

**Continuous magma mixing and cumulate separation in the High Tatra
Mountains open system granitoid intrusion, Western Carpathians
(Poland/Slovakia): a textural and geochemical study.**

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ABSTRACT

In this study the formation of the polygenetic High Tatra granitoid magma is discussed. Felsic and mafic magma mixing and mingling processes occurred in all magma batches composing the pluton, but were developed to different extents. The magma mixing and mingling processes are documented by the typical textural assemblages, which include: mafic microgranular enclaves (MME), mafic clots, felsic clots, quartz-plagioclase-titanite ocelli, biotite-quartz ocelli, poikilitic plagioclase crystals, chemically zoned K-feldspar phenocrysts with inclusion zones and calcic spikes in zoned plagioclase. Geochemical modelling indicates the predominance of the felsic component in subsequent magma batches, however, the amount of mafic component increased with time. Magma mixing is considered to be a first-order magmatic process, causing the magma diversification. Influx of mafic, low viscosity and volatile-rich magma stimulated the formation of cumulates, both mafic and alkali feldspar-dominated types. The cumulate formation and the squeezing of remnant melt by filter pressing points to fractional crystallization acting as a second-order magmatic process. Mantle origin of the admixed magma input is suggested on the basis of geochemical and Rb-Sr, Sm-Nd and Pb-Pb isotopic data.

Key words: Tatra granitoids, magma mixing, cumulate formation

1. Introduction

Most of the granitoid magmas are the result of complex interplay of many processes, involving the interaction of different melts. The interaction of melts from different sources, called magma mixing, regarding variable proportions of the end-member components, produces characteristic textural

assemblage, used to identify the mixing phenomena (Hibbard 1991; Baxter and Feely 2002), mineral characteristics (Müller et al. 2005; Słaby et al. 2008) and the geochemical and isotopic compositions of the mixed magmas (Frost and Mahood 1987; Burda et al. 2011). Typically linear element covariations are a characteristic feature of the hybrid magmas, but they cannot be used as an unequivocal criterion, as similar trends could result from several processes, such as a small degree of magma fractionation and cumulate separation (Fourcade et al. 1992; Wiebe et al. 2002; Słaby and Martin 2008).

Magma mixing, which typically causes thermal and mechanical instabilities in magma can lead, together with shearing during flow, to the formation of magmatic cumulates and layering (Vernon and Paterson 2008 and references therein). An assumption of magma mixing also allows us to understand the formation of other sedimentary-like structures, providing information about magma migration, batholith construction and cooling (Paterson et al. 1998; Žak et al. 2009; Gawęda and Szopa 2011). As the magmatic histories of granitoid plutons can span a long time (e.g. Müller et al. 2005; Miller et al. 2011) the incremental assembly of discrete magma pulses is considered to be a typical mode of their construction (e.g. Coleman et al. 2004; Glazner et al. 2004; Paterson et al. 2011).

In this study we deal with the synkinematic, polygenetic Tatra granitoid pluton formed during the time span of c. 30 Ma (Gawęda et al. 2016), which is the key-point for an understanding the Variscan geological history of the Inner Western Carpathians (Fig. 1 a). The Tatra Massif is the northernmost crystalline massif in the Inner Western Carpathians (Fig. 1 a), weakly affected by Alpine deformations (Jurewicz 2005) and offering a unique opportunity to trace the pre-Alpine geological processes.

The aim of this paper is to study the magmatic processes, forming the youngest part of the Tatra intrusion, called the High Tatra granite, on the basis of textural, isotopic and geochemical data and to discuss the magma sources and consequences of continuous magma mixing, fractionation and cumulate formation as well as the inter-relations of these processes. The changing mafic-felsic proportions in the magma mixtures are also debated in terms of tectonic processes which occurred during the closure of the Rheic Ocean and the termination of the Variscan orogeny.

2. Geological setting

The crystalline basement of the Tatra Mountains is one of several crystalline basement units within the Tatricum Unit of the Alpine belt of the Central Western Carpathians (Fig. 1 a, b). It comprises polygenetic Variscan granitoids, which predominate volumetrically, a metamorphic envelope, migmatized to different degree (Burda and Gawęda 2009; Gawęda et al. 2016), all overlain by the Mesozoic sedimentary formations (Fig. 1 c). The composite granitoid intrusion has recently been interpreted to have been formed by the repeated magma influx into an active shear zone over a c. 30 Ma period (Gawęda et al. 2016). That long lasting granitoid magmatism was a result of the multistep subduction of oceanic crust and the collision of the Proto-Carpathian terrane with a volcanic arc and finally with Laurussia. Traditionally, the older granitoids (370-355 Ma; Burda et al. 2011; Gawęda et

al., 2016) were called the common Tatra type, while the younger granitoids (350-340 Ma; Burda et al., 2013; Gawęda et al, 2016), predominating in the eastern part of the massif, were called the High Tatra type (Fig. 1 c; Kohut and Janak 1994). In the common Tatra granite the mingling-mixing processes are restricted to quartz-diorite mafic precursors and their vicinity, e.g. unusual granitic apatite-rich cumulates (Szopa et al. 2013). The High Tatra granite is characterised by an abundance of mafic enclaves and xenoliths of country rocks (Gawęda 2008; Gawęda and Szopa 2011) and offers the wide opportunity to study the magma's interaction. In all samples magmatic foliation and lineation are evident and indicate a top-to the SE magma movement, concordant with the metamorphic foliation in the host rocks (Gawęda and Szopa 2011).

The present structure of the Tatra Massif reflects brittle tectonics, related to multistage uplift and massif division into small tectonic blocks during the age interval of 32-9 Ma (Anczkiewicz et al. 2015 and references therein). Asymmetric exhumation of the massif with its Alpine sedimentary cover caused its tilting to the north along the currently active Sub-Tatric Fault (Fig. 1 c) at a present-day tilting angle of c. 30 degrees (Grabowski and Gawęda 1999).

3. Sampling strategy and analytical methods

3.1 Sampling

Geological observations and sampling were made over the High Tatra intrusion (Fig. 1c). Selected vertical profiles, with well-developed magmatic layering, schlieren and cumulates were sampled in detail for petrographical, geochemical and isotopic investigation. Sampling was based on the procedure described in detail by Gawęda and Szopa (2011). Representative samples of granitoids, were collected for petrography and geochemistry, with the permission of the Polish Ministry of Environment and the Tatra National Park (Fig. 1c).

3.2 Microscopy and whole-rock analysis

Thin sections for petrographical observations were cut perpendicularly to the magmatic foliation and parallel to the magmatic lineation, as shown by Gawęda and Szopa (2011). Microscopic observations of 384 thin sections were carried out at the Faculty of Earth Sciences, University of Silesia, using an Olympus BX-51 microscope. The observations were used to select representative samples, less affected by secondary alteration (see Gawęda and Włodyka 2012), for whole-rock geochemical and isotopic investigations. The analyses were determined by XRF for major and Large Ion Lithophile trace Elements (LILE) and by ICP-MS for High Field Strength Elements (HFSE) and Rare Earth Elements (REE) in the Bureau Veritas Minerals (Canada). Preparation involved lithium borate fusion and dilute digestions or hot four-acid digestion for ICP-MS, LiBO₂ fusion for XRF and lithium borate decomposition or aqua regia digestion for ICP-MS. Loss on Ignition (LOI) was determined at 1000°C. REE were normalized to C1 chondrite (Sun and McDonough 1995).

3.3 Electron probe micro-analyses (EPMA) and cathodoluminescence (CL)

Microprobe analyses of main and accessory minerals were carried out in the Inter-Institutional Laboratory of Microanalyses of Minerals and Synthetic Substances, Warsaw, using a CAMECA SX-100 electron microprobe. The analytical conditions were: acceleration voltage 15 kV, beam current 20nA, counting time 4 s. for peak and background, beam diameter 1-5 μm , peak count-time of 20 s and background time of 10 s. Standards, analytical lines, diffracting crystals and mean detection limits (in wt%) were as follows: rutile – Ti ($K\alpha$, PET, 0.03), diopside – Mg ($K\alpha$, TAP, 0.02), orthoclase – Al ($K\alpha$, TAP, 0.02), Si – ($K\alpha$, TAP, 0.02) and K ($K\alpha$, PET, 0.03), albite – Na ($K\alpha$, TAP, 0.01), wollastonite – Ca ($K\alpha$, PET, 0.03), hematite – Fe ($K\alpha$, LIF, 0.09), rodohrozite – Mn ($K\beta$, LIF, 0.03), phlogophite – F ($K\alpha$, TAP, 0.04), Cr_2O_3 – Cr ($K\alpha$, PET, 0.04), ZirconED2 – Zr ($L\alpha$, PET, 0.01), Nb_2O_3 -MAC – Nb ($L\alpha$, PET, 0.09).

3.4 Sr, Nd, Pb Isotope analyses

All sample preparation and isotope analyses were conducted at the Irish National Centre for Isotope Geochemistry at University College, Dublin. Samples were spiked with three separate solutions enriched in ^{87}Rb and ^{84}Sr , ^{147}Sm and ^{150}Nd . Teflon distilled acids were added to the sample powder after addition of the spike solutions. Samples were digested in a 5:1 mixture of 5 ml *ca* 49% HF and 1 ml *ca* 15M HNO_3 . Samples were passed through columns containing Sr-Spec ion exchange resin and Rb, Sr, REE and Pb collected separately.

Sr and Nd isotope analyses were performed on a Thermo Electron Triton TIMS instrument in static multi-collector mode. Typical sample loads of ~ 300 ng Nd, ~ 100 ng Sm and 300 ng Sr were analysed, in the case of Sr with the addition of a Ta activator to enhance ionisation. Rb, Sr, Sm and Nd concentrations, and corrections to natural isotope ratios for the presence of spike solutions and machine mass fractionation, were made offline after analysis. During the time of sample analyses, SRM 987 gave a $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.710246 ± 15 (2SD, $n=9$), and La Jolla gave a $^{143}\text{Nd}/^{144}\text{Nd}$ value of 0.511842 ± 5 (2SD, $n=8$). Pb and Rb were analysed on a Neptune Multi-Collector ICP-MS. For Pb isotope analyses, thallium was added to samples and a $^{203}\text{Tl}/^{205}\text{Tl}$ value used was 0.418922 and was applied to the Pb isotope data for mass bias correction using the exponential law. Over the course of analyses SRM 981 ($n=10$) gave the following values: $^{206}\text{Pb}/^{204}\text{Pb}=16.932$, $^{207}\text{Pb}/^{204}\text{Pb}=15.483$ and $^{208}\text{Pb}/^{204}\text{Pb}=36.671$. For Rb analyses sample were doped with Zr and a natural $^{90}\text{Zr}/^{91}\text{Zr}$ value of 4.588 was used for mass bias exponential law correction after Waight et al. (2002) and Nebel et al. (2005).

In this study we also use the Rb-Sr and Sm-Nd isotope analyses from Gawęda (2008, 2009). The model ages were calculated relative to the depleted mantle model of De Paolo (1981a,b). Initial Nd, Sr, Pb values were recalculated assuming an age of 340 Ma as the end of the magmatic activity (Burda et al. 2013; Gawęda et al. 2014; Gawęda et al. 2016).

4. Results

4.1 Rock textures and mineral chemistry

The High Tatra granitoid intrusion is composed of the layered and non-layered series, intercalated with each other in different proportions (Gawęda and Szopa 2011; Gawęda et al. 2016). Among the non-layered granitoids two granitoid types, porphyritic and equigranular can be distinguished, both showing an oriented fabric (Fig. 2a). Many of the investigated rock-samples show a combination of textures typical of mixing-mingling phenomena, defined as the “textural assemblage” (Hibbard 1991). Such textures are ubiquitous mostly in the layered and schlieren-type granitoids (Fig. 2c), but they can also be found in the interleaved non-layered (homogeneous) granitoid portions.

Mafic microgranular enclaves (MME) are usually elongated to schlieren or irregular in shape or (Fig. 2c, d), or rarely oval (Fig. 2e), from 3 x 8 cm to 20 x 45 cm in size. The grain size of the MME is visibly smaller than in the host granite and they are locally rimmed by a biotite selvage (Fig. 3a). They are composed of zoned plagioclase (An₄₀₋₂₅), blade-shape “hydrogenic” biotite (Fig. 3b), with $fm = 0.47-0.50$ (Table 1), xenomorphic K-feldspar, showing inverted barium zonation, magnetite and magnetite-ilmenite exsolutions after ulvospinel (Gawęda and Szopa 2011). Locally the phenocrysts of biotite can be found, showing sieve texture, and abundant K-feldspar inclusions (Fig. 3c). Accessory phases are apatite (see Gawęda et al. 2014), allanite-epidote and zircon.

Quartz-plagioclase-titanite ocelli form elongated (up to 4 mm) patches, composed of quartz or plagioclase-quartz core, rimmed by titanite and partly by biotite crystals (Fig. 3d). Plagioclase show normal zonation with andesine (An₃₈₋₃₂) cores and oligoclase (An₂₀₋₂₅) rims. Titanite is usually zoned in respect of Fe, Al and Y, substituting for Ti and Ca (Table 2).

Biotite-rimmed quartz ocelli are common near the contact with and inside mafic microgranular enclaves and in mafic schlieren. They consist of quartz core rimmed by the biotite flakes ($fm \sim 0.58$; Ti = 0.37-0.39 a.p.f.u.; Table 1).

Plagioclase crystals with “calcic spike” zoning are present in all types of granitoid rocks. They are idiomorphic, 2-10 mm in size, mostly of oligoclase composition, showing sharp compositional discontinuities (up to 50% of anorthite molecule in plagioclase; Fig. 4a,b), called “calcic spikes”. Such a texture is usually attributed to magma mixing (Hibbard 1991; Baxter and Feely 2002; Burda et al. 2011).

K-feldspars phenocrysts with inclusion zones and pronounced barium zonation, 0.5 to 6.0 cm in size, could be found elsewhere in the Tatra granitoid rocks. They show both normal and inverted chemical zonation, marked by mineral micro-inclusions (Fig. 3 e). Zonation is expressed in the Ba content and consequently the resulting change in intensity and shade of blue CL colour (Fig. 4 e). In case of the inverted zonation the homogeneous feldspar cores have the composition range Or₉₂₋₉₃Ab_{5.5-5}Cn_{2.6-1.4} whilst the perthitic mantles show a higher celsjan content (Or_{91-76.6}Ab_{5-20.6}Cn_{3-6.8}) bordered by the rows of oligoclase inclusions (An₂₄₋₁₄; Fig. 4 c, d). Locally rapakivi textures can be noted, expressed as overgrowths of oligoclase-albite (An₂₅₋₇) on K-feldspar (Fig. 3 f). Ternary feldspar geothermometry

(Nekvasil 1991), applied to the K-feldspar phenocrysts with inclusion zones, gave the temperatures in the range 721-644°C (Table 3) which are interpreted as conditions at or close to equilibrium.

Poikilitic plagioclase crystals, rich in biotite, apatite, K-feldspar and magnetite inclusions occur mostly at the contacts of granite and MMEs or inside MMEs.

Felsic magmatic enclaves (FME) occur as oval to round segregations, from 1.5 cm to c. 10 cm in size, inside the homogeneous biotite granodiorite (Fig. 2 f). They are composed of a mosaic of boxy-cellular plagioclase crystals (Fig. 3 g), showing greenish luminescence and normal chemical zonation (An₂₇-An₁₅), with apatite inclusions and interstices filled by blue-luminescing K-feldspar (Fig. 4 f), showing irregular Ba enrichment both near the crystal rims and inside the crystals. Ternary feldspar geothermometry was applied to the felsic clots and yielded an equilibrium temperature range of 620-632°C, whilst for the surrounding granites ternary feldspar geothermometry gave the equilibrium temperature of 577-609°C (Table 3).

Mafic clots, ranging from 1 mm up to 2 cm in size (Fig. 3 h), are aggregates of biotite, magnetite-ilmenite intergrowths, locally with remnants of original ulvöspinel, zoned REE-epidote, amphibole (Mg-hornblende to tchermakitic hornblende; Gawęda et al. 2016). They are interpreted as remnants after pyroxene or other minerals, not stable in the granitoid system (Hibbard 1991).

Cumulative textures (Fig. 2b), as well as syn- and late-magmatic deformation, are observed elsewhere (Gawęda and Szopa 2011; Szopa et al. 2013; Gawęda et al. 2016). The most typical are:

Opaque-rich cumulates are present as the 8-20 cm thick bases of graded layers (*sensu* Gawęda and Szopa 2011; Fig. 2 b). They are composed of magnetite-ilmenite intergrowths, biotite (chloritized to some extent) and plagioclase (oligoclase-andesine). Apatite, xenotime, monazite and zircon are also concentrated in the basal cumulates, implying some gravitational settling. The magnetite-ilmenite exsolutions after ulvöspinel were used for geothermometric calibrations, according to the Spencer and Lindsley (1981) model and gave temperatures in the range 770 – 820°C (Table 4). Mafic cumulates at the base of layers are associated with the presence of felsic pods, mostly irregular, locally lens-like in shape and composed of andesine plagioclase and interpreted as arrested melt portions, percolating upward by filter pressing (Gawęda and Szopa 2011).

Feldspar-rich cumulates form lenses tens of centimeters thick and up to few metres long, composed of K-feldspars megacrysts (2-6 cm long), forming closely-packed aggregates (Gawęda and Szopa 2011). K-feldspars are normally zoned in Ba. Apart from K-feldspars, the cumulus phases are deformed biotite and accessories, whilst the matrix is formed of quartz, albite, muscovite and biotite.

Apatite-rich cumulates, with apatite reaching 11-13 %vol., were found both as an isolated enclave in granitoid (Gawęda 2008) and *in situ* (Szopa et al. 2013). Apatite, together with plagioclase, K-feldspar, biotite and accessories (zircon, xenotime, monazite) is a cumulus phase.

Antecrysts and enclaves of older granite pulses are present elsewhere, especially inside the High Tatra granite (Gawęda 2008) and have been interpreted in terms of petrological cannibalism and magma recycling (Gawęda et al. 2016).

4.2 Whole-rock chemical and Sr-Nd-Pb isotopic compositions

Granitoid rocks of the High Tatra Mountains cover the quartz-monzonite-granodiorite-granite fields on the $\text{Na}_2\text{O}+\text{K}_2\text{O}$ versus SiO_2 diagram whilst the cumulates classify as monzonite to foid-monzogabbro (Fig. 5 a).

4.2.1 Homogeneous granitoids

High Tatra granitoids are typically weakly peraluminous ($\text{ASI} = 1.10 - 1.2$), with Rb/Sr ranging from 0.05 to 0.49 (Appendix 1). The Nd/Th ratio is in the range of 2.2 to 3.9, with strong positive correlation of both elements ($r^2 = 0.88$). Inverse correlations of Fe_2O_3 , MgO, CaO, P_2O_5 , TiO_2 , versus SiO_2 are observed (Fig. 5 b, c, e, f, g). Two distinct granite populations are marked in the case of CaO, and alkali versus SiO_2 plots (Figs. 5 a, b, f), correlated with two distinct age groups with maxima at 345 Ma and 340 Ma. Chondrite-normalized REE patterns (Sun and McDonough 1995) are moderately to weakly fractionated ($\text{Ce}_\text{N}/\text{Yb}_\text{N} = 32.37\text{-}2.33$) and show negative to absent Eu anomalies ($\text{Eu}/\text{Eu}^* = 0.45\text{-}1.01$; Appendix 1).

Initial strontium isotope ratios, recalculated to 340 Ma, are in the range of 0.705-0.708, whilst $\epsilon_{\text{Nd}}^{345}$ ranges from 0.84 to -4.36 (Table 5; Fig. 6 a) and T_{DM} model ages extend from 0.99 to 1.39 (Table 5). The measured $^{206}\text{Pb}/^{204}\text{Pb}$ ratios range from 18.62 to 18.88, whilst $^{207}\text{Pb}/^{204}\text{Pb}$ ratios range from 15.66 to 15.67 (Table 5), plotting within the lower crust field, trending towards the EMII source (Fig. 6 b).

4.2.2 Cumulates and associated fractionated melts

Cumulative rocks show a wide range of chemical compositions, depending on the type of cumulate: apatite-rich (Gawęda 2008; Szopa et al. 2013), feldspar-rich and opaque/biotite-rich ones.

Feldspar-rich cumulates, observed in the High Tatra type, are compositionally dependent on the major mineral components: alkali feldspar or plagioclase crystals and they consequently show low LREE fractionation and feldspar-dependent negative and positive Eu anomalies ($\text{Ce}_\text{N}/\text{Yb}_\text{N} = 6.15\text{-}13.15$; $\text{Eu}/\text{Eu}^* = 0.76$ and 4.64; Appendix 2).

Opaque/biotite-rich cumulates, present in the youngest granitoid batches, are generally low in SiO_2 , (26.92-58.29 %wt.), show TiO_2 contents $> 1\%$, Fe_2O_3 contents from 7.49 to 40.27 %wt. and Zr and REE enrichment ((up to 1743 ppm of Zr, 407.22-2666.77 ppm of total REE; Appendix 2) due to the physical concentration of the accessory minerals (zircon, apatite, monazite, Fe-Ti oxides; Fig. 2 b). Fractionated melt pods have a leucogranite composition, with SiO_2 in the range of 73.62-76.09 %wt., ASI of 1.07-1.27, Rb/Sr ranging from 0.37 to 0.49 and are poor in Zr and REE (Appendix 2). Their chondrite-normalized REE patterns show positive Eu anomalies and medium to weak fractionation (Appendix 2).

5 Discussion

5.1 Definition of magmatic processes

Previously published geochronological data, the major and trace element geochemistry and Sr-Nd-Pb isotope compositions indicate the presence of two distinct magmatic cycles. In both of these cycles

textural assemblages are typical of magma mixing and mingling processes. On the other hand, magmatic layering and the presence of cumulates (Fig. 2a and Gawęda and Szopa 2011) indicate that fractional crystallization and crystal separation must be invoked, with crystal removal to the cumulates and melt extraction. The $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$ vs Al_2O_3 diagram (Fig. 7) efficiently discriminates between the fractional crystallization and mixing (Słaby and Martin 2008) and indicates that mixing predominated over fractional crystallization, governing the composition of the resultant magmas. Field and petrographic observations indicates that the magma compositions in the High Tatra granite were also strongly controlled by crystal segregation processes, probably driven by: gravity-driven accumulation, flow sorting, deposition on the magma floor, filter pressing and density currents (Gawęda and Szopa 2011; Szopa et al. 2013).

5.1.1 Magma mixing processes

The textural assemblages found in High Tatra granites clearly point to magma mixing and mingling (Figs. 2 a-f; 3 a-h). MMEs and mafic clots are typical remnants of coeval mafic magma introduced during granitoid intrusion and represent different stages of mixing-mingling with another magma (Didier and Barbarin 1991; Crowley and Feely 1997; Clemens and Bezuidenhout 2014). Felsic clots, however, are relatively rare in granitoids and their origin is not so clear. They were previously interpreted as disrupted early chilled margins (Didier, 1991), as pressure-quenched magma from within the chamber (Flood and Shaw 2014) or as a late-stage silicic melt, modified by interaction with mafic magma (Waight et al. 2007). In the case of felsic clots occurring in the HighTatra granitoids, the purely feldspar nature of the enclaves, normal An zonation of boxy-cellular plagioclases and dull-blue luminescence in the marginal parts with light blue cores of the matrix K-feldspars (Fig. 4 f) caused by Ba substitution suggest rather kinetically driven crystal growth governed by local fluctuations in a heterogeneously mixed magma (Słaby and Götze 2004). The ternary feldspar temperature range of 620-632°C (Table 3) suggest late magmatic equilibration inside the felsic clots.

Anorthite-rich spikes in plagioclase crystals (Figs. 4 a, b), are usually interpreted in terms of mafic (rich in Ca) and felsic (poor in Ca) magma interplay (Hibbard 1991). The zoned K-feldspar phenocrysts with rows of inclusions (Figs. 3 e; 4 c, d) and local plagioclase (oligoclase-albite) mantling (rapakivi structure; Fig. 3 f) might result from both felsic - mafic magma mixing (Hibbard 1991; Słaby et al. 2007) and sub-isothermal decompression during intrusion resulting in changes in water content (Nekvasil 1991; Eklund and Shebanov 1999) or both processes acting. Quartz-plagioclase-titanite ocelli and biotite-rimmed quartz ocelli are attributed to magma mixing during crystal nucleation, e.g. early in the magma crystallization history (Hibbard 1991; Baxter and Feely 2002).

Magma mixing mass balance calculations according to Fourcade and Allège (1981) were applied to set of homogeneous granitoid samples, showing two linear trends on CaO versus SiO_2 variation diagram (Figs. 5 f). For the supposed mixing process the geochemical mass balance law: $C_m = X_A \cdot C_A + (1 - X_A) \cdot C_B$ (Rollinson 1993) was used for major and trace elements to test the mixing hypothesis. For the purpose of this study A represents a felsic component and B - a mafic component and X_A is a weight

fraction of the felsic melt. C_A , C_B , C_m are concentrations of a given element in felsic, mafic and mixed melts (Appendix 1). For the derived equation $y = X_A \cdot x$ (where $y = C_m - C_B$ and $x = C_A - C_B$). The slope of the straight line represents the degree of mixing (Rollinson 1993; Słaby and Martin 2008).

In case of the 345 Ma granitoid event 68% of felsic component was calculated while the youngest magmatic episode, dated at 340 Ma shows the 61% of felsic component (Fig. 8 a, b). That is in accord with isotopic data ($I_{Sr}^{345} = 0.705-0.708$, $\epsilon_{Nd}^{340} = 0.90$ to -4.32 ; Table 5) pointing to the presence of mantle-influenced magma in both cycles.

5.1.2 Cumulate separation and filter pressing

Cumulate formation from the magmas due to differences in viscosity and shear strain during intrusion is an efficient way to fractionate some elements and could explain the displacement of cumulate samples from the linear mixing trends (compare Fig. 5 b-g). The lowering of the viscosity of the Tatra granitoid magma could have been a result of a high content of volatiles (H_2O , B_2O_3 , F, P_2O_5) enabling the formation of layering (Gawęda and Szopa 2011; Gawęda et al. 2013). The opaque/biotite-rich cumulates, found in these granitoids, form a quasi-linear trend, almost perpendicular to linear trends observed for both High Tatra granitoid batches (Fig. 7). These cumulates show Zr and REE enrichment and relatively low SiO_2 content (Appendix 2) which possibly resulted from the physical accumulation of dense, early crystallized minerals (zircon, monazite, apatite, spinel) in a predominantly liquid magma. The low Zr content in some fine-grained leucocratic granite varieties and in K-feldspar-rich cumulates, suggest that in the leucocratic magma portions zircon crystallized from melt squeezed from the crystal-laden portions, after leaving the heavy cumulate fraction. In the latter case the gravitational separation, enhanced by the shear-influenced crystal segregation from the crystal-mush during flow could be assumed to be the main process (Gawęda and Szopa 2011).

Another line of evidence for cumulate separation is provided by the almost vertical linear trends in logarithmic plots of compatible *versus* incompatible elements (Figs. 9 a, b) for High Tatra granitoids. Assuming biotite and spinel are the Zn- and V-bearing phases in 345 cycle cumulates with a cumulate fraction of 5% (Table 7) the calculated $Kd_{Zn}^{Bt/melt}$ at 7.94 – 17.0 and $Kd_V^{sp/melt}$ at 7.0 – 22.8 are realistic for melts of intermediate to granitoid composition (Ewart and Griffin 1994). All these observations and calculations are in agreement with field observations (Fig. 2b).

The composition of the modal layers, presented in the Qtz-Ab-Or ternary diagram point out the haplogranitic character of the leucocratic upper parts of the layers, plotting in the “thermal valley” for mean pressure of 5 kbar (Fig. 10; Johannes and Holtz 1996; Pupier et al. 2008) which is in accord with former pressure computations suggesting 4-6 kbar pressure interval (Gawęda and Szopa 2011). In Qtz-Ab-Or ternary diagram samples plot in the field of primary K-feldspar crystallization, what is in agreement with petrographical observation, pointing out that the K-feldspars were the early crystallizing phases in High Tatra granitoid magma. Assuming the melt start to crystallize as quartz-Kfs cotectic and segregate the early crystallizing phases (K-feldspar) we can suggest the fractional crystallization as a

process governing the modal layers formation, expelling the interstitial melt from the cumulate to the top of each layer.

5.1.3. *Interaction of magma mixing and filter pressing in selected magma batches*

Magma mixing is observed in both magma pulses, whilst the different types of cumulates are associated with selected magma portions. In all granitoids the feldspar-rich cumulates are typically found (Gawęda and Szopa 2011). As feldspars are the predominant source of Ba and Sr one can expect linear trends on Harker diagrams. The observed chaotic patterns in Ba and Sr *versus* SiO₂ diagrams (Figs. 11 a, b) could result from the recycling and accumulation of feldspars in the dynamic environment and their chaotic entrainment into new magma portions (Gawęda et al. 2016). As result, most of the feldspar phenocrysts could be treated as antecrysts. Small magma batches accumulating over time and being out of equilibrium could produce similarly chaotic geochemical patterns (Słaby et al. 2011).

As the crystal fractionation occurred in a mixed magma environment we suggest that the mixing is a first-order and predominant process, whilst cumulate separation and filter pressing of the remnant melts developed as second-order processes, which overprinted all the primary magma variations.

5.2 The role of source rocks in the compositional diversity of Tatra granitoids

Although magma mixing seems to be the important process, the source of the components is important in understanding the whole history of magmatic evolution. The High Tatra granitoids are strongly peraluminous, contain abundant K-feldspars and muscovite, with biotite as the only mafic phase and rare accessory titanite and epidote-allanite. However, the textures point to the operation of the mixing and mingling. The spread of ϵ_{Nd} values, together with spread of I_{Sr} values is usually interpreted as a result of melting of heterogeneous magma sources. That is supported by the major and trace element geochemistry (Fig. 12 a-c). In the High Tatra granitoid body the old metasedimentary and metaigneous sources are imprinted in the isotopic composition, with an occasionally seen mantle input (sample 1_GB; Table 5) and in most cases mixed S/I isotopic characteristics, recorded in the Sr, Nd and Pb isotopic systems (Table 5; Figs. 6 a, b). The High Tatra granitoids might reflect a contribution from a relatively Th-enriched mantle (EM II) and/or crustal fluids during melting (Rudnick and Gao 2004), supported by the predominance of Th over U in magmatic epidote (compare Burda et al. 2011; 2013). The $^{206}\text{Pb}/^{204}\text{Pb}$ *versus* $^{207}\text{Pb}/^{204}\text{Pb}$ diagram suggests a lower crustal origin for common Tatra granitoids and an EMII source influence for the High Tatra granitoids (Fig. 6 b). Even if only one sample shows typical mantle signatures (Table 5), we cannot totally exclude a mantle derivation for the mafic magma components, contributing to the Tatra granitoid body, as they could have been obscured by the interaction with the predominant crustally-derived melts. All the magmatic pulses contributing to the Tatra granitoid intrusion represent a transition between I and S type granites, which is a reflection of the magma mixing/mingling as well as the recycling of earlier granitoid material (petrological cannibalism) during the incremental growth of the intrusion (Gawęda et al. 2016).

T_{DM} model ages in the range 1.00 – 1.35 Ga (Table 5) are devoid of any geological significance and are younger than the apparent crustal residence ages calculated for the Europe Variscan Fold Belt (1.4 – 1.7

Ga; Liew and Hofmann 1988), but they may reflect a small involvement of Mezo-Neoproterozoic crustal components in the origin of the analysed granitoids. However it is worth underlining the relatively small scatter of T_{DM} ages in the common Tatra granites, whilst a larger scatter and younger T_{DM} ages are observed in the High Tatra granitoids (Table 5). That fact could reflect the contribution of variable sources in the younger episodes of partial melting and High Tatra granitoid incremental intrusion.

All these observations make it difficult to reconstruct the geotectonic conditions at every stage of granitoid pluton formation. However, the problem of a mantle-derived magma contribution in High Tatra granitoids needs discussion.

Typically the explanation of the occurrence of mantle-derived magma is slab break-off along the orogenic belt, causing a thermal anomaly in the upper mantle and asthenosphere upwelling, which induces partial melting of the lower crust, resulting in granitoid magmatism (Davies and von Blanckenburgh 1995). Similar scenarios, with asthenosphere upwelling through the slab window during the last stages of Variscan collision was proposed for the southern Variscides, being a result of the collision of Gondwana with southern Galatian terranes (Cassini et al. 2015; Fianacca et al. 2015). In the described case of the Tatra granitoids a collision of the Gondwana promontory with the arc and finally with Laurussia is suggested (Gawęda et al. 2016), with possibly slab break-off in the final stages of the process, resulting in the mantle-derived magma input and fast uplift.

6. Conclusions

1. Magma mixing and mingling, acting at every stage of a long magmatic history of the Tatra granitoid pluton, seems to be the most important, first-order magmatic process. In the youngest High Tatra granitoid pulse two magma batches differ in the proportions of mafic and felsic magmas, which caused their compositional diversity, mostly by the crystal fractionation.
2. Cumulate separation and filter pressing of the residual liquid are the second-order processes, found in the High Tatra granitoids. Their development depended mainly on magma viscosity, volatile contents and shear-stress, so cumulates are commonly found in the younger High Tatra granitoids, whilst in the older common Tatra granitoids they are more sporadically found.
3. The primary source diversity was an important process in magma formation history, but may have been obscured by later processes, such as magma mixing and mingling, petrological cannibalism and crystal fractionation. In the case of the High Tatra granitoids the mantle magma input can be assumed to predominate. The increasing mafic (lower crustal- and mantle-derived) component in the 345-340 Ma magmas might have been a result of slab break-off, asthenosphere upwelling and partial melting of the lower crust.

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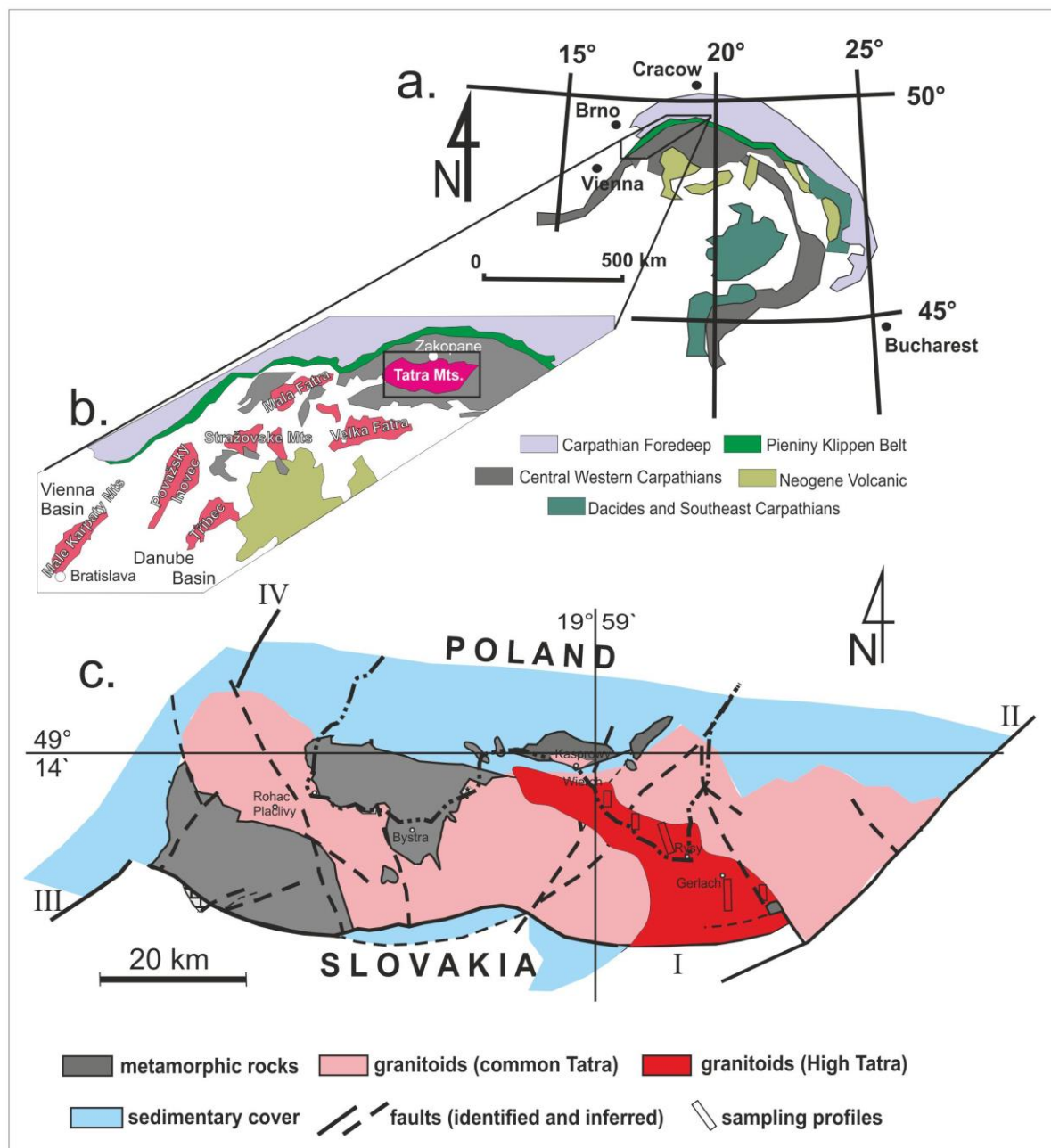


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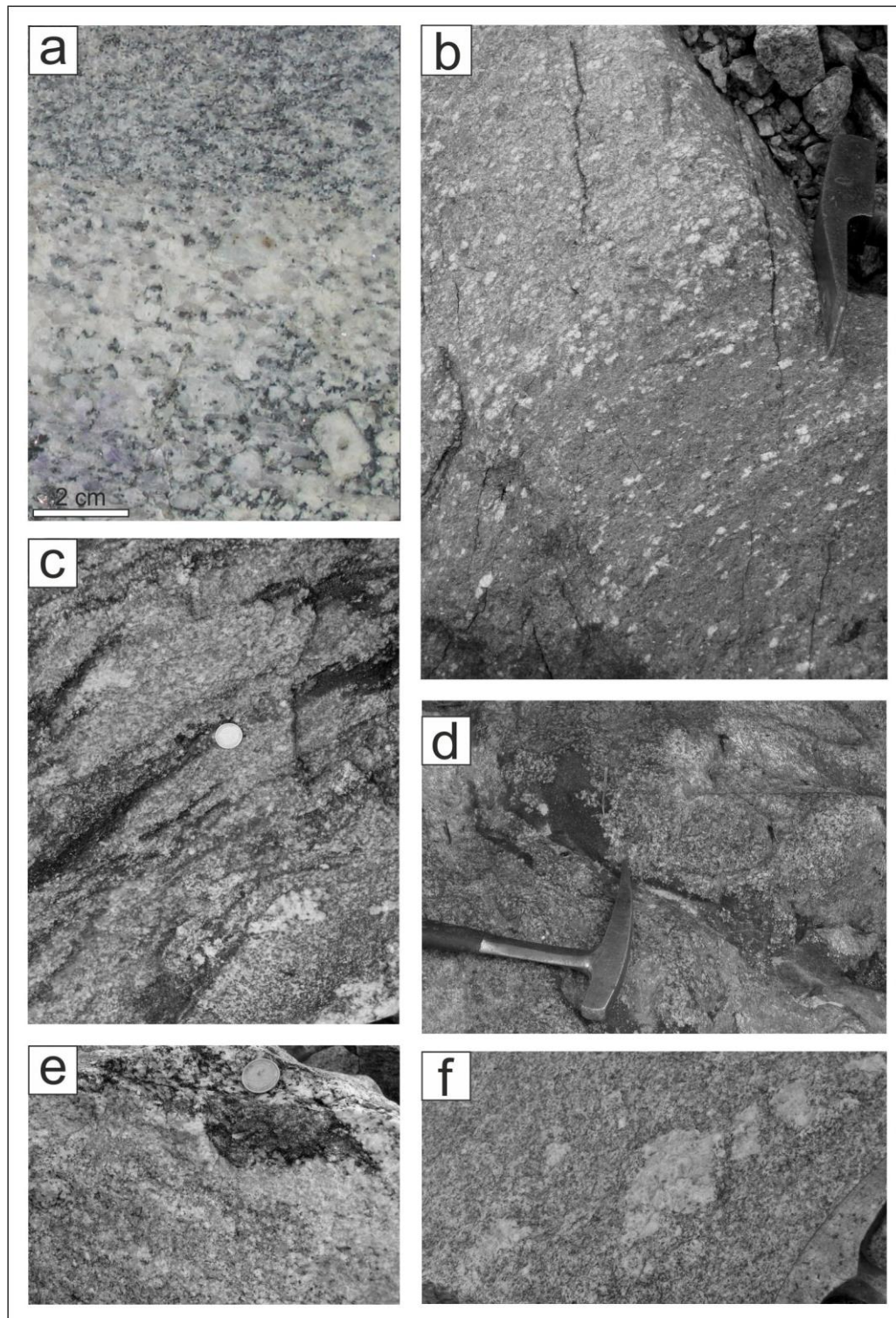


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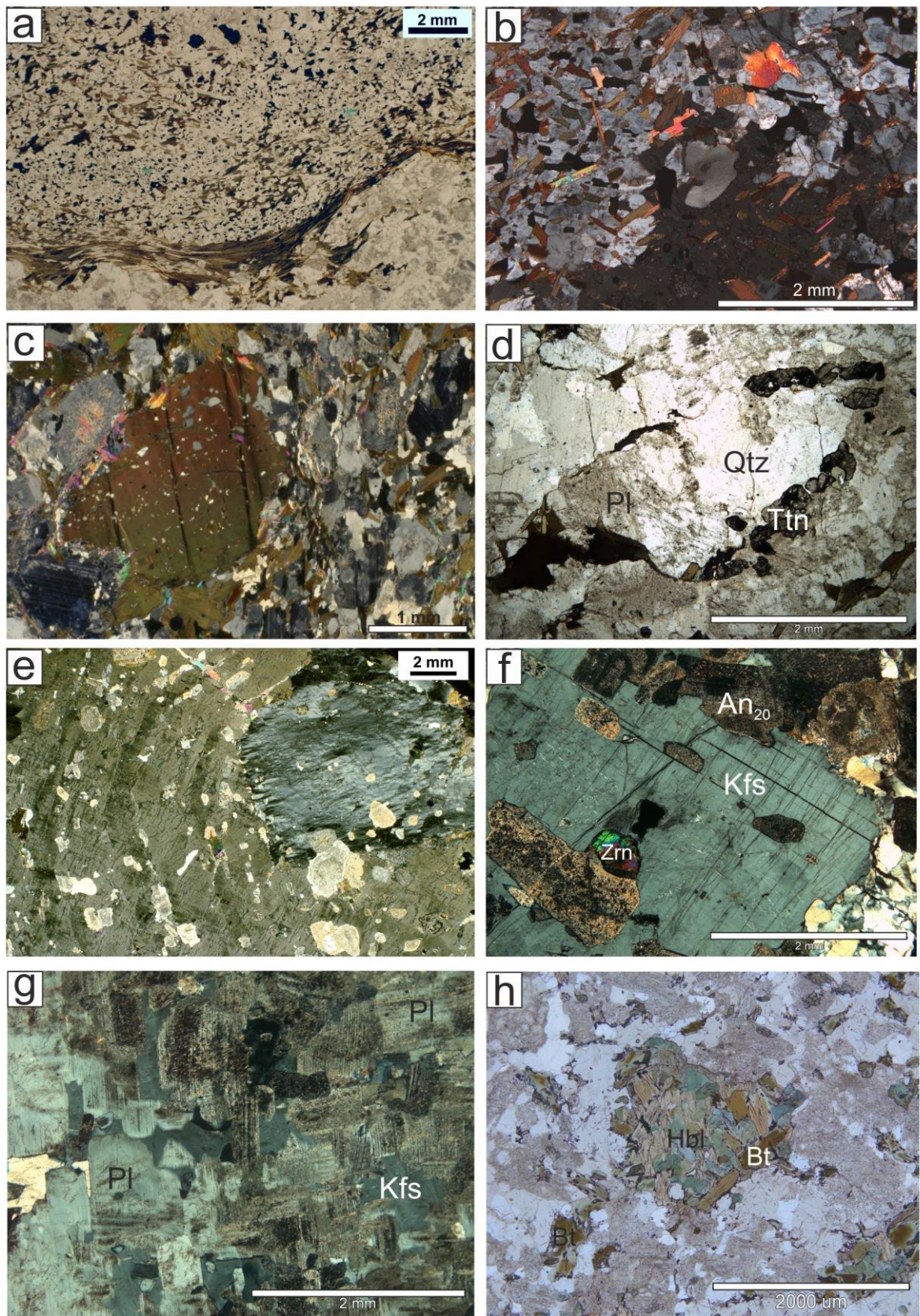


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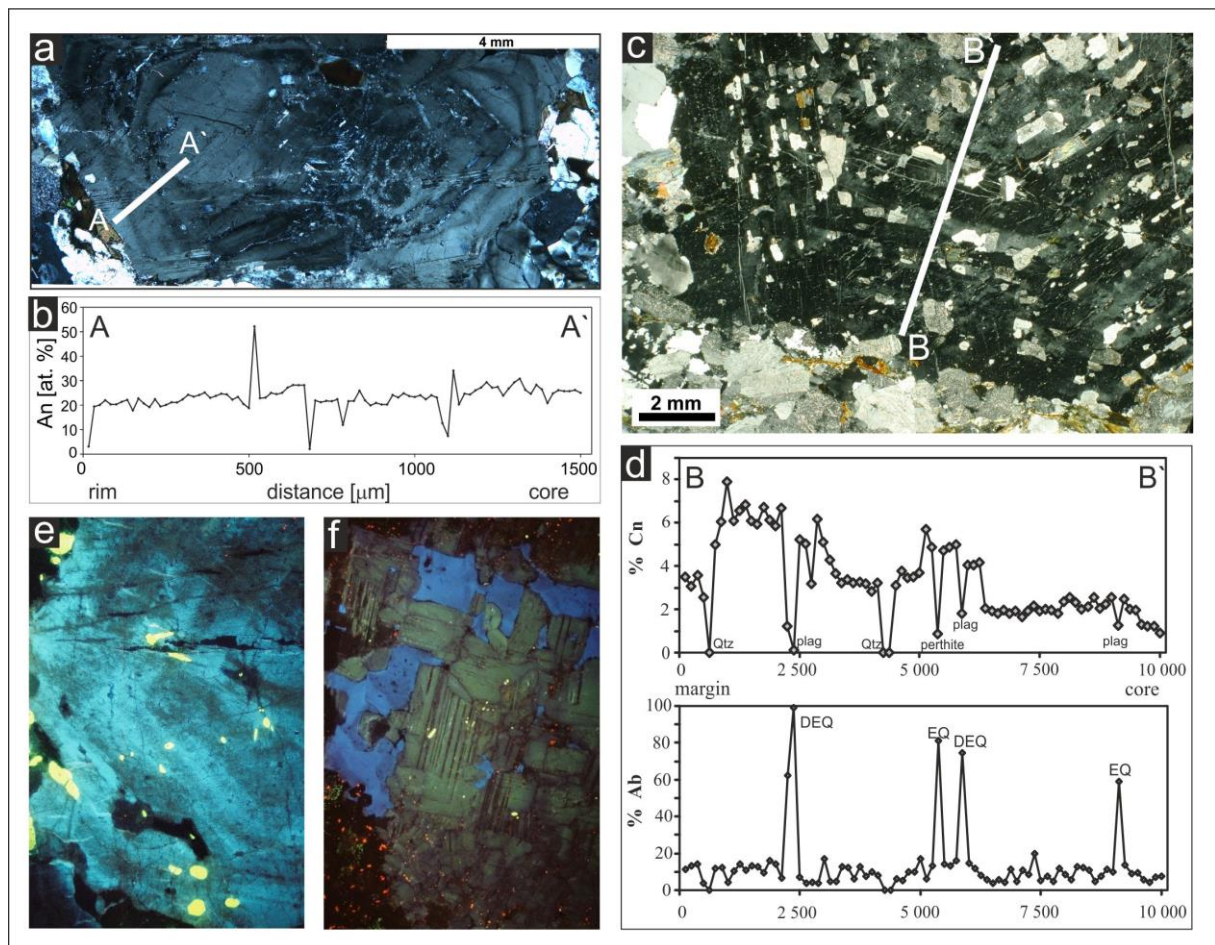
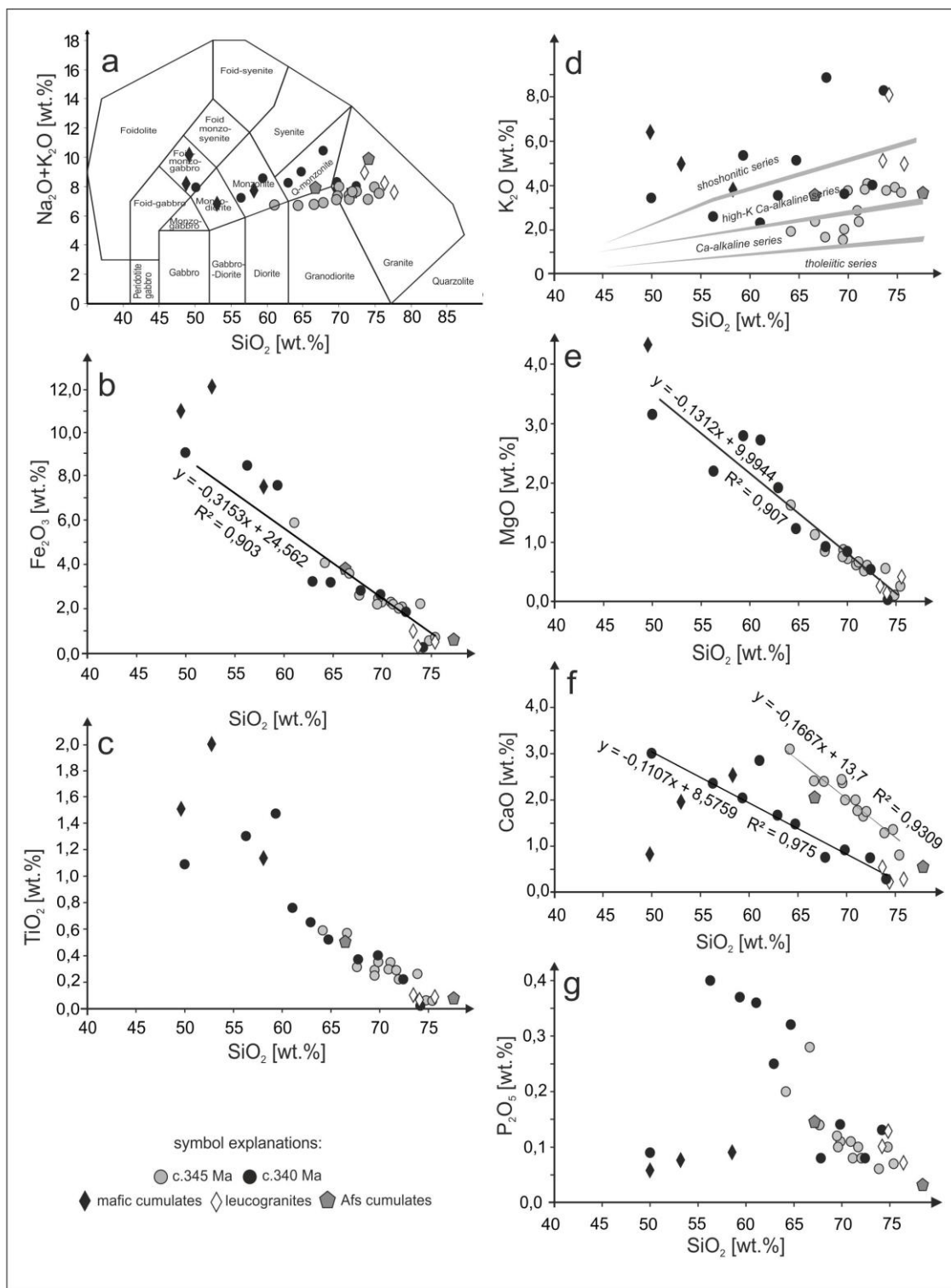


Figure 4



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578 Figure 5

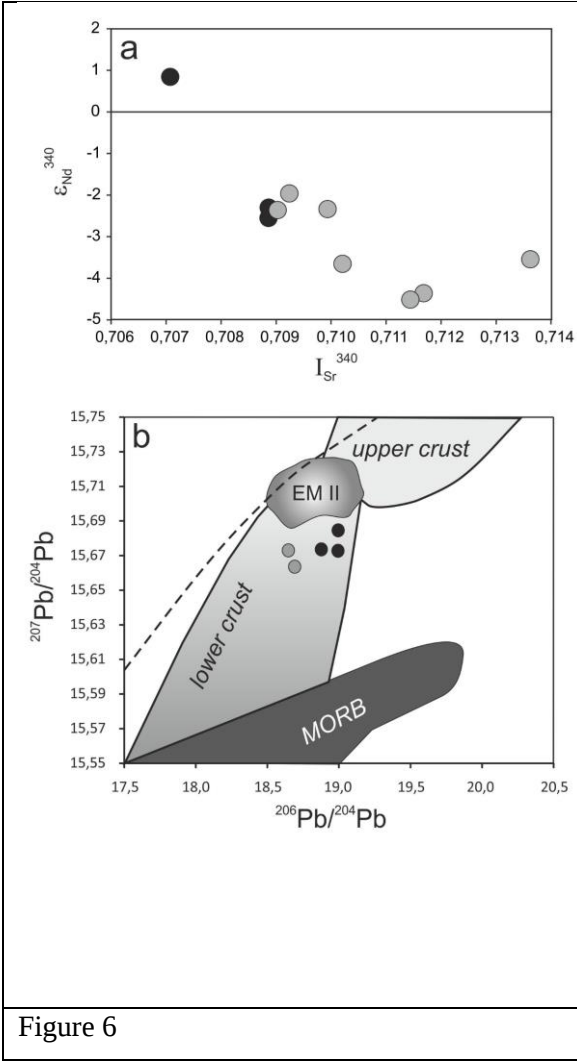


Figure 6

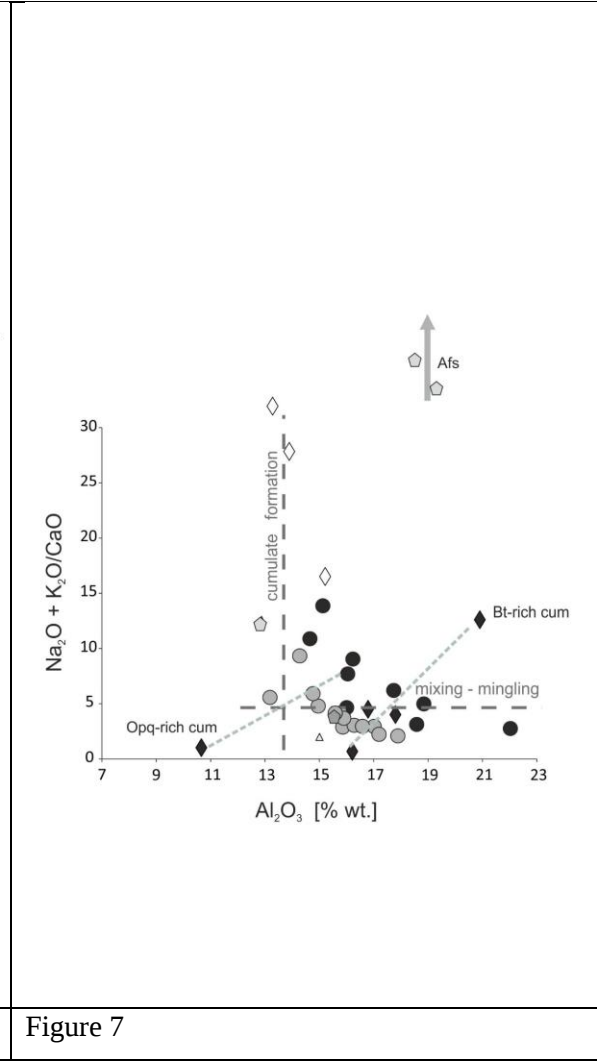


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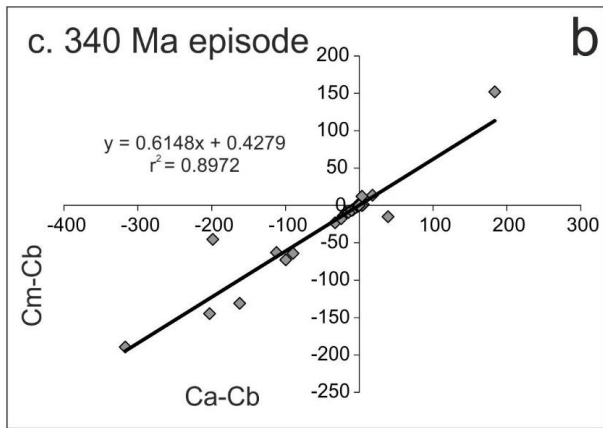
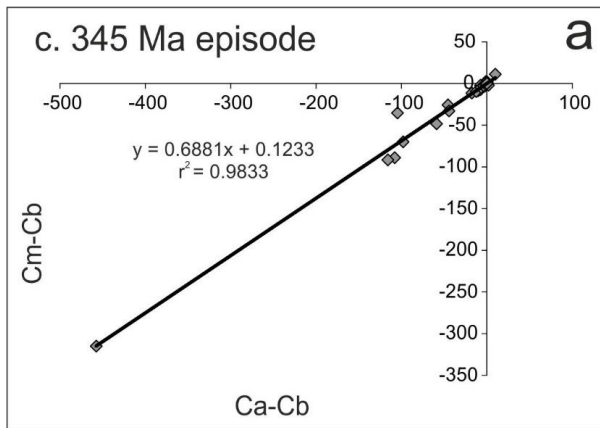


Figure 8

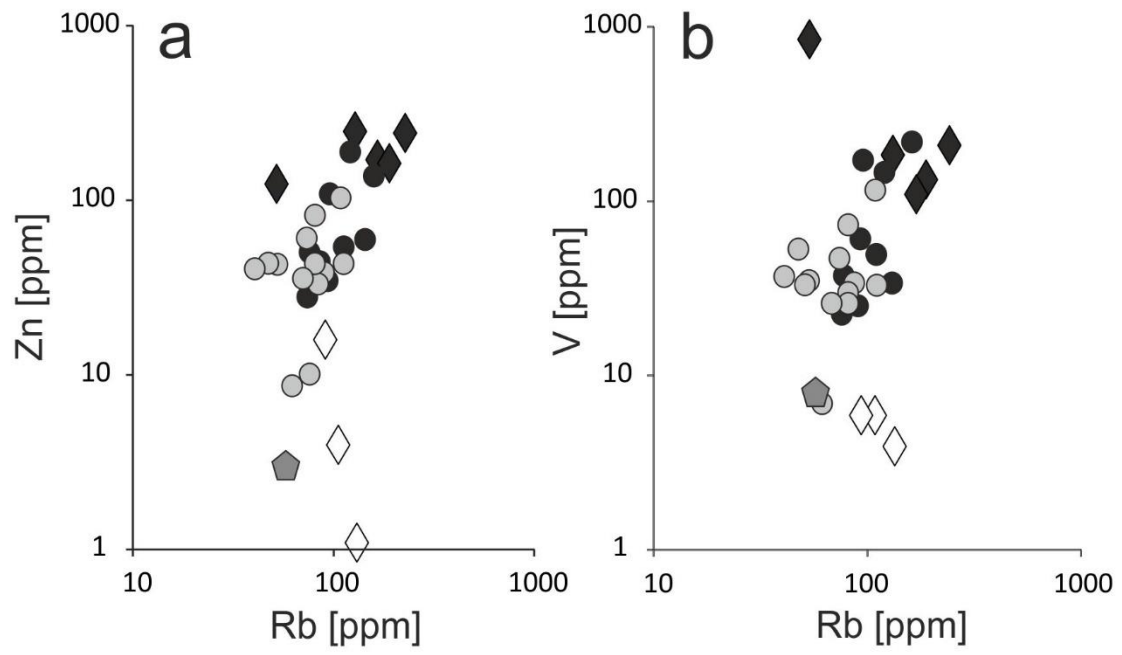


Figure 9

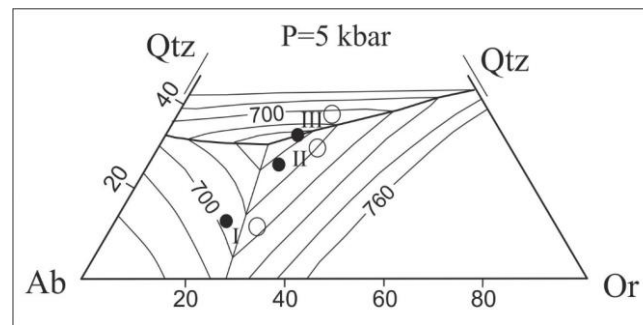


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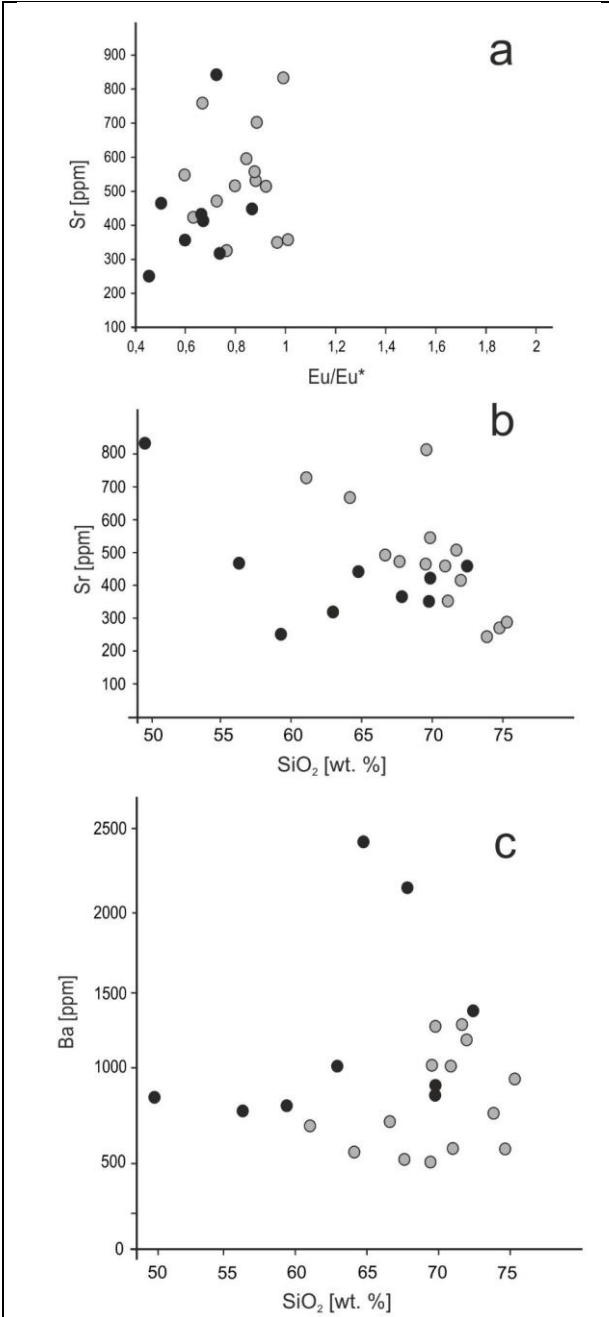


Figure 11

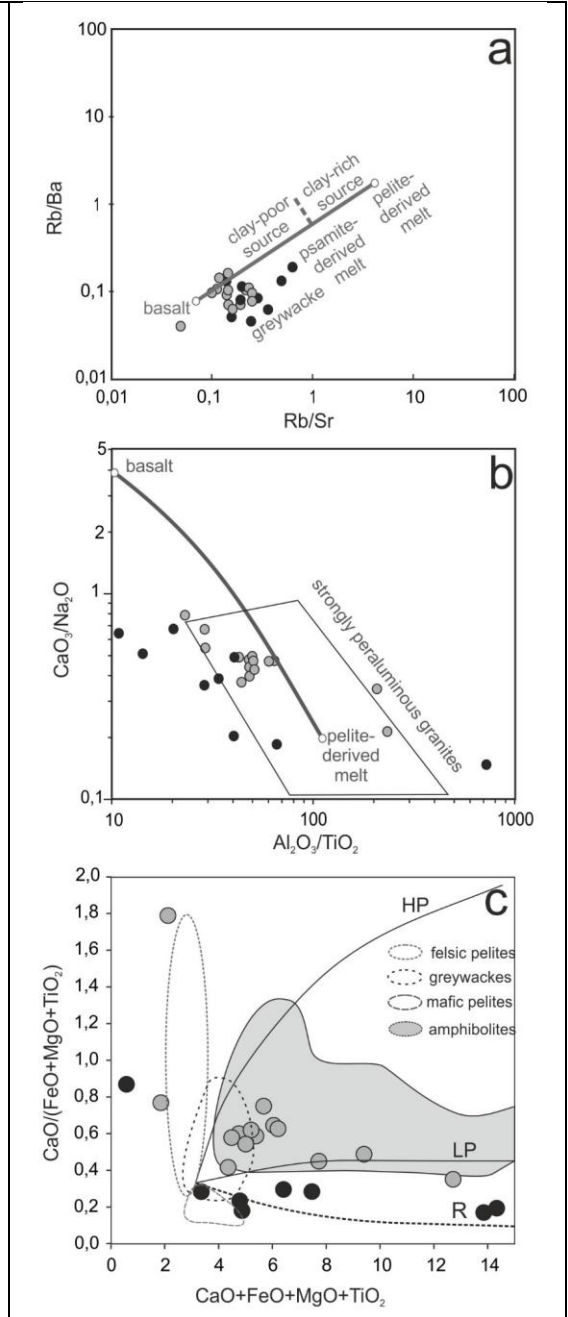


Figure 12

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Figure caption

Figure 1

A simplified geological sketch of the Carpathian Chain with geographic co-ordinates with the location of the Central Western Carpathians (a), the position of the Variscan crystalline cores in the Central Western Carpathians with the marked location of the Tatra Mountains (b) and schematic geological map of the Tatra Mountains with the location of samples used for zircon U-Pb dating (c).
Explanations: I – Sub-Tatric Fault, II – Ružbachy Fault, III – Choč Fault, IV – Krowiarki Fault (compilation from Gawęda et al. 2016)

Figure 2

Textures resulted from magma mixing-mingling in the Tatra granitoid intrusion: a) a contact of fine-grained, more mafic granitoid (upper part) with slightly porphyritic medium-grained felsic granitoid (lower part); b) magmatic layer with opaque-rich cumulate at the base (hammer as a scale); c) mafic schlieren in the mingling zone (1 EURO coin as a scale); d) irregular mafic magmatic enclave (MME) inside the High Tatra granitoid (hammer as a scale); e) small lens-shape MME inside the homogeneous granitoid (1 EURO coin as a scale); f) felsic magmatic enclaves (FME) inside the High Tatra granodiorite.

Figure 3

Microtextures of the Tatra granitoids, typical of magma mixing-mingling: a) sharp contact of MME with granite, underlined by biotite selvage; b) internal part of MME, with “hydrogenic” blade-shape biotite; c) biotite porphyrocrystal, showing sieve texture, with Kfs inclusions; d) titanite (Ttn) rimming the quartz (Qtz) and plagioclase (Pl) and forming an ocelli; e) an internal fragment of alkali feldspar phenocryst, with chemical zonation underlined by the rows of plagioclase inclusions and older K-feldspar in the core; f) border of a alkali feldspar phenocryst, with oligoclase An_{20} overgrowths; g) internal structure of FME with boxy-cellular plagioclase crystals (Pl) and K-feldspars (Kfs) filling the space between them; h) mafic cloth composed of hornblende (Hbl) and biotite (Bt), inside the homogeneous granitoid.

Figure 4

Micro-zonation of feldspars: a) zoned porphyrocryst of plagioclase and its chemical profile (b) with calcic “spike” up to 50% of anorthite molecule; c) zoned alkali feldspar, with rows of inclusions, underlining the chemical zonation, expressed as changes in celsian and albite contents (d). CL imaging of alkali feldspar phenocryst, marking the change in Al-O-Al defects concentrations; b) CL imaging of plagioclase (greenish) and K-feldspar (blue) from FME;

Figure 5

Major elements versus SiO_2 variation diagrams of High Tatra granitoids.

Figure 6

Isotopic composition of the High Tatra granitoids. a) ϵ_{Nd}^{340} versus I_{Sr}^{340} diagram for the selected Tatra granitoid samples; b) Plot of the Tatra granitoid samples in the $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ diagram and their relation to several sources (lower crust, upper crust, EMII, MORB after Rudnick & Gao, 2003). Symbols as on Figure 5.

Figure 7

The $(Na_2O+K_2O)/CaO$ vs Al_2O_3 diagram, discriminating between magma mixing and fractional crystallization (after Stáby & Martin, 2008): High Tatra granitoids. Symbols as on Figure 5.

Figure 8

Mixing tests for the selected magma batches forming the Tatra granitoid pluton: a) c. 345 Ma granitoid; b) c. 340 Ma granitoid.

649 Figure 9
650 A logarithmic plot of compatible (Zn, V) versus incompatible (Rb) elements for High Tatra granitoids, their
651 cumulates and squeezed leucocratic melts. Symbols as on Figure 5.
652

653 Figure 10
654 Plot of the bulk composition of selected High Tatra layered granitoids in the Qtz-Ab-Or projection at $P_{H_2O} = 5$
655 kbar from Johannes & Holz (1996). black circles - projection points of the base parts of the layers; open circles -
656 projection points of the upper parts of the layers.
657

658 Figure 11
659 Feldspar-dependent trace elements variation diagrams of common and High Tatra granitoids: a) Sr
660 concentration *versus* Eu anomaly (Eu/Eu*); b) Sr concentration *versus* SiO₂; c) Ba concentration *versus* SiO₂.
661

662 Figure 12
663 Source discrimination diagrams for Tatra granitoids: (a and b) after Sylvester 1998, (c) after Patiño-Douce 1999.
664 Symbols as on Figure 5.
665
666