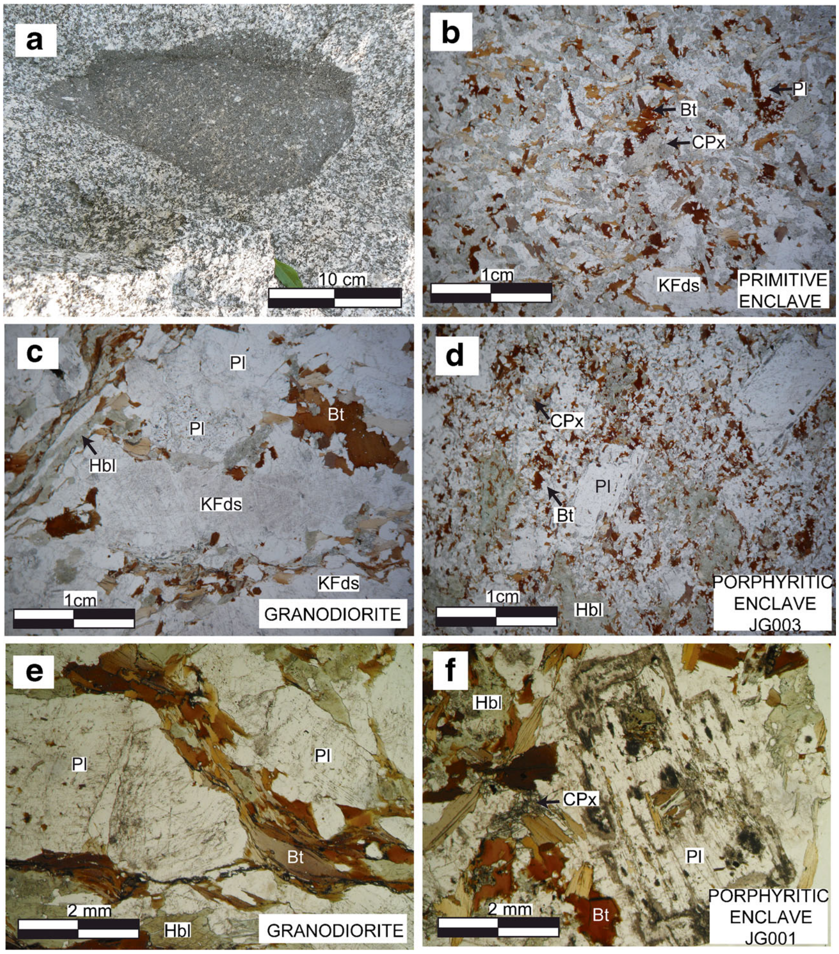


Fig. 2 **a** Field photo of monzodioritic porphyritic enclave and surrounding granodioritic host; images b, c, and d are stereoscopic microscope images of **b** primitive enclave, **c** granodiorite and **d** porphyritic enclave; images e and f are petrographic microscope images (*plane polarized light*) of **e** granodiorite and **f** porphyritic enclave

and 477 ppm (Fig. 4). All granodiorite samples are enriched in incompatible elements and the light REE's (Fig. 5). All samples have negative Eu, Nb, Ta, and Ti anomalies.

Enclaves are dark, fine-grained, and range from few centimeters to 1 meter in size (Fig. 2a). There are two types of enclaves, porphyritic enclaves and enclaves without phenocrysts (the primitive enclaves).

The porphyritic enclaves (JG001, JG002, JG003, JG005) contain plagioclase phenocrysts (Fig. 2a, d, f). The plagioclase may be one cm in the longest dimension, similar to those occurring in the host (Fig. 2c, e), but they are generally smaller than the largest plagioclase grains present in the granodiorite. The phenocrysts are surrounded by a fine-grained matrix composed of plagioclase, amphibole, clinopyroxene, biotite, K-feldspar, and quartz (Fig. 2d, f). Proportions of dark to light minerals are similar in the four porphyritic enclaves studied. Light minerals (plagioclase, K-feldspar, quartz) comprise around 35–45 vol.% of the rock and dark minerals (clinopyroxene, amphibole and biotite) around 55–65 vol.%.

The enclave without phenocrysts (JG004) is composed predominately of clinopyroxene, biotite, amphibole, K-feldspar, and plagioclase (Fig. 2b). Plagioclase is anhedral and surrounds euhedral mafic minerals. The enclave is rich in dark minerals (clinopyroxene, amphibole and biotite), which comprise around 80 vol.% of the rock. Because of its mineral and chemical composition (see below) and lack of plagioclase phenocrysts, the enclave is referred to here as a "primitive enclave."

In both types of enclaves, the mafic minerals have compositions similar to the mafics in the host (Fig. 3a, c). Amphibole in enclaves is Mg-hornblende to actinolite (Fig. 3a). Clinopyroxene occurs only in enclaves and it is all diopside (Fig. 3b). Plagioclase in the porphyritic enclaves has a higher anorthite content than plagioclase in the granodiorite or the primitive enclave (Fig. 3d).

The enclaves have different chemical compositions compared to that of granodiorite. SiO_2 content in the porphyritic enclaves is lower than in granodiorite and ranges from 50.9 to 55.3 wt.%, whereas MgO and CaO are higher than in granodiorite host and range from 5.9 to 7.1 wt.% and from 6.6 to 8.4 wt.%, respectively (Fig. 4). The JG005 enclave has, for many elements, a chemical composition closer to that of the granodiorite than all of the other porphyritic enclaves, but the other enclaves do not plot on what would be considered a compositional mixing line between the granodiorite and the primitive enclave (Fig. 4). Sr is slightly lower in the porphyritic enclaves than in the granodiorite and ranges from 434 to 456 ppm (Fig. 4). The primitive enclave has SiO_2 = 50.3 wt.% and MgO = 9.6 wt.%, CaO = 11.9 wt.%. The Sr content of this rocks is the lowest of any of the rocks analyzed for this study at 299 ppm (Fig. 4). All the enclaves are enriched in incompatible elements and light REE's and are characterized by

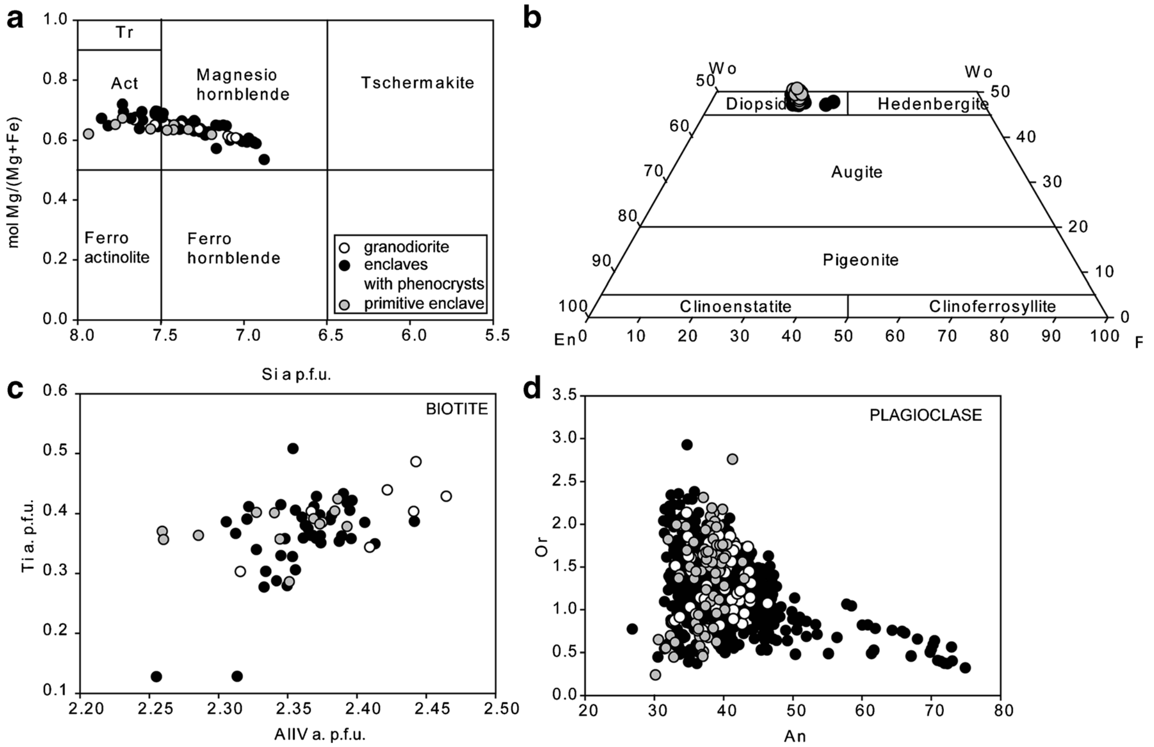


Fig. 3 Comparison of the composition of major minerals from the granodiorite and the enclaves, **a** amphibole; classification after Leake et al. (1997), **b** pyroxene; classification after Morimoto (1989), **c** biotite, **d** plagioclase

negative Eu, Nb, Ta, and Ti anomalies (Fig. 5). The primitive enclave has the highest LREE concentrations (Fig. 5).

Table 1 Major and trace element chemical composition of three granodiorite samples (GD1–GD3) and one enclave sample (JG005)

Sample	GD1	GD2	GD3	JG005
SiO_2	58.58	57.96	57.83	55.35
Al_2O_3	15.32	14.99	15.46	14.33
Fe_2O_3	6.33	7.01	6.83	7.27
MgO	4.67	5.16	5.03	6.6
CaO	5.72	5.64	5.89	6.68
Na_2O	2.9	2.59	2.86	2.3
K_2O	3.92	4.35	3.49	4.86
TiO_2	0.75	0.69	0.82	0.82
P_2O_5	0.39	0.41	0.41	0.38
MnO	0.1	0.12	0.11	0.13
LOI	0.9	0.6	0.9	0.8
Sum	99.63	99.56	99.66	99.57
Be	3	5	4	3
Sc	20	34	21	26
V	137	149	148	171
Co	38.4	35.8	40.9	53
Ni	47	40	42	62
Ga	19.5	18	19.2	17.3
Rb	173.9	163.1	178.7	188.9
Sr	477.4	460.2	462.9	434
Y	28.3	60.3	24.3	30.3
Zr	162.3	184.3	184.5	194.2
Nb	12.8	12.4	14.6	13.1
Sn	4	5	4	4
Cs	7.7	7.6	11.5	5.8
Ba	1,205	1,621	966	1,520
La	35.2	44.9	30	30.1
Ce	73.8	100.9	63.8	66.2
Pr	9.09	13.58	8.12	8.9
Nd	35.6	58.4	31.7	35.4
Sm	7.49	14.14	6.57	7.78
Eu	1.48	1.89	1.42	1.42
Gd	5.98	12.92	5.6	6.36
Tb	0.97	2.09	0.87	1.06
Dy	4.93	11.25	4.39	5.76
Ho	0.94	2.1	0.84	1.03
Er	2.55	5.75	2.32	2.83
Tm	0.39	0.82	0.32	0.44
Yb	2.4	4.89	2.12	2.74
Lu	0.34	0.66	0.33	0.39
Hf	4.7	5.8	5.7	5.1
Ta	0.8	1	1	0.7
Th	14.9	14.4	11.9	12.6
U	5.5	7	8.4	2.3

The whole rock geochemical analyses for the other enclave samples used in this study and the analytical procedures used are reported in Pietranik et al. (2013)

Plagioclase: zoning and composition

Granodiorite Plagioclase in granodiorite shows oscillatory zoning and the anorthite component ranges from An_{32} to An_{47} (Fig. 6a, b). The plagioclase grains contain small inclusions of biotite, amphibole and K-feldspar (Fig. 6a, b). Orthoclase content ranges from 0.7 to 2.4 mol% and Sr concentrations are between about 550 ppm and 900 ppm (Fig. 7).

Primitive enclave Plagioclase in the primitive enclave is subhedral to anhedral (Fig. 6f) and the grains are smaller than those in the granodiorite and the plagioclase phenocrysts in the porphyritic enclaves (Fig. 6). The An content ranges from An_{30} to An_{43} and the variations within a single grain are less pronounced than those in plagioclases from the granodiorite or the porphyritic enclaves. Most of the grains have An contents ranging from An_{34} to An_{43} and one grain has a notably lower An content, An_{30} to An_{35}. Orthoclase content in these feldspars ranges from 0.6 to 2.4 mol% and Sr concentration are around 250 to 900 ppm (Fig. 7).

Porphyritic enclave Plagioclase grains in all the porphyritic enclaves are similar petrographically in that they occur both as larger phenocrysts (up to several mm in the longest dimension, Fig. 6c, d, e; Fig. 8) and as smaller grains in the surrounding matrix (less than 0.5 mm, Fig. 9).

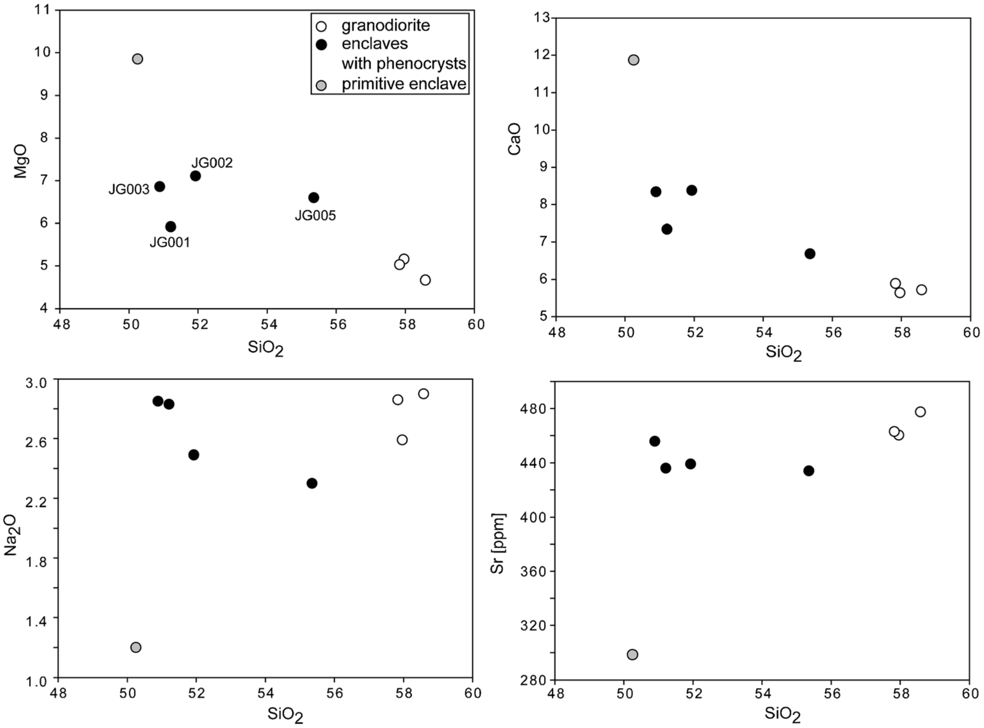
Based on observations of five to eight grains from each enclave, the plagioclase phenocrysts have three zones:

1. A core with $An_{32–52}$ which may contain numerous inclusions of other minerals (mainly K-feldspar, biotite, apatite, and amphibole — Fig. 6c, d, e).

   The An content in the core varies in an oscillatory manner from An_{31} to An_{47}. This arrangement of zones of different An content and inclusions is similar to that observed in the granodiorite plagioclase grains.
2. A high An zone characterized by an abrupt increase in An content from that in the interior (up to An_{72} — Fig. 8).

   This zone is invariably located approximately 100 μm from the crystal rim and is usually 50–100 μm wide. The An content is irregular within the zone varying in an oscillatory or patchy manner from An_{45} to An_{72} (Fig. 8c). The high An zone usually follows the euhedral shape of the core but the zone is not continuous and gaps in it are filled with plagioclase of core or rim composition (Fig. 8d). The high An zones are easily visible under the microscope when the high An zone is sericitized and the

Fig. 4 Whole rock MgO, CaO, Na_2O and Sr concentrations plotted against SiO_2 for in granodiorites, porphyritic enclaves, and the primitive enclave



gaps are filled with clear, unaltered plagioclase (Fig. 2f). In some places inclusions of other minerals occur within the high An zone (Fig. 8c). A high An zone was not analyzed in the JG001 enclave because the zones in that sample are strongly sericitized (Fig. 7). The zones in that thin section are probably similar to those in the other enclaves, however, as suggested by the shape of the sericitized material (Fig. 2f).

3. A normally zoned rim that surrounds the high An zone (Fig. 8).

   The An content in the rim decreases from An_{47} to An_{30} but individual rims may exhibit a less pronounced decrease in An such as from An_{45} to An_{35}. The change in An content between high An zone and rim is very abrupt (Fig. 8a, b, c).

Matrix plagioclase grains in the porphyritic enclaves may include zones similar to those in the phenocryst plagioclases (core, high An zone and rim, Fig. 9a), but more commonly they have a high An zone as the core surrounded by a normally zoned rim (Fig. 9b) or the whole grain is normally zoned similar to the rims on the phenocryst plagioclase grains. These latter matrix grains do not contain high An-plagioclase (Fig. 9c, d). Overall, however, the matrix plagioclases have An and Or ranges similar to those exhibited by the phenocryst plagioclase grains as well as similar Sr concentrations (Fig. 10).

Comparison of plagioclase analyses from the porphyritic enclaves shows that An and Or ranges are similar in all the enclaves for the high An zones, the cores, and the rims (Figs. 7 and 10). Sr content differs between different porphyritic enclaves and it is higher in plagioclase rims in enclaves JG003 and JG005 (up to 1,000 ppm) than in JG002 (up to 900 ppm) and the lowest is in JG001 (up to 830 ppm, Fig. 7). These modest differences do not correlate with the differences in whole rock Sr content (Fig. 4).

Comparison of the plagioclase compositions among only the five enclaves themselves (Fig. 7) shows that the range in An content in plagioclase from the primitive enclave is more restricted than the An content range in the plagioclases from the porphyritic enclaves (Fig. 7a). Anorthite component below An_{34} is scarce in the plagioclase from the primitive enclave (present only in a single grain), whereas such low values are common in many of the grains in the porphyritic enclaves (Fig. 3d). The Sr concentrations in the primitive enclave plagioclase range more widely than it does in the plagioclase from the porphyritic enclaves and also extends to lower values (Fig. 7c). The proportion of Or in plagioclase is similar between both enclave types but extends to higher values for the primitive enclave than it does for the four porphyritic enclaves.

Discussion

Magma mixing processes recorded in plagioclase

The similarity of structure, chemical composition, and zonation style of the cores of plagioclase phenocrysts from the

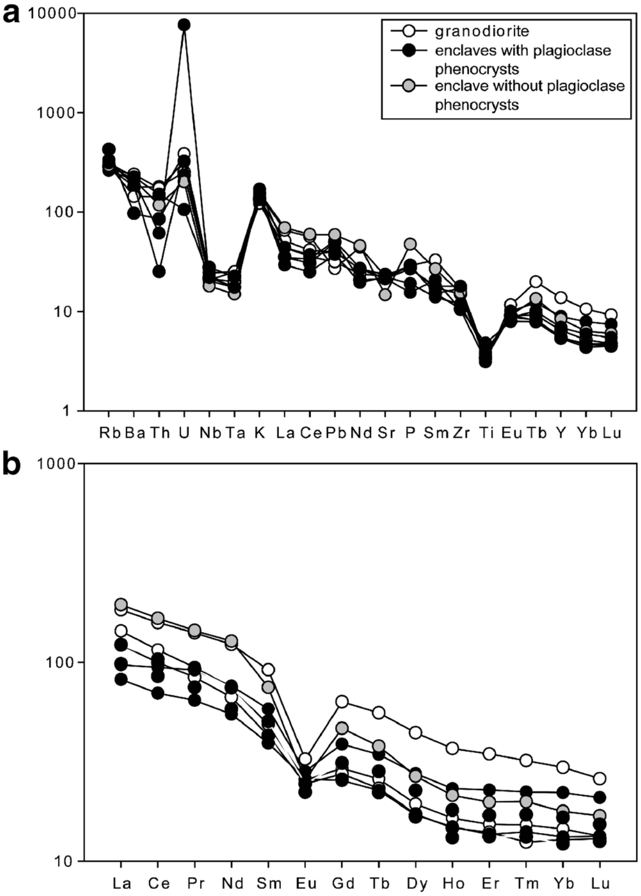


Fig. 5 **a** Primitive mantle normalized incompatible trace element diagram for granodiorite, primitive enclave and porphyritic enclaves. The normalizing values are from Sun and McDonough 1989. **b** chondrite-normalized REE patterns for the same samples shown in a). The normalizing values are from Anders and Grevesse 1989

porphyritic enclaves with plagioclases from the host granodiorite implies the transfer of plagioclase from the host granodioritic magma into the monzodioritic magma via magma mixing. Absence of plagioclase phenocrysts in the primitive enclave suggests that interaction between this enclave and the host magma was limited. Therefore, the whole rock composition of the porphyritic enclaves must have been modified by interaction with the granodioritic magma, whereas the primitive enclave composition is less hybridized and closer to the original mafic magma that was injected into the host.

The mixing process probably proceeded by both crystal and melt transfer and it is difficult to separate those two processes by studying only the whole rock compositions. However, plagioclase commonly shows marked zoning because of sluggish NaSi-CaAl interdiffusion and therefore a transferred plagioclase crystal has the potential to record changes in the melt composition from which it crystallized and to provide more detailed information on the magma mixing process.

In the Kośmin intrusion, magma mixing was recorded in the plagioclase of each analyzed porphyritic enclave in a similar way despite the differences in their whole rock composition. In each case, the transferred plagioclase was slightly resorbed and an approximately 100 μm wide, high An zone (up to An$_{72}$) was produced on its rim. This was followed by crystallization of a low An rim (up to An$_{47}$). The An variations in the high An zone are expressed in an oscillatory or patchy manner. Similar zonation has been observed in plagioclase from other intrusions containing mafic enclaves (e.g. see Elburg 1996 for an example from Australia, Janousek et al. 2004 for an example from the Czech Republic). These and other occurrences suggest that a common process may be responsible for plagioclase resorption when plagioclase is transferred from more felsic to more mafic magma.

High An zones can be formed by a number of different mechanisms including an increase in temperature, changes in water fugacity, or changes in the melt composition. For example, the plagioclase solidus and liquidus are strongly depressed when water activity increases in the system (Housh and Luhr 1991; Nekvasil 1992), whereas plagioclase composition is only slightly affected by pressure change with fixed water content (Nekvasil 1992). In natural systems, resorption of plagioclase and crystallization of high An zones has been attributed to many different processes including changes in magma composition due to recharge of more mafic magma (e.g. Tepley et al. 1999; Ginibre et al. 2002; Browne et al. 2006; Nicotra and Viccaro 2012), transfer of crystals between two different magmas (e.g. Waight et al. 2000), or transfer within one magma with temperature or water content gradients (e.g. Loomis and Welber 1982). In the Kośmin intrusion, the high An zone formed after the plagioclase was transferred from the granodioritic magma with a relatively low Ca/Na ratio (around 2.3, on a molar basis) into monzodioritic magma with significant higher Ca/Na ratio (around 11). Such a process should induce crystallization of higher An plagioclase that would be in equilibrium with a higher Ca/Na melt. However, interestingly, plagioclase that presumably crystallized originally in the higher Ca/Na melt (the primitive enclave) has a lower An content (only up to An$_{43}$) than that of high An zones (up to An$_{72}$, Fig. 9). Therefore, crystallization of plagioclase with An$_{50–72}$ cannot be solely attributed to crystallization from the primitive magma. We hypothesize that it is the hybridization process that induces dissolution of plagioclase and subsequent crystallization (reprecipitation) of the high An zones. If the granodiorite contained more water than the mafic melt (as suggested by the common occurrence of hornblende and biotite in the host granodiorite) then hybridization (mixing) could lead to an increase in water content in the enclave magma. This hypothesis is supported by the decreasing ratio of clinopyroxene to hornblende in the porphyritic enclaves compared with the primitive enclave. The consumption of clinopyroxene and production of hornblende would also produce a higher Ca/Na melt which would be in equilibrium with the higher An plagioclase.

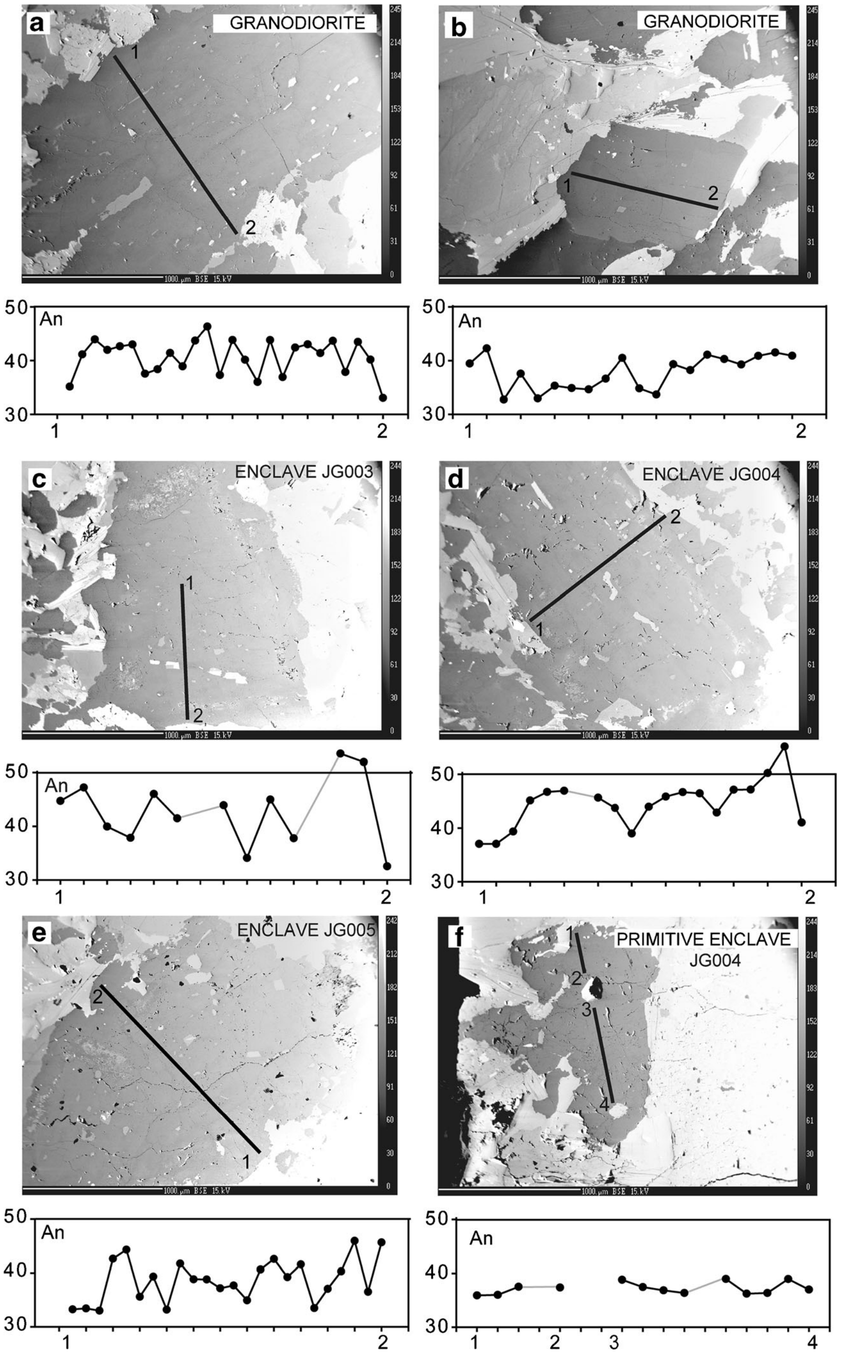


Fig. 6 Photomicrographs of representative plagioclase from granodiorite, porphyritic enclaves, and the primitive enclave. *Black lines* indicate the lines of traverse along which preliminary microprobe analyses were collected. Anorthite content along the traverse of each plagioclase is shown in the graph below the photomicrograph, *grey lines* mark gaps in the traverses resulting from failed analyses (e.g. low totals, analyses mixed with secondary minerals or inclusions)

Another potential record of the conditions of plagioclase crystallization comes from the plagioclase Sr content. Comparison of Sr concentration in plagioclase within a single porphyritic enclave may provide information on the evolution of melt composition as the plagioclase crystallized. The composition of plagioclase in the JG003 and JG005 enclaves is similar and these enclaves preserve the most complete record of plagioclase crystallization. However, these two enclaves differ in whole rock composition with JG005 being closer to the granodiorite composition and being the only enclave plotting on the theoretical mixing line between the granodiorite and the primitive enclave (Fig. 4). JG001, 002 and 003 all have lower MgO and CaO contents and higher Na_2O and Sr than would be generated by simple mixing of two magmas having the compositions of the primitive enclave and the granodiorite (Fig. 4). This indicates that some processes in addition to magma mixing were responsible for the evolution of the whole rock composition. Probable processes include fractional crystallization of enclave magma or compositional differences inherited from the magma source (e.g. Słaby and Martin 2008). However, despite differences in whole rock composition between porphyritic enclaves JG005 and

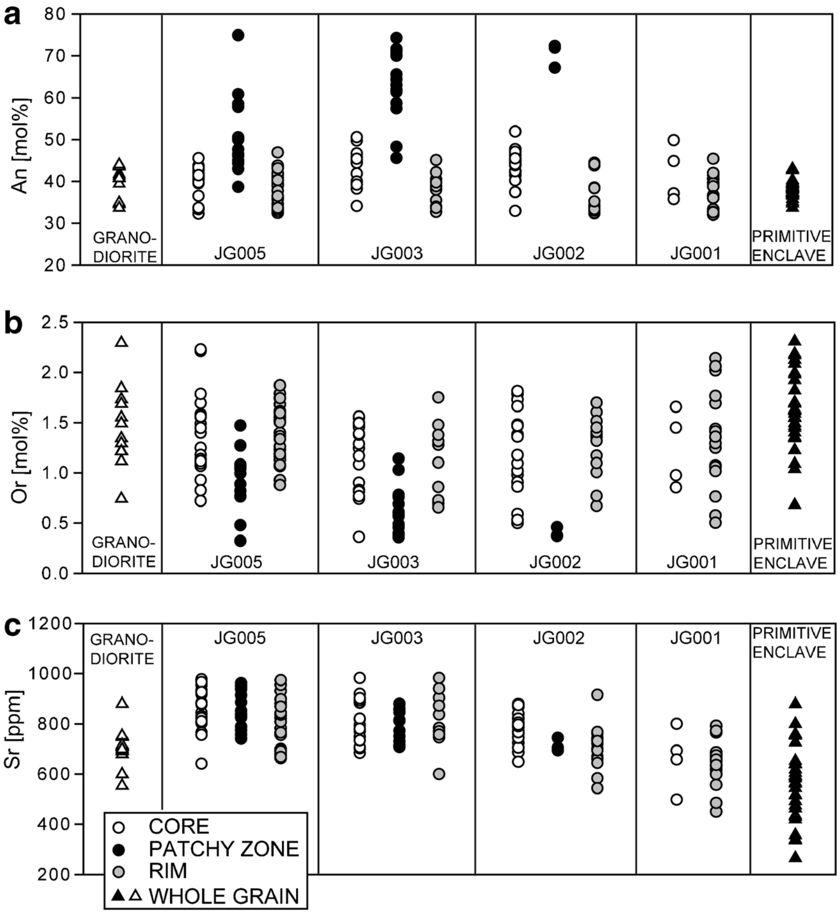


Fig. 7 Comparison of the anorthite and orthoclase component and the Sr content of plagioclase from granodiorite, porphyritic enclaves, and the primitive enclave

JG003, the An and Sr in their plagioclases are generally similar suggesting that the evolution of melt during plagioclase dissolution/reprecipitation was also similar.

Strontium partitioning depends on An content in the melt and it is higher for plagioclase richer in albite component (Bindeman et al. 1998; Zajacz and Halter 2007; Severs et al. 2009). Therefore, the similar Sr concentrations in the cores, high An zones, and the rims of the plagioclase from the porphyritic enclaves would suggest an increase in Sr in the melt after the plagioclase transfer into the enclave and then a decrease in Sr as the low An rim crystallized. This is contrary to what is expected from the whole rock composition. In Kośmin, the mafic magma should have lower Sr concentrations than the felsic host as suggested by whole rock Sr content in the primitive enclave (around 300 ppm) and in the granodiorite (460–480 ppm). The probable explanation for the increase in Sr in the melt during the high An zone crystallization is that plagioclase was a late phase in the primitive enclave and it started crystallizing only after the onset of hybridization and plagioclase transfer from the granodioritic melt. Consequently, the partially crystallized enclave melt could be enriched in Sr because Sr is incompatible in early crystallizing mafic minerals. This is consistent with the high Sr observed in some plagioclase grains from the primitive enclave (Fig. 7). The plagioclase with the highest Sr content probably crystallized shortly after plagioclase saturation in the primitive enclave melt. The decrease in Sr in the melt after high An zone crystallization is expected owing to extensive plagioclase crystallization in the fine grained matrix. The plagioclase crystallized from the primitive enclave shows a decrease in Sr content down to values lower than those observed in plagioclase rims from the porphyritic enclaves (Fig. 7). This is consistent with the overall higher Sr content during rim crystallization in porphyritic enclaves compared with that in the primitive enclave. The higher Sr contents were probably induced by mixing of the higher Sr concentration granodiorite melt with the original primitive magma. It is interesting to note that the mixing between a more primitive melt lower in Sr and a felsic melt higher in Sr is recorded in plagioclase rims but not in the high An zone crystallized immediately after the plagioclase transfer.

The comparison of plagioclase compositions between different enclaves and the granodiorite host shows low concentrations of Sr in plagioclases from the granodiorites compared with plagioclase cores from two porphyritic enclaves (JG005 and JG003). This may reflect heterogeneities in Sr

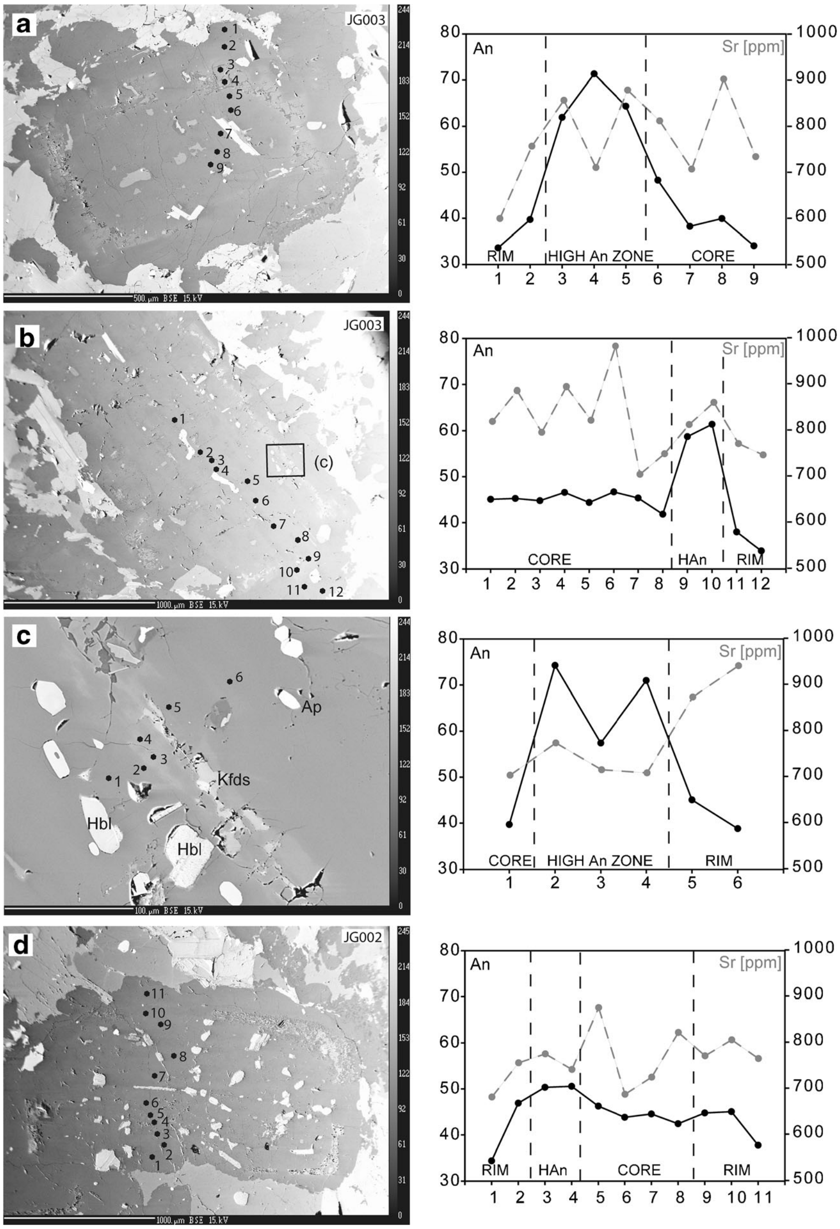


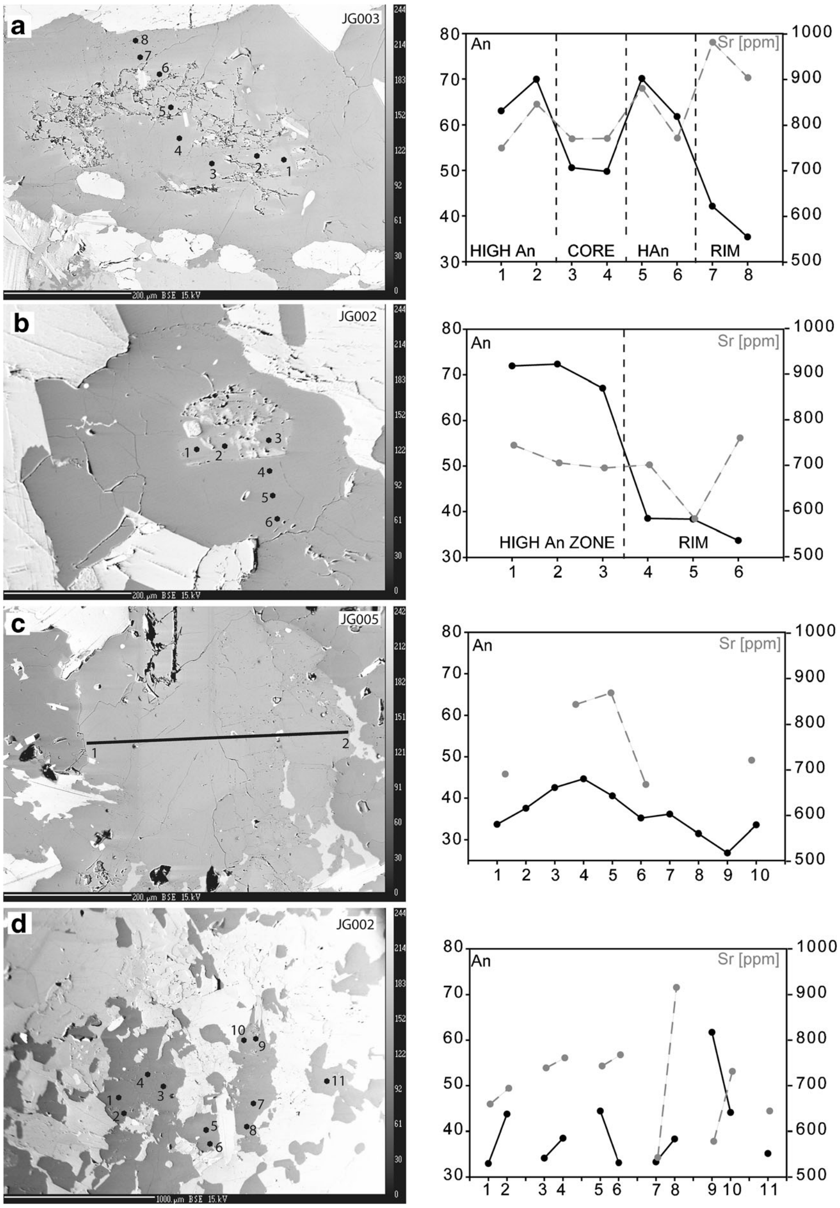
Fig. 8 Photomicrographs of representative plagioclase phenocrysts from the enclaves with numbered dots showing the locations of microprobe analyses. An (*solid*) and Sr (*dashed*) microprobe analyses from the traverse lines are shown to the right. The rectangular box labeled "(*c*)" in photomicrograph b is the area shown in photomicrograph c. See text for the description of how the "*core*," "*high An*" and "*rim*" zones were defined

concentration in the granodioritic host or may be due to a lack of analyses of the cores of the largest plagioclase grains in the granodiorite. These large grains were probably the earliest phases to crystallize in the granodiorite magma and should have the highest Sr content. Another possibility is that the whole rock composition does not reflect the composition of the magma from which the plagioclase crystallized because of later hybridization and/or accumulation effects. Thus, it is difficult to use variations in Sr concentrations in plagioclase between enclaves in Kośmin to provide information on mixing process — there are too many variables affecting Sr partitioning. Differences in Sr concentration in plagioclase from porphyritic enclaves probably record differences in melt composition, but these may arise either from inherited heterogeneities in the granodioritic magma or from the mixing of different proportions of host/enclave magma with initially different Sr contents. The two processes cannot be resolved on the basis of Sr concentration alone and without more exhaustive analyses of the granodiorite plagioclases.

Comparisons between plutonic plagioclases

We compared plagioclase from the Kośmin intrusion to plagioclase from enclaves in another Variscan granitoid rock in Poland, the Gęsiniec Intrusion (Pietranik and Koepke 2009). Plagioclases from enclaves in the two intrusions have different anorthite versus orthoclase distributions (Fig. 11). These

Fig. 9 Photomicrographs of representative matrix plagioclases from the enclaves with numbered dots showing the locations of microprobe analyses. Anorthite and Sr microprobe analyses from the traverse lines are shown to the right. See text for the description of how the "*core*," "*high An*" and "*rim*" zones were defined



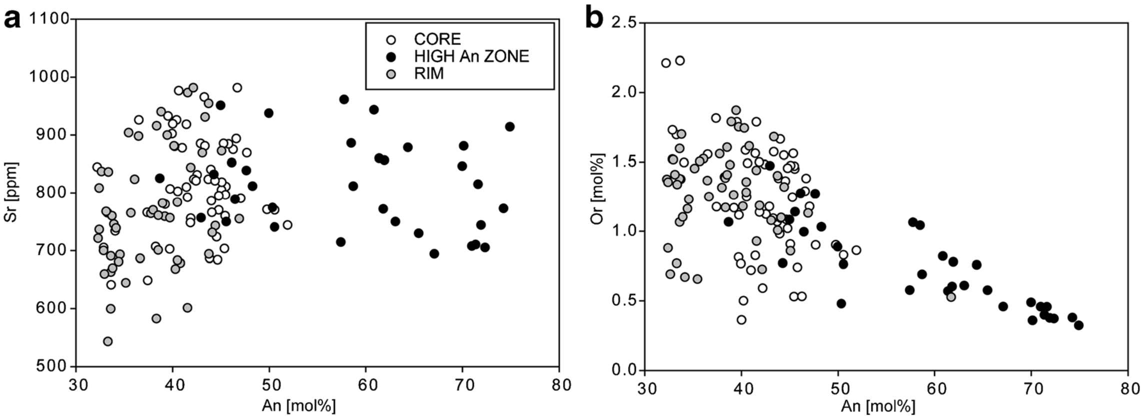


Fig. 10 Graphs of An component versus Or component and Sr for plagioclases from the enclaves. See text for descriptions of how "*core*," "*high An*" and "*rim*" zones were defined

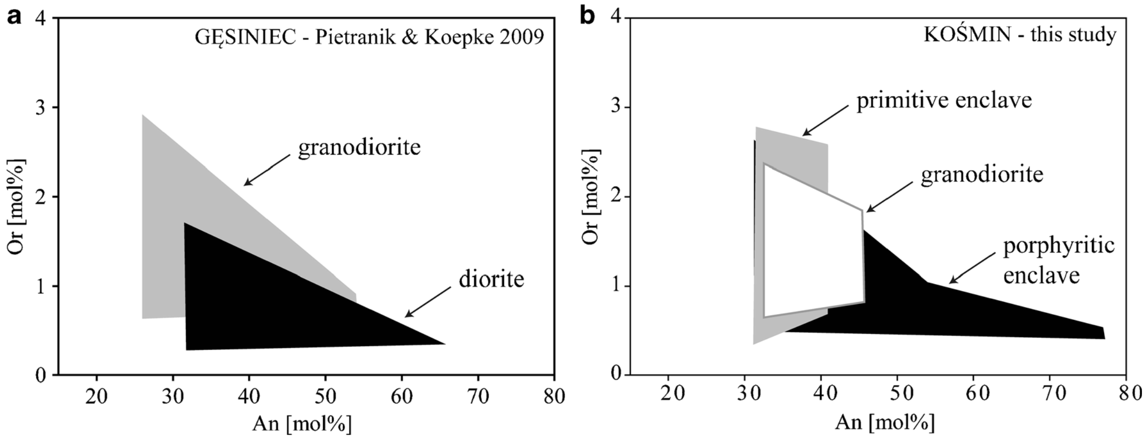


Fig. 11 Graphs of An versus Or for plagioclase from **a** the Gęsiniec Intrusion (modified after Pietranik and Koepke 2009) and from **b** this study

differences probably reflect different processes during host-enclave interaction. Pietranik and Koepke (2009) suggested that different An versus Or distribution, as well as different minimum An content, in plagioclase from granodioritic host and dioritic enclave in the Gęsiniec Intrusion (Fig. 9a) indicate that the two magmas did not mix. Instead, a dioritic dike was destroyed by the intruding granodiorite and a mostly solid diorite was incorporated into the granodiorite. The diorite dike rock was affected only by late magmatic processes. In the Kośmin intrusion both host and enclave plagioclase are characterized by similar distribution of An versus Or and similar minimum An content (Fig. 9b), whereas the primitive enclave generally has a higher minimum An content. We suggest that this is the result of mixing between granodiorite and primitive monzodiorite magmas and crystallization of plagioclase rims in porphyritic enclaves from the hybrid melt rich in granodiorite component. On the other hand, the different An-Or distribution for plagioclase in the primitive enclave is consistent with only limited interaction of the enclave with the granodioritic host.

The different An versus Or patterns (Fig. 11) for the Kośmin and Gęsiniec intrusions indicate that An and Or composition of plagioclase is an easily applied, straightforward tool that may help to distinguish between magmatic and late-magmatic scenarios of diorite-granodiorite interaction. This is important because plagioclases commonly exhibit similar zoning and the grains typically have of a zone with high An content surrounded by a zone with much lower An. We suggest that An-Or distribution in plagioclase in other intrusions be investigated to determine if this observation has any general applicability.

Conclusions

Two types of mafic microgranular enclaves occur in the granodioritic host in the Kośmin Intrusion: primitive enclaves that were not affected by magma mixing and porphyritic enclaves that were hybridized with granodioritic magma. The plagioclase from the porphyritic enclaves analyzed in this study records magma mixing processes between granodioritic host and monzodioritic magmas. The enclave plagioclases have cores with similar An content and identical oscillatory zoning as plagioclases in the granodiorite, implying that the cores were resorbed, probably subsequent to the transfer of the plagioclases from the granodioritic to the monzodioritic magma. The plagioclases have a thin high-An zone near the rim. The high-An zone, crystallized after resorption of the transferred plagioclase, is consistent with a simple, one-way transport of plagioclase from the granodioritic host to the enclaves. High An plagioclase in the matrix crystallized from a hybridized magma which probably had a higher water content than the melt of the primitive enclave was also more mafic and hotter than the magma of the granodioritic host. Sr concentration in plagioclase indicates that transfer took place before the onset of plagioclase crystallization in the enclave magma, and extensive crystallization of plagioclase proceeded after the plagioclase grains were incorporated into the enclave magma. The Sr concentration in the hybrid melt was higher than in the primitive magma, but the mixing with higher Sr magma was recorded only in plagioclase rims and not in the high An zone. Hybridization in the system is also recorded in the plagioclases by the An versus Or distribution. The An versus Or distribution is similar for porphyritic enclaves that have interacted with hybrid magmas but different for primitive enclaves that were not affected by mixing. The implication is that plagioclase populations as a whole may record the general processes that lead to mafic-felsic magma interaction. In the case of the Kośmin intrusion, the similarity between An versus Or distribution in plagioclase from the granodioritic host and the enclaves suggests interaction during the main magmatic stage, i.e. magma mixing and transfer of granodioritic melt into the enclave. In a case where the interaction took place during the late magmatic stage, the distribution of An versus Or in plagioclase crystallized in felsic and mafic magmas would have been different.

Acknowledgments J. Gruszczynska and A. Winiecka helped to locate representative samples of the Kośmin enclaves. Master thesis of J. Gruszczynska (Gruszczynska 2010) contributed to this manuscript. AP acknowledges grant no. N N307 105235 by the Polish Ministry of Science and Higher Education. Comments by Marco Viccaro and an anonymous reviewer and the editor Martin Okrusch are gratefully acknowledged.

References

Adamuszek M, John T, Dabrowski M, Podladchikov YY, Gertisser R (2009) Assimilation and diffusion during xenolith-magma interaction: a case study of the Variscan Karkonosze Granite, Bohemian Massif. Miner Petrol 97:203–222

Anders E, Grevesse N (1989) Abundances of the elements: meteoric and solar. Geochim Cosmochim Acta 53:197–214

Bindeman IN, Davis AM, Drake MJ (1998) Ion microprobe study of plagioclase-basalt partition experiments at natural concentration level of trace elements. Geochim Cosmochim Acta 62:1175–1193

Browne BL, Eichelberger JC, Patino LC, Vogel TA, Uto K, Hoshizumi H (2006) Magma mingling as indicated by texture and Sr/Ba ratios of plagioclase phenocrysts from Unzen volcano, SW Japan. J Volcanol Geotherm Res 154:103–116

Dziedzicowa H (1963) “Syenites” of the Niemcza Zone. Arch Mineral 24:5–109 (in Polish)

Elburg MA (1996) Evidence of equilibration between microgranitoid enclaves and host granodiorite, Warburton Granodiorite, Lachlan Fold Belt, Australia. Lithos 38:1–22

Ginibre C, Wörner G (2007) Variable parent magmas and recharge regimes of the Parinacota magma system (N. Chile) revealed by Fe, Mg and Sr zoning in plagioclase. Lithos 98:118–140

Ginibre C, Kronz A, Wörner G (2002) Minor-and trace-element zoning in plagioclase: implications for magma chamber processes at Parinacota volcano, Northern Chile. Contrib Mineral Petrol 143: 300–315

Gruszczynska J (2010) Magma differentiation in granodiorite from Kosmin: geochemical modeling in micro-scale. Master thesis, University of Wroclaw

Housh T, Luhr JF (1991) Experimental plagioclase-melt equilibria for water-saturated andesite and basalt. Am Mineral 76:477–492

Janousek V, Braithwaite CJR, Bowes DR, Gerdes A (2004) Magma mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Sazava intrusion, Central Bohemian Pluton, Czech Republic. Lithos 78:67–99

Kocak K, Zedef V, Kansun G (2011) Magma mixing/mingling in the Eocene Horoz (Nigde) granitoids, Central Southern Turkey: evidence from mafic microgranular enclaves. Mineral Petrol 103: 149–167

Leake BE, Woolley AR, Arps CE, Birch WD, Gilbert MC, Grice JD, Hawthorne FC, Kato A, Kisch HJ, Krivovichev VG et al (1997) Nomenclature of amphiboles; report of the subcommittee on amphiboles of the International Mineralogical Association, Commission on New Minerals and Mineral Names. Am Mineral 82:1019–1037

Loomis TP, Welber PW (1982) Crystallization processes in the rocky hill granodiorite pluton, California: an interpretation based on compositional zoning of plagioclase. Contrib Mineral Petrol 81:230–239

Lorenc MW (1998) Rb-Sr isotope study of the Niemcza Zone intrusive rocks (Lower Silesia). Arch Mineral 51:153–164 (in Polish)

Lorenc M, Kennan P (2007) Intrusive rocks from the Niemcza zone (Lower Silesia, Poland) in the light of petrologic and Rb-Sr isotope studies. Arch Mineral Monogr 1:253–259

Morimoto N (1989) Nomenclature of pyroxenes. Subcomission of new minerals and mineral names. International mineralogical association. Can Mineral 27:143–156

Nekvasil H (1992) Feldspar crystallization in felsic magmas: a review. Trans R Soc Edinb Earth Sci 83:399–407

Nicotra E, Viccaro M (2012) Unusual magma storage conditions at Mt. Etna (Southern Italy) as evidenced by plagioclase megacryst-bearing lavas: implications for the plumbing system geometry and summit caldera collapse. Bull Volcanol 74:795–815

Oberc-Dziedzic T, Puziewicz J (1995) Age and origin of granitoids from the Fore-Sudetic Block (in Polish). Przewodnik LXVI Zjazdu PTG: 273–284

Oliver GJH, Corfu F, Krough TE (1993) U-Pb ages from SW Po land: evidence for a Caledonian suture zone between Baltica and Gondwana. J Geol Soc Lond 150:355–369

Perugini D, Petrelli M, Poli G (2006) Diffusive fractionation of trace elements by chaotic mixing of magmas. Earth Planet Sci Lett 243: 669–680

Pietranik A, Koepke J (2009) Interactions between dioritic and granodioritic magmas in mingling zones: plagioclase record of mixing, mingling and subsolidus interactions in the Gęsiniec Intrusion, NE Bohemian Massif, SW Poland. Contrib Mineral Petrol 158(1):17–36

Pietranik A, Storey C, Kierczak J (2013) Niemcza diorites and monzodiorites (Sudetes, SW Poland): a record of changing geotectonic setting at ca. 340 Ma. Geol Q 57(2):325–334

Puziewicz J (1987) Petrography, origin and autometamorphism of quarto-syenite and pegmatite from Piława Górna. Arch Mineral 43:5–22 (in Polish)

Puziewicz J (1988) Plagioclase-pyroxene-biotite rock from the Koźmice quarry, Niemcza zone (Sudetes, SW Poland): The first occurrence of vaugnerite in Polish Sudetes. Mineral Pol 19(2):59–66

Puziewicz J (1990) Amphiboles and other accompanying Fe-Mg minerals from quartz- monzodiorite from Przedborowa (Lower Silesia). Arch Mineral 45(1–2):61–78 (in Polish)

Puziewicz J (1992) Origin of the Koźmice granodiorite (Niemcza zone, Lower Silesia). Arch Mineral 47(2):95–146 (in Polish)

Puziewicz J, Radkowska M (1990) Forms of the zircon crystals from granitoids and syenitoids/dioritoids from the Niemcza Zone (Lower Silesia): insight into the magma petrogenesis. Arch Mineral 46(1–2):123–143 (in Polish)

Severs MJ, Beard JS, Fedele L, Hanchar JM, Mutchler SR, Bodnar RJ (2009) Partitioning behavior of trace elements between dacitic melt and plagioclase, orthopyroxene, and clinopyroxene based on laser ablation ICPMS analysis of silicate melt inclusions. Geochim Cosmochim Acta 73:2123–2141

Shcherbakov VD, Plechov PY, Izbekov PE, Shipman JS (2011) Plagioclase zoning as an indicator of magma processes at Bezymianny volcano, Kamchatka. Contrib Mineral Petrol 162:83–99

Słaby E, Martin H (2008) Mafic and felsic magma interaction in granites: the hercynian karkonosze pluton (Sudetes, bohemian massif). J Petrol 49:353–391

Słaby E, Śmigielski M, Śmgielski T, Domonik A, Simon K, Kronz A (2011) Chaotic three-dimensional distribution of Ba, Rb, and Sr in feldspar megacrysts grown in an open magmatic system. Contrib Mineral Petrol 162:909–927

Sun SS, McDonough WF (1989) Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes.

In: Saunders AD, Norry MJ (eds). Magmatism in the Ocean Basins. Geol Soc London, Special Publications 42:313–345

Tepley FJ III, Davidson JP, Clynne MA (1999) Magmatic interactions as recorded in plagioclase phenocrysts of chaos crags, Lassen volcanic center, California. J Petrol 40(5):787–806

Viccaro M, Giacomoni PP, Ferlito C, Cristofolini R (2010) Dynamics of magma supply at Mt. Etna volcano (Southern Italy) as revealed by textural and compositional features of plagioclase phenocrysts. Lithos 116:77–91

Waight TE, Maas R, Nicholls IA (2000) Fingerprinting feldspar phenocrysts using crystal isotopic composition stratigraphy: implications for crystal transfer and magma mingling in S-type granites. Contrib Mineral Petrol 139:227–239

Xiong FH, Ma CQ, Zhang JY, Liu B (2012) The origin of mafic microgranular enclaves and their host granodiorites from East Kunlun, Northern Qinghai-Tibet Plateau: implications for magma mixing during subduction of Paleo-Tethyan lithosphere. Miner Petrol 104:211–224

Zajacz Z, Halter W (2007) LA-ICPMS analyses of silicate melt inclusions in co-precipitated minerals: quantification, data analysis and mineral/melt partitioning. Geochim Cosmochim Acta 71: 1021–1040