Typology and internal structure of zircons from the granites of the Krušné hory – Erzgebirge batholith and associated rhyolite and granite porphyry (Czech Republic)

Typologie a vnitřní stavba zirkonů žul krušnohorského batholitu a na něj vázaného rhyolitu a žulového porfyru (Czech summary)

(10 text–figs., 1 plate)

ALEXANDRA KODYMOVÁ – MIROSLAV ŠTEMPROK

Český geologický ústav, Klárov 3, 118 21 Praha 1

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Dimensions, typology and internal structure of zircon crystals was studied on 5 samples of granites from the Western pluton of the Krušné hory/Erzgebirge granite batholith, a sample of granite porphyry and a sample of the Teplice rhyolite from the Eastern pluton area. Zircons indicate a considerable genetic unity of the rocks examined. According to zircon typology the granite of the Older Intrusive Complex belongs to the granites of mixed crustal and mantle origin whereas the granites of the Younger Intrusive Complex to the granites of crustal origin. Five zones of growth were determined in the zircon crystals which are unevenly distributed in different types of rocks examined. There is no correlation based on zircons between the "granite porphyries" in the western pluton area (granites from Doubí) and the granite porphyry from the eastern part of the batholith.

Introduction

The Late Variscan Krušné hory – Erzgebirge granite batholith of Central Europe has been studied for almost 150 years. Its genesis, however, still remains subject of discussions. One of the essential problems is whether the batholith was formed by a continuous magmatic evolution in Late Variscan time from a single source or whether several sources existed in the time of granite genesis, emplacement and origin of associated volcanic rocks. The paper attempts to use mainly zircon typology in comparing individual members of the granite series and of associated volcanic rocks to contribute to elucidation of these questions.

Samples were taken from seven main granites, granite porphyry and rhyolite of the area which are in the authors' opinion representative to demonstrate the Late Paleozoic evolution of the batholith. The samples were taken from the Czech part of the batholith.

Geologic position

The Krušné hory – Erzgebirge granite batholith of Late Variscan age is located in the Krušné hory and Slavkovský les areas in the Czech Republic and in the Erzgebirge and Vogtland in Germany. The batholith continues to the Smrčiny – Fichtelgebirge but this part was not the subject of the present study.

The batholith is partly hidden and its size is estimated to be about 6000 km^2. It intruded in the Late Variscan time (330 – 290 m.y.) in the Upper Proterozoic gneisses and Cambro–Ordovician schists and phyllites which were folded and metamorphosed during Variscan orogenesis. The batholith consists of three major outcrop areas (Western, Middle and Eastern) (fig. 1) corresponding to partly hidden plutons.

The magmatites of the batholith are grouped into two major compositionally different intrusive complexes (table 1). The granites of the Older intrusive complex (OIC) (approx. 330 to 305 m.y.) are predominantly monzogranites (Tischendorf and Förster 1990, Štemprok 1986) with Mg – Fe biotites, plagioclase An_{10-30} and with average SiO_2 about 70 %, TiO_2 0.5 and CaO 1.7%. Rb varies between 170 – 300 ppm, Sr is relatively high 125 – 300 ppm. The Zr content of the granites ranges between 100 and 250 ppm.

The granites of the Younger Intrusive Complex (YIC) are mostly syenogranites with alkali feldspars (albite and orthoclase), plagioclase An_{10-20}, Fe – Mg biotites, common accessory topaz and fluorite. Average SiO_2 is about 74 %, TiO_2 0.13 % and CaO 0.65 % (Štemprok 1986). Rb varies from 400 to 900 ppm, Sr is lower than 50 ppm. Zr contents range from about 20 to 150 ppm (fig. 2) in the main types of the YIC granites but are higher (to about 170 ppm) in the so called intermediate granites which built up the marginal, presumably upper parts of the YIC granites. Intermediate granites contain alkali feldspars, plagioclase An_{10-20}, biotite, muscovite,

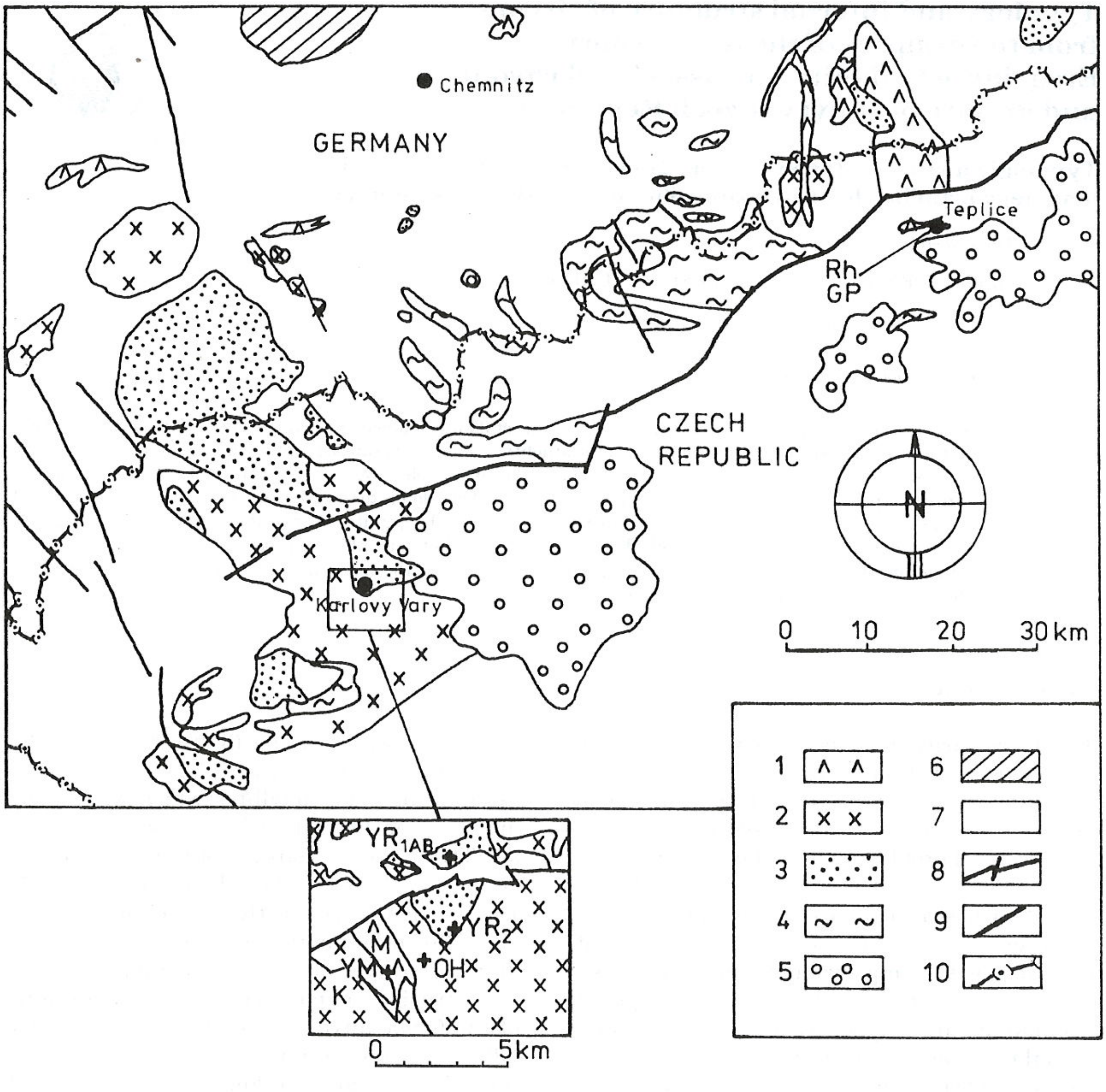


Fig. 1. Geological situation of the sample location in the Krušné hory Mts. area and the Slavkovský les in the Czech Republic. Sampling sites indicated by symbols in table 1. *1* – Variscan rhyolites and granite porphyries, *2* – OIC granites, *3* – YIC granites, *4* – orthogneisses, *5* – Neovolcanics and their tuffs, *6* – granulites, *7* – Pre-Upper Paleozoic fundament and platform cover, *8* – the Krušné hory/Erzgebirge major fault zones, *9* – faults, *10* – state frontier

accessory garnet, rutile and in places dumortierite and have on average 72 % SiO_2, 0.27 % TiO_2 and 0.9 % CaO.

The origin of the Teplice rhyolite (fig. 1) and the associated granite porphyry in the Eastern Krušné hory temporaly coincides with the interval between the formation of two magmatic complexes (OIC and YIC) (table 1). The extrusion of the Teplice rhyolite has been dated as Westphalian on the basis of plant relics (M. Šimůnek in Jiránek 1988). The Teplice rhyolite is a complex rhyolite – dacite body consisting of the fine-grained, porphyritic rhyolites and ignimbrites on the surface with mafic inclusions consisting of quartz and hornblende interpreted as possible restites. The typical composition of the surface variety of the rhyolite shows 76 % SiO_2, 0.12 % TiO_2 and 0.42 % CaO. The content of Rb is about 310 ppm and that of Sr 60 ppm. The average zirconium content is 238 ppm (Štemprok 1986).

The granite porphyry is a dark brown or violet rock with potash feldspar phenocrysts to 2 cm in a fine-grained granitic groundmass. The average SiO_2 is about 70 %, TiO_2 0.56 % and CaO 0.86 (Schovánková 1993), Rb is equal to 270 ppm,

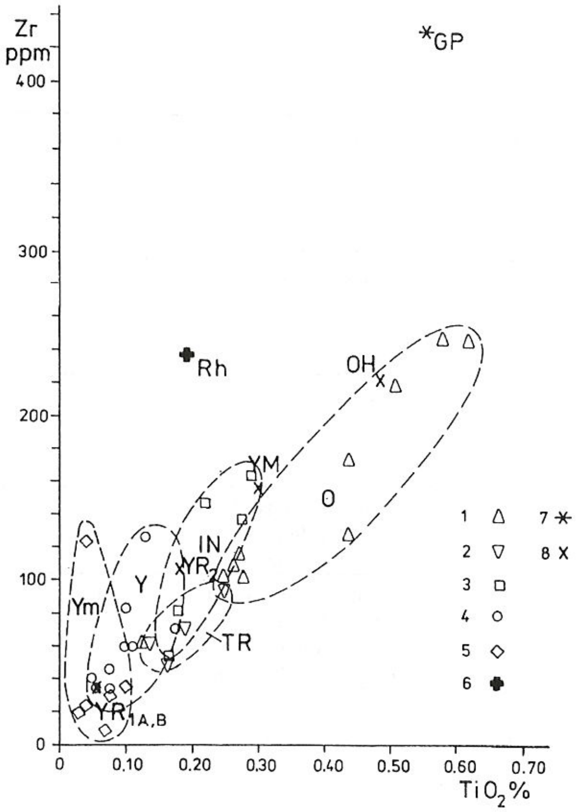


Fig. 2. The Zr/TiO_2 relationship in the rock units from which zircons were studied (explanations of symbols in table 1) with the data by Lange et al. (1972), Štemprok (1986), Breiter et al. (1992), Schováňková (1993) and new data Štemprok et al. (1992) and Štemprok (unpublished data). *1* – OIC granites (O), *2* – transitional granites (TR), *3* – intermediate granites (IN), *4* – YIC granites (Y), *5* – metasomatically altered YIC granites (Ym), *6* – Teplice rhyolite (Rh), *7* – granite porphyry (GP), *8* –rocks in the sample areas

Sr 120 ppm. Zirconium content is high about, 430 ppm (fig. 2).

The amount of zirconium in the granites decreases from the OIC granite where it is the highest to the YIC ones (fig. 2). However, the highest amount of Zr is in the rhyolite and granite porphyry.

Sampling sites and procedure

The sampling sites of the granites, rhyolite and granite porphyry are shown in fig. 1 and in table 2. In the Western pluton the main sampling site was on the profile along the Teplá river from the Březová water dam to the southeastern edge of the town of Karlovy Vary. This profile includes the granites of the OIC (OH), intermediate granites (YM) and the granites of the YIC from the immediate contact zone with the OIC granites (YR2). The most geochemically evolved granites were taken as two samples of the YIC (YR1A and YR1B) granites at the cliff at the railway bridge over the Ohře river in Karlovy Vary occurring in two textural varieties (non porphyric YR1A and porphyric YR1B).

From the eastern Krušné hory (Erzgebirge) the samples of the granite porphyry (GP) and of the Teplice rhyolite (Rh) were taken in the town of Teplice, below the astronomic observatory.

The samples R1A and R1B were taken by F. Mrňa during sampling for K–Ar determinations. They were treated in the laboratory of the Geological Survey in Prague and heavy concentrate separated in heavy liquids by a standard procedure.

The rest of the samples are granite or porphyry eluvia panned and their concentrates separated in heavy liquids (samples taken by A. Kodymová and A. Elznic).

The crystals were observed and measured under the binocular microscope. The length and the breadth of the crystals was measured on 150 specimens. The crystal form was documented in total number of 50 to 100 specimens. In contrast to the procedure proposed by Pupin (1980) the crystals were described in the position hkl for the basic pyramide as (111). For the studies of

Table 1. Position of sampled igneous rocks in the sequence of the magmatism in the Krušné hory – Erzgebirge batholith

Older Intrusive Complex (OIC)
Gabbrodiorites (Granodiorites)
OH – Biotite Monzogranites (Adamelites)
Transitional Granites
Two-mica Monzogranites
P – Porphyries
Rh – Rhyolites (Dacites)
GP – Granite Porphyries
Younger Intrusive Complex (YIC)
YM – Porphyritic Micrograntes (Intermediate Granites)
YR – Biotite Syenogranites
YR1A, B – Two-mica Syenogranites
Lithium Albite Granites (Apogranites)

Table 2. Localities and zircon properties

symbols	granite name	igneous complex	locality	colour	transparency	face determibility (%)
OH	biotite monzogranite	OIC	Březová Teplá river valley 1.5 km NE of the dam wall	beige to brownish	semitransparent alteration (transparent with clouded parts to fully clouded)	~100
Rh	Teplice rhyolite	P	Teplice, Písečný vrch, below the astron. observatory	beige	transparent	~100
GP	granite porphyry	P	Teplice, Písečný vrch below the astron. observatory	rose	transparent	~100
YM	biotite microgranite	YIC	Březová, dam on the Teplá river (swimming site)	colourless	semitransparent, less clouded (metamict parts)	80
YR_2	biotite syenogranite	YIC	Karlovy Vary Teplá river valley SW margin	colourless	mostly transparent with admixture of semiclouded crystals to 0.5 mm	70
YR_{1A}	two-mica syenogranite	YIC	Karlovy Vary bridge over the Ohře river	colourless single crystals yellowish to brownish (metamict)	transparent and semitransparent	74
YR_{1B}	two-mica syenogranite	YIC	Karlovy Vary bridge over the Ohře river	beige	semitransparent to semiclouded, in single crystals transparent or clouded	100

Table 3. Accessory minerals in heavy fractions

rock symbol	predominant	subordinate	rare
OH	apatite, amphibole, augite, ilmenite	garnet, rutile, zircon	monazite, diopside, anatase, clinozoisite, tourmaline, titanite, staurolite, topaz, opaque globules, actinolite, epidote
YM	augite, garnet, ilmenite	apatite, amphibole, rutile, zircon	clinozoisite, magnetite, topaz, epidote, zoisite, moissanite, tourmaline, actinolite
YR_2	amphibole, garnet, ilmenite	augite, rutile, diopside (?), actinolite, topaz, titanite, zircon	anatas, apatite, epidote, disthen, clinozoisite, tourmaline
YR_{1A}	pyrite, titanomagnetite	ilmenite, zircon, monazite, apatite, (hematite), topaz	rutile, cassiterite, anatase, diopside, tremolite, tourmaline
YR_{1B}	pyrite, titanomagnetite, ilmenite	hematite, zircon, monazite, topaz	rutile, anatase, epidote, apatite, tourmaline, garnet, galena, actinolite
Rh	magnetite, Ti-magnetite, hematite	leucoxen, ilmenite, zircon, apatite, anatase, diopside, opaque globules	maghemite, pyrite, garnet, nigrin, rutile, tourmaline, augite, amphibole
GP	magnetite, titanomagnetite, leucoxene	ilmenite, hematite, augite, apatite, zircon, amphibole	anatase, diopside

the internal habit the crystals were examined under the polarizing microscope in the transmitant light not considering their size and shape. For the evaluation only the crystals were used on which the internal structure was visible and this could also be drawn. The crystals were drawn without the design machine in a simplified way in which cracks and irregularities on the surface were omitted. Thus usually 50 to 125 individuals from a larger number of examined crystals were evaluated.

Accessory minerals

Studies of accessory minerals were carried out on granites and associated volcanic rocks in the Czech and German part of the batholith. Accessory minerals from the kaolinized granite from Karlovy Vary were determined by Rösler (1902). Zircons from the granites of the Erzgebirge, from the massifs of Niederbobritsch, Schellerhau, Eibenstock, Bergen – Lauterbach and Kirchberg were studied by Hoppe (1963). The crystals are mostly zonal with three generations of zones. The clear zircons have forms which could not originate in granitic environment and may come from gneisses. Zircons with earlier nuclei and later overgrowths from the Western Erzgebirge granites were described by Hallbauer (1961). There are two kinds of zircons: colourless with inclusions and zonal mostly clouded. The latter predominate in ratio 2:1. There are zircons which have the properties of both the kinds of zircons. However, there are mostly zonal zircons around earlier normal core.

The association of the accessory minerals in the Erzgebirge granites was given by Lange et al. (1972). Accessory minerals from the Slavkovský les granites were described by Fiala (1968) and the properties of accessoric zircon from various types of the Teplice rhyolite by Štemprok and Lomozová (1980).

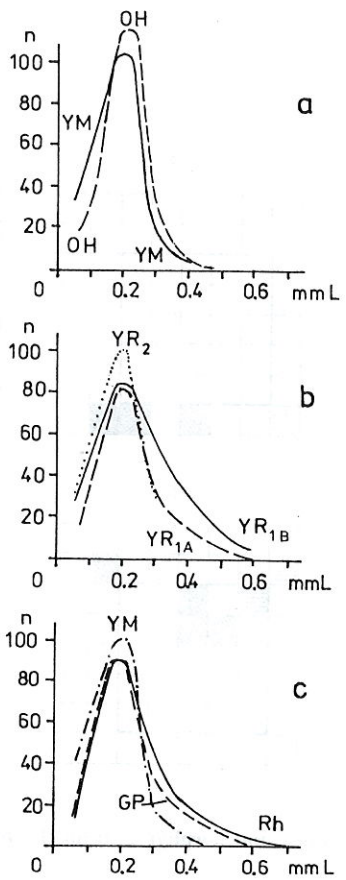


Fig. 3. Frequency (n) of the length (L) distribution of zircons in the OIC granite (OH) compared to the earliest YIC granite (a), in YIC granites (b) and of the earliest YIC granite (YM) compared to the Teplice rhyolite and granite porphyry (GP). The curve length determines the difference between the minimum and maximum length of crystals in the population.

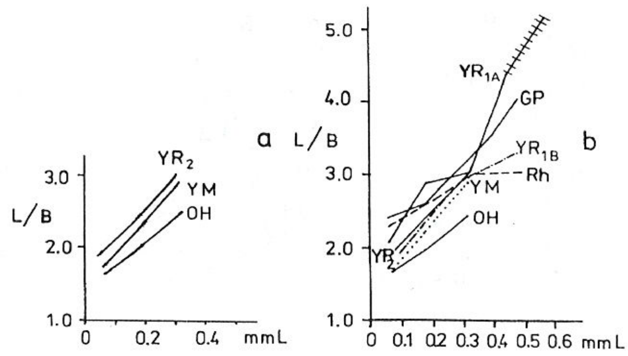


Fig. 4a,b. The increase of the coefficients of elongation (L/B) with the length of zircon crystal (L) for the OH, YM and YR2 granites (a) and for the OH, YM, YR1A, YR1B, Rh and GP samples (b). The curves connect arithmetic means of elongation coefficients in the groups with a constant interval of lengths. The crossed part of the YR_{1A} curve is on the basis of a single sample. For symbols see table 1.

The association of accessory minerals in the samples examined is shown in table 3. Accessory minerals are differred according to their abundance in the heavy concentrate into three categories classified as predominant, subordinate and rare. Zircon belongs in most of the samples to the category of subordinate or predominant accessories. Ilmenite along with titanomagnetite is one of the most abundant opaque accessories which accords with the classification of the granites to the ilmenite series granitoids according to Ishihara (1977). Magnetite is a predominant accessory in rhyolite and in granite porphyry. Apatite accompanies zircon in most of the samples. Topaz is a current accessory of the granites of the YIC exept for microgranite where it is rare. The presence of garnet as predominant or subordinate accesory is significant in early members of the evolution series (OH, YM and YR2). The presence of subordinate augite and amphibole in the OIC granite (OH) accords with its earliest position in the magmatic cycle. Pyrite and cassiterite in the sample YR1A testifies to its possible more pronounced postmagmatic alteration as contrasted with other igneous rocks examined.

Earlier studies of zircons

Systematical study of the zircon crystals has been narrowed to the application of three principal methods using mainly statistical methods (earlier literature summarized by Pupin and Turco 1972).

a) measurements of crystal dimensions (length, breadths, elongations), arithmetic means of length and breadth and their

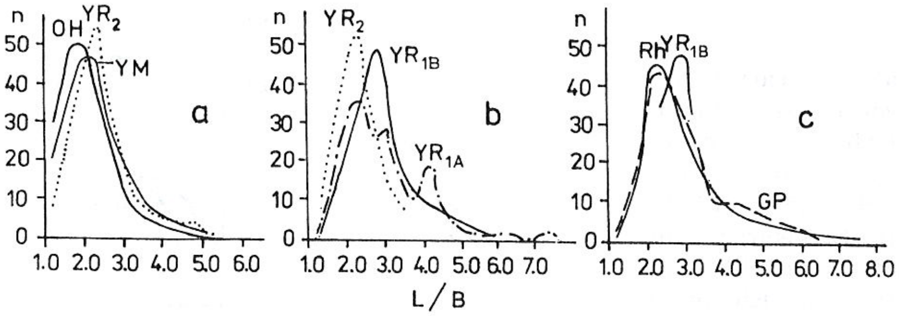


Fig. 5. The distribution frequencies (n) of the coefficients of elongation (L/B) of zircon crystals in the OH,YM and YR2 granites (a), in the YIC granites (b) and the porphyries compared to YR1B. For symbol explanation see table 1

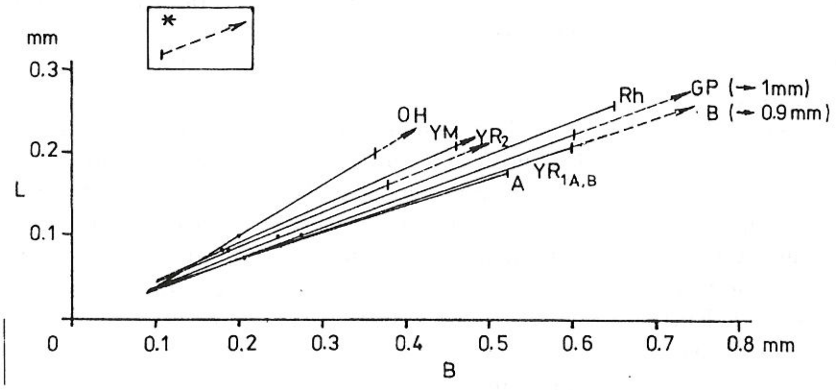


Fig. 6. Reduced major axes (RMA) according to the method by Larsen–Poldervaart (1957) characterizing the relationship between the lengths and breadths in individual populations. The axes transect the points of average length and breadth of crystals under the angle whose tangent expresses the ratio of both standard deviations. In rectangle ✱ the symbol of the extention of the length in the whole sample

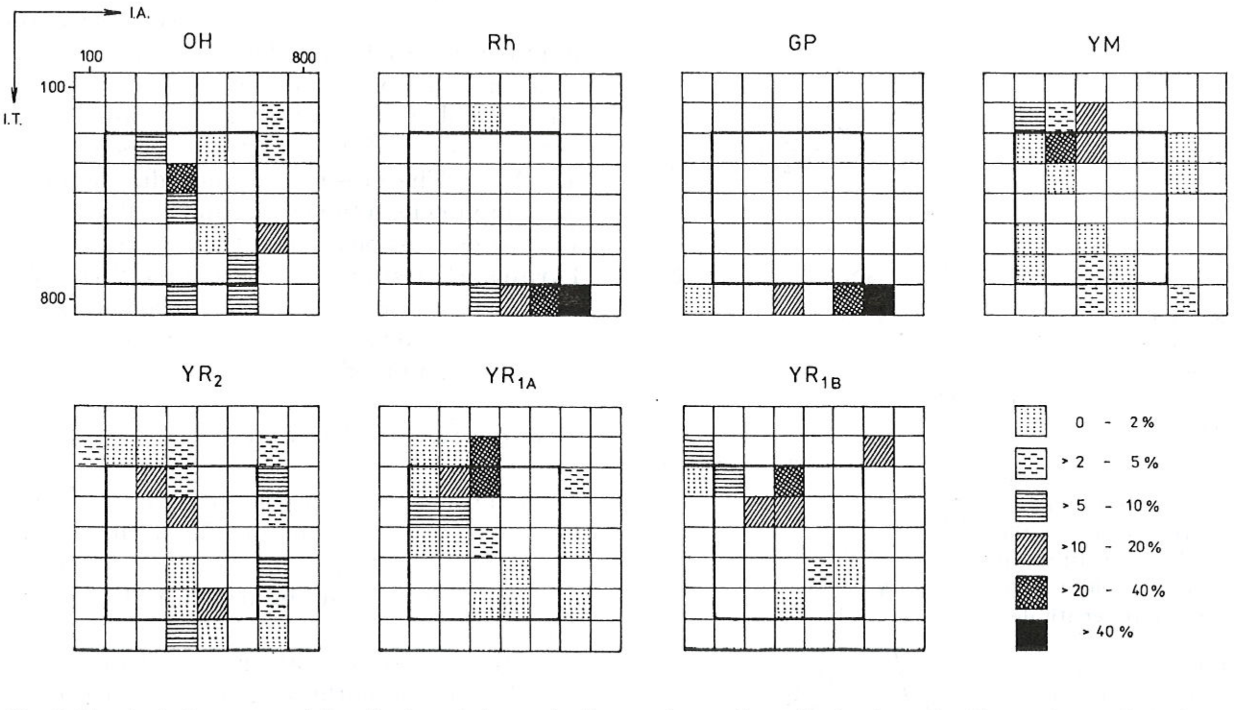


Fig. 7. Typologic frequency of distribution of zircons in the granites and porphyries from the Krušné hory – Erzgebirge granite batholith. For symbols see table 1

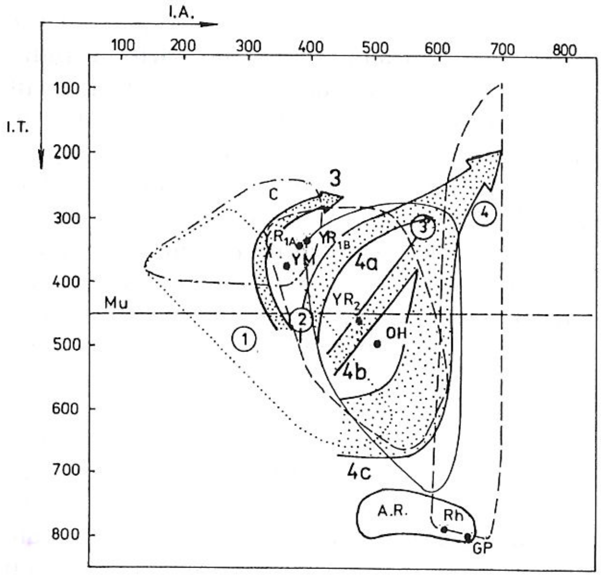


Fig. 8. Distribution of mean points of studied zircon populations in typologic diagrams of Pupin (1980) with marked global typological evolutionary trend of populations. I.A. index agpaicity – Al/alkaline ratio; I.T. index temperature. Igneous rock fields (numbers in circles): *1* – diorites, quartz gabbros and diorites, tonalites, *2* – granodiorites, *3* – monzogranites and monzonites, *4* – alkaline and hyperalkaline syenites and granites, *c* – cordierite-bearing rocks, *A.R.* – alkaline series rhyolites from anorogenic complexes. Global typological evolutionary trend lines (dotted): *3* – granites of crustal or mainly crustal origin – intrusive aluminous monzogranites and granodiorites, *4* – granites of crustal + mantle origin, hybrid granites; *a,b,c* – calc alcaline series granites (granodiorites + monzogranites); *Mu* – muscovite

standard deviations (Larsen and Poldervaart 1957) evaluated statistically or expressed as reduced major axis (RMA). The results are summarized by Poldervaart (1956). Sedimentary origin of zircon can be deduced from the large proportion of crystals with the elongation coefficient less than 2.0.

b) crystal typology was elaborated in detail by Pupin and Turco (1972). The chemical composition of the crystallizing environment plays the leading role in the growths of bipyramides. In the environment rich in Al the pyramide (311) is developed while in strongly alkaline and poor in Al the pyramide (111) predominates. Pupin (1980) elaborated in detail the typology of zircons applied to the origin of rocks in relation to the crust and mantle derivation.
In the granitic zircon population the (110) individuals represent an earlier form enclosed as inclusion in other varieties while zircons with (100) appear as later forms where (110) faces are obscured by later overgrowths.

c) nuclei investigation is not a common method in zircon studies. Hoppe (1963) differentiates in granites earlier clear crystals (Altbestand) which may predominate over the crystals formed within the granite itself. The origin of the earlier zircons can be occasionally observed in metamorphites. As early nuclei can regarded those which do not show any growth of granitic forms. The surface of the nuclei is commonly with impurities, often in the shape of needle-like crystals.

Rounded and anhedral forms typical of sediments have been observed in granitoids supporting the suggestions that zircons may survive through several cycles of crystallization (Veniale et al. 1968).

Morphology and dimensions of zircons

Zircon crystals are mostly columnar in shape, regularly grown with acute edges. Transparent, light beige zircon is well recrystallized. In semitransparent zircons the fresh, younger shell includes badly crystallized core with numerous bubbles. Occasionally the core predominates over the shell (e. g. in OH sample). Then the crystal is more or less brownish (table 2) and metamict. Sometimes also the youngest last zone

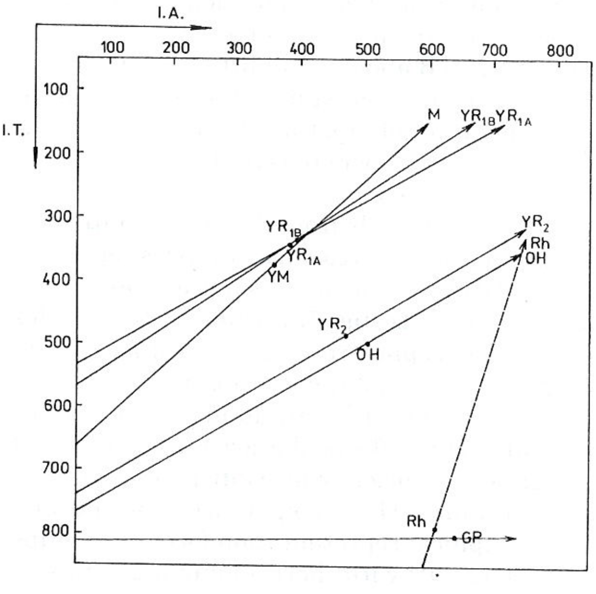


Fig. 9. Lines of calculated typological evolutionary trend (T.E.T.) of the sample populations, drawn in mean points of samples. They represent the scatter in crystal populations around the mean point from fig. 8. Sample Rh is identical with GP (tg = 0); the result is distorted by the presence of a foreign crystal in association (broken line). For sample symbols see table 1

is metamictly developed on the surface of some crystals with (100) prisms. This zone is most commonly in OH sample of the OIC granite. In YR granites it is discontinuous in the form of clouded ongrowths. Clouded crystals are whitish if not covered by limonite.

Zircon in the rhyolite and granite porphyry is always transparent, penetrated by numerous inclusions. At the surface they are needle–like, in deeper parts more rod–like (chlorapatite?). On its surface there are common submicroscopic inclusions of the groundmass or limonitized pseudomorphoses or mineral fragments (andesine or augite). Some cavities are so large that a part of a regular crystal is completely missing. The interior of the cavities may be step–like with ridges and depressions.

The most common medium length of zircon crystals is 0.2 mm. In the histograms of the length distribution, the curves of zircons of the OH, YM and YR2 granites are practicaly identical (fig. 3a,b,c). The samples YR1A, YR1B, Rh and GP have in addition a substantial participation of crystals with the length of 0.3 to 0.6 mm (fig. 3) which affects their arithmetic mean of length.

The fig. 4 (a,b) shows the increase of the elongation with the raising length of crystal. The fig. 4(a) summarizes the difference between the main representatives of the granites showing the intermediate position of the microgranite (YM). The grain size limit of 0.3 mm appears decisive for evaluation of zircon population. At the length 0.3 mm the zircon crystals have the elongation coefficient L/B about 3.0 (a little less in the OH granite). In larger crystals of YR1A, B and in GP the elongation of crystals sharply raises with increasing length whereas in the rhyolite it remains unchanged.

Zircon crystals from the OIC granite have the mean elongation coefficient L/B less or nearly 2.0. In OH and YM there is a great proportion of short crystals (fig. 5a) while in YR samples and in the Teplice rhyolite as well as granite porphyry these crystals are absent (fig. 5b,c) or they are replaced by an admixture of larger crystals. This affects the arithmetic mean of elongation coefficient which differs from the histogram values. Thus elongation coefficients and their graphical representation form two groups of samples: OH with short columnar crystals on one side and YR1A, 1B, GP and Rh with large and columnar crystals to needle ones on the other. The YM and YR2 are transitional (fig. 5).

In fig. 6 the statistical evaluation of the previous data according to the method proposed by Larsen and Poldervaart (1957) is shown. The RMA lines (reduced major axes) represent the relationship of lengths and breadths in individual populations. The lines intersect the point of the average length and breadth of crystals in a sample under the angle whose tangent represents the ratio of standard deviations. The length of the line (crossed) is determined by the distance between the minimum and maximum length of crystals found in quarter of the population. The dashed line (✱ in rectangle) expresses the presence of larger crystals in sample whose limit is given in brackets. The figure shows that the samples from the same localities are characterized by a similar angle of lines. The samples from the rhyolite and granite porphyry as well as from the YR1B granite have a larger average length of crystals. Zircon crystals from the OH granite differ clearly from others in all aspects as shown in fig. 6.

Typology

Many kinds of accessory zircon are represented in the populations examined including very rare tabular zircon (Pupin 1976, 1985). Bipyramidal crystals were not ascertained.

A more exact characteristics of the crystal forms was obtained from the analysis according to the method proposed by Pupin (1980). The results are plotted in the diagram in figs. 7 and 8 which was obtained on the basis of examination of 70 to 90 % determinable crystals.

All the crystal forms in the population are plotted into a rectangular typological diagram (fig. 7) whose horizontal axis evaluates the importance of the combination of high and low pyramides (I.A.) whereas the vertical axis shows the combination of (110) and (100) prisms (I.T.). From the starting I.A. value 100 the importance of bipyramide (311) decreases towards the I.A. 800 value at the expense of the bipyramide (111). Similarly in the direction of the axis I.T. the significance of the prism (100) is gradually decreased at the expense of the prism (110). The points for all crystals in the diagram are represented (fig. 7) by a mean point (fig. 8) and its trend line TET (fig. 9). The lines in the mean point intersect horizontal axis at an angle whose tangent is equal to the ratio of both the standard deviations. The line terminates on the limit of the area occupied by a given population.

The increasing index I.T. expresses the raising temperature of completed crystallization of individual varieties of zircon represented in the population in which in addition to the completed forms the relics of earlier stages of crystallization are preserved.

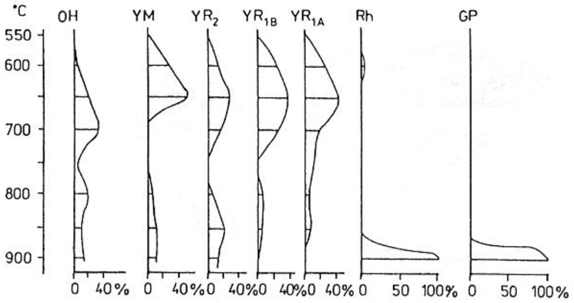


Fig. 10. Typological distribution I.T. of zircons studied in the temperature ranges after Pupin (1980). For symbols of samples see table 1

On the basis of zircon typology Pupin (1980) characterized the fields of zircons in igneous intrusives (fig. 8) and indicated their main trends of differentiation.

Microgranite (YM) (fig. 8) and the more evolved YIC granite from Karlovy Vary (YR1A and B) fall into the field of igneous rocks with cordierite in that part which overlaps with the field for granodiorites. The samples of the YR2 granite and that of the OIC granite (OH) is located in the field for granodiorites, monzogranites and monzonites which agrees with petrology of both the groups.

In the same diagram the principal trends for the distribution of mean points according to Pupin (1980) are given. The points for YR1A, B and YM are close to the trend band 3 for intrusive aluminous monzogranites and granodiorites classified with the granites of crustal or mainly crustal origin. The YR2 granite lies on the trend band 4b of calc – alkaline series granites which are characteristic of the crustal + mantle origin whereas the point for the OIC granite is between the 4b and 4c bands of calc – alkaline granites.

The zircon samples from the Teplice rhyolite and from the granite porphyry are classified with the field of alkaline series rhyolites from anorogenic complexes (A.R.) which is also close to the field for alkaline, hyperalkaline syenites and granites (4) after Pupin (1980).

The trend lines T.E.T. of crystals in studied samples evaluated on the basis of statistical treatment of the mean points and their standard deviations in the diagram after Pupin (1980) are given in fig. 9. The trend lines for the YR1 granites are close to each other and they are paralel, the line of YM is different. The lines of YR2 and OH granite have mutually parallel course to YR1A. The position of the mean points and of the trend lines for the rhyolite and GP are completely different from intrusive rocks. The slope of the Rh line is strongly affected by the presence of a foreign zircon crystal which might have been assimilated (see also fig. 7).

The estimation of the temperatures based on the treatment of the I.T. index is given in fig. 10 using the combination of the (110) and (100) prisms. According to Pupin (1980) the prism (110) originates at higher temperature than the prism (100) which appears at 850 °C subordinately. Its significance gradually increases and becomes dominant at 600 °C. It disappears completely at 550–600 °C when crystallization of columnar zircon terminates.

The fig. 10 shows that in all the granites examined the crystals from the period of crystallization between 700 to 600 °C prevail. The last crystallization temperatures of zircons from the rhyolite and granite porphyry are completely different. Earlier crystallization above 900 °C was not preserved and it was superimposed by a younger one which terminated between 850 to 900 °C.

The crystallization interval between 800 and 900 °C is supressed in the granites where the relative peak of maximum last crystallization is about 700 °C in the OIC granite (OH sample) and 650 °C in the YIC granites which agrees well with their position in the evolution line.

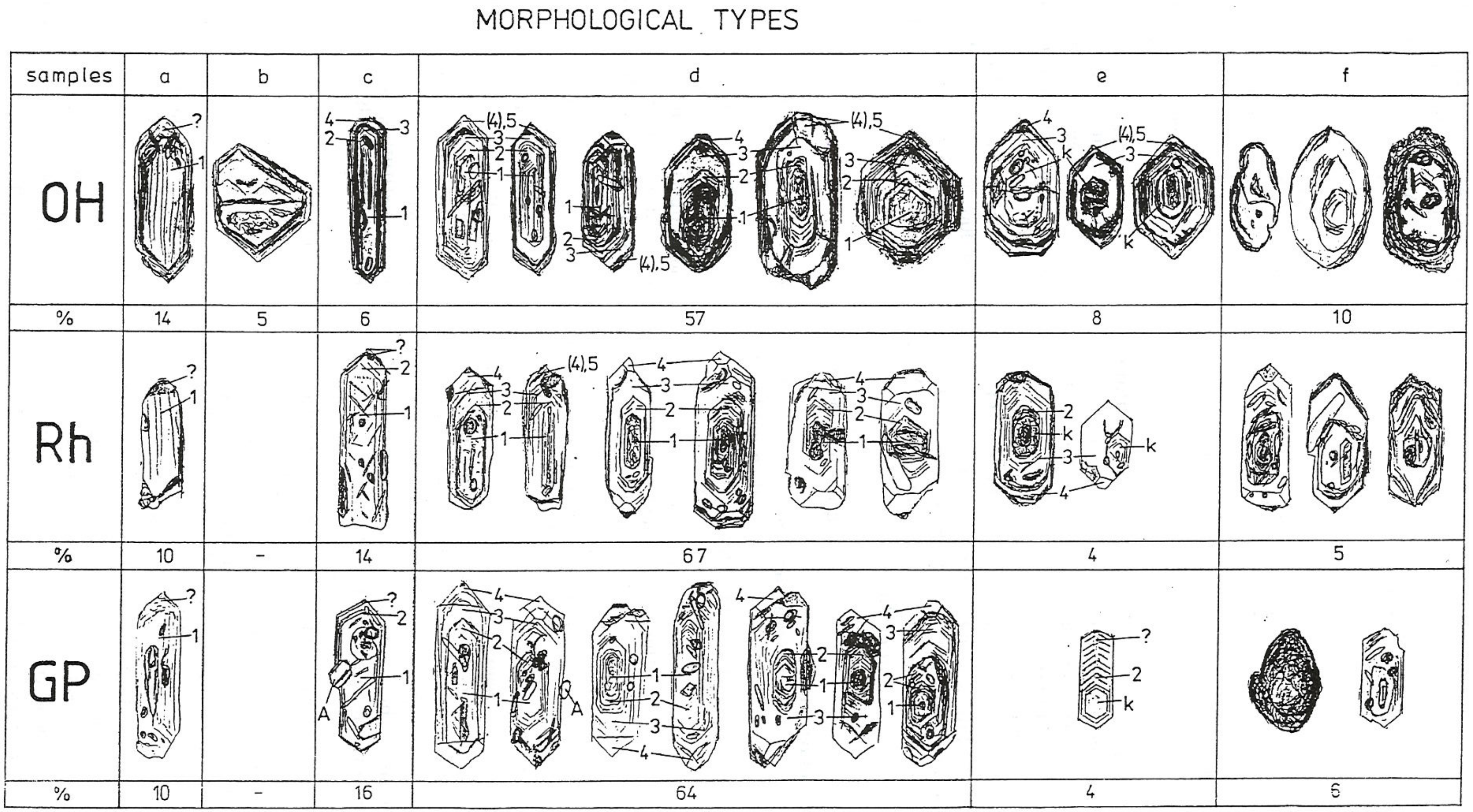
Internal structure

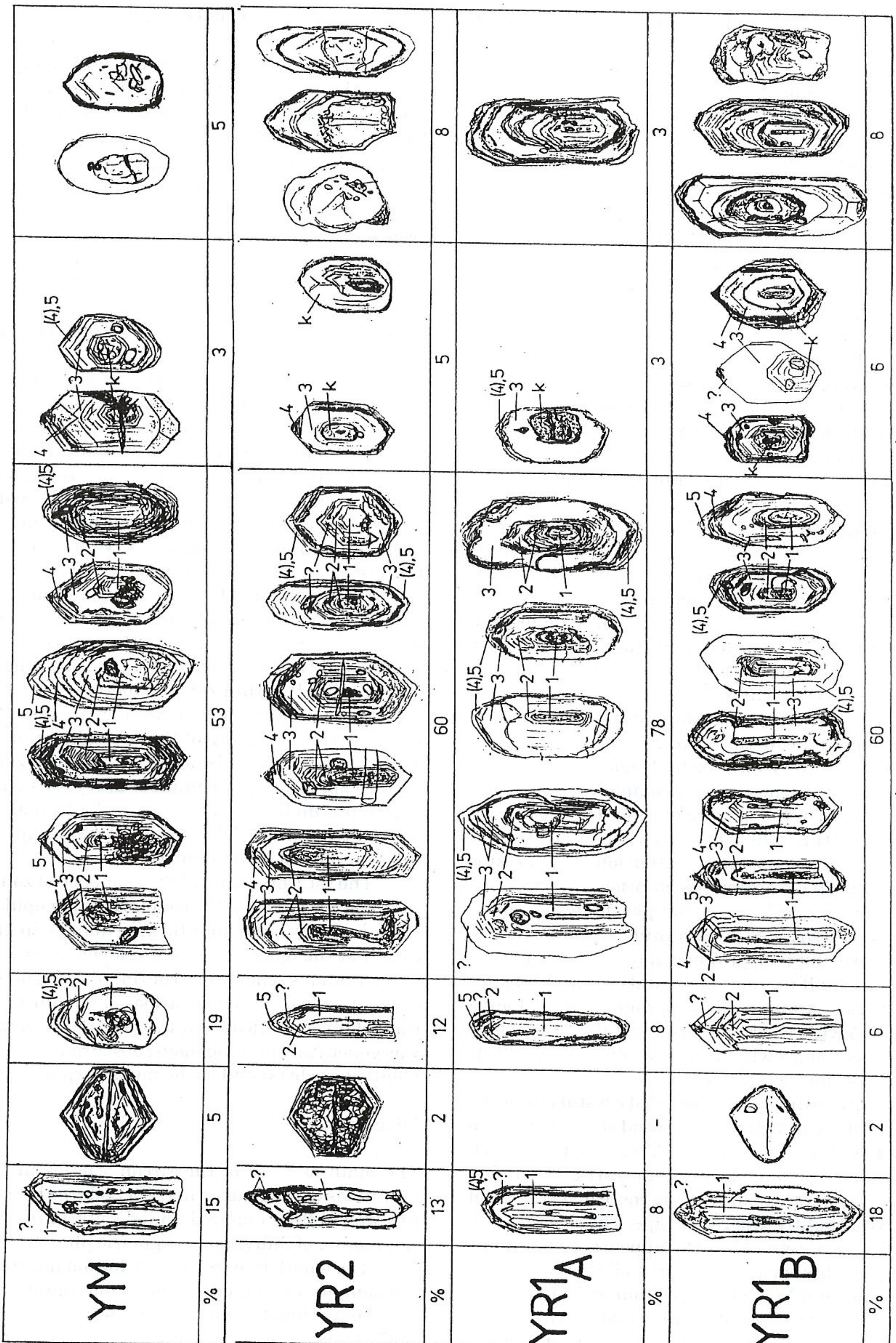
The development of zircon crystals in the samples examined is shown in Pl. 1 where only the most important and best developed crystals were selected to characterize types found in the population and their important variations. Approximate frequency of the types examined in all specimens is expressed by numbers in % in the columns a to f.

By comparing the internal forms of crystals it can be ascertained that in the population there occur less common crystals different from others (e.g. tabular crystals up to 5 % or the forms with rounded surface or core, column f in Pl. 1 constituting 3 to 10 % of population). However, the bulk of the zircon crystals is formed by forms which repeat a constant model of growth (other columns in Pl. 1) which make up 85 % of the population.

In this model there are repeated in a constant sequence five stages of development. In addition to two of them characterized by typological examination (figs. 7 and 8) there are three in addition. In the crystal section these zones are manifested by a more pronounced line or by a mechanical disturbance of an earlier crystal (its breaking, depressions on its surface or by the presence of bubbles). The following zone continues by a different crystallization (different trend of elongation, different pyramide, partial zoning and clouding). The greatest difference in

Plate I. Morphological types of zircon crystals
A – apatite, 1–5 zone number, ? – number is not clear. Columns: a) longitudionally zonal relics (1) with thin overgrowth of uncertain classification, (b) tabular zircon, c) relics of zircon needles (1,2) with overgrowth of uncertain classification, d) completely developed zircon crystals. In nuclei they contain needles (type c, zones 1 and 2 without overgrowths) or their fragments (zone 1 and 2). The thickiest 3 zone occupies the largest part of the volume. On the surface there occurs the 4th zone with (110) occasionally covered by the zone 5 with (100), e) completely developed crystals with an earlier crystal in the core (k), f) different crystals, probably of foreign origin.




YM
%
15
5
19
53
3
5
YR2
%
13
2
12
60
5
8
YR1A
%
8
-
8
78
3
3
YR1B
%
18
2
6
60
6
8

zones observed is in case that the volume of a crystal is occupied by the earliest zone (Pl. 1, a and b columns) at the expense of younger zones (columns c and d) or vice versa.

The crystals with evidently completed development constitute from 53 to 81 % of all the populations (Pl. 1, column d). More simple crystals composed mainly of the earliest zone 1 (Pl. 1, column a, c) may be regarded as relics. They are identical with the seed crystals of the nuclei of predominant crystals (Pl. 1, columns d, first crystals of sample row). In many crystals their fragments are in such position (column d, remaining crystals in the row).

The surface of the relics is formed by very thin overgrowths of a uncertain number without distinct boundaries which cannot be closely defined. In the case of the column a, they have some undistinctly longitudinally zonal crystals in their cores without an uniform terminal ending *(zone 1)*. They constitute from 8 to 18 % of the total population. In the column c the core of zircons is composed of recrystallized longitudinally zonal crystals with a low but sometimes also a high pyramide *(zone 2)*. They represent 6 to 19 % of the population. In YM sample they are broken to many coarse fragments in relict form. The boundary with the next second zone is not always clear.

In the completely developed crystals (Pl. 1, column d) the distinct *zone 2* overgrowths on the surface of the zone 1 or its fragments. Crystals possess a distinct core of completely developed crystals. On the surface of relics (Pl 1, columns a and b) this zone 2 is badly visible. The second zone is characterized by extension of the crystal length. The overgrowths on prismatic faces are thinner than those on the pyramides. In most crystals the low bipyramide predominates. However, high bipyramide may also occur reaching the half number of crystals in the YR samples. Sometimes both the pyramides may change (Pl 1, YR1A, column d, last crystal) or they show a repeated growth of the low bipyramide (Pl. 1, GP, column d, fourth crystal).

According to the model of crystals from the time of the growth of the second zone, there were formed *"earlier crystals"* (Pl. 1, column e) which probably belonged to others of the above described crystals but they are more disturbed and have a slightly different shape. The crystal k (Pl. 1, YR2, column e) has the appearence of a relic. It probably formed the cores of crystals in OH sample and YR1B (Pl. 1, column e, last crystal). In isometric concentrically zonal "earlier crystals" with a globular symmetry (column e, middle crystals) the overgrowth predominated over the core, if the core existed at all.

The following *zone 3* overgrew the cores formed by earlier, often long and broken crystals of the zone 2 (column d) also by "earlier crystals" and by some foreign crystals (Pl. 1, YR2, column f, last crystal). It is mostly clear and thick, independent of the form of its cores constituting commonly a substantial part of the crystal volume. The breadth of most crystals increased during the growth of this zone. High pyramide formed only one end of crystals (YR2, column d, second crystal). It is developed at the maximum in a half of crystals. The surface of crystals with (111) is commonly disturbed. In porphyries the surface of the zone 3 is indistinct towards the next 4th zone. However, its presence may be presumed from the doubled ends of crystals.

The *zone 4* overlies the zone 3 and it forms crystals with the prism (110). In the typological diagram (fig. 7) it appears with I.T. 800 and with its decrease it is covered by the zone 5. The prism (110) is definitely missing at I.T. values of 200. Both the zones are mostly thin.

Zone 5 is best defined by a typological diagram. This zone is missing in the porphyries. In the granites this zone ovegrowths inclusions of biotite and thus it is considered to be younger than biotite. It is thin zonal to metamict.

Continuous trend of crystal evolution initiated at the beginning of the crystallization of zircon with zone 2 and ending with the 5th zone can be expressed by the number of crystals with high bipyramides. It mostly slightly decreases, only in the sample YM it rapidly grows up. In the samples YR1B it is constant.

The interpretation of the sequence of zones in zircon crystals and the comparison of populations has a genetic significance mainly in the case that the igneous rocks developed according to the Bowen's scheme of a continuous magmatic crystallization. However, it looses its substantial genetic significance if the origin of crystals was genetically heterogenous, obscured by sedimentary cycle (s) and /or by metamorphism.

Discussion

The main purpose of the zircon studies in the granitoids of the Krušné hory/Erzgebirge batholith was to find a more detailed criteria in distingushing of individual magmatic phases.

The length frequency distribution has in all the samples examined a similar maximum (fig. 3). The arithmetic mean of the lengths is less uniform as consequence of incorporation of the lengths of less frequent large crystals.

The largest zircon crystals were observed in the granite porphyry to 1 mm size and in the YR1B granite where they are up to 0.9 mm large and the fragments of crystals 0.5 mm size are common.

According to Lyakhovich (1963) the crystal size depends on the melt viscosity which is in a direct relationship to the amount of volatiles. As early as (1886) Chrustchoff noticed that in the igneous rocks with porphyritic phenocrysts zircons are the larger the better porphyritic structure of the rock is developed. Thus the longest crystals are in granite porphyry (rhyolite) and in the porphyric YR1B.

The coefficients of elongation of zircon crystals in the porphyries (P) and YIC granites (table 1) expressed as the peaks of histograms (fig. 5) or as arithmetic means are always larger than 2.0 (correspond well to the interval 2.0 and 3.0 in which most the granites occur according to Poldervaart, 1956). Large prismatic crystals with the elongation larger than 4.0 are according to Poldervaart in a minority of granites. They are present in the samples YR1 and GP where they form a local maximum. According to Poldervaart (1956) the elongation of zircon crystals depends on Zr concentration in the time of crystallization whereby longer crystals grow at lower concentrations of Zr. Crystal elongation increases with a quicker solidification of granitoids (proximity of ancient surface, apical parts of the massifs, hybridization, small size of the granite bodies etc., Poldervaart 1956, Lyakhovich 1963 etc.). Yushkin et al (1966) found the dependence of the average elongation of averaged size crystals on the decreasing average depth from the ancient surface.

By using the arithmetic means of lengths (the first value) and reading the corresponding elongation values in fig. 5 (second value) we obtained the following data: OH – 0.20 mm, 2.05, YM – 0.18 mm, 2.3, YR2 – 0.19 mm, 2.40, YR1A – 0.2 mm, 2.9, YR1B – 0.27 mm, 2.9, Rh – 0.25 mm, 2.85 and GP – 0.25, 2.85.

These values along with other data from diagrams (fig. 4) justify to differentiate three groups of igneous rocks which may express the different depth conditions of magmatic crystallization.

The first group includes the OH (OIC) granite which is characterized by a mean elongation of 2.05. This granite might have crystallized at relatively greatest depth. The OH zircons have the largest proportion of short crystals and the elongation of crystals grows most slowly with the crystal length. Crystals above 0.5 mm are absent.

The second group is characterized by the elongation of averaged size crystal of 2.3 to 2.4 (sample YM and YR2) in which also the large crystals are missing. The proportion of short crystals is intermediate.

The third group includes the youngest YIC granites (YR1A) and the porphyries (P) with elongation of the averaged size crystal from 2.85 to 2.90. They have a substantial admixture of larger and more elongated crystals and on the surface of crystals there are numerous cavities.

Thus, the YIC granites and porphyries represent near surface, occasionally subvolcanic bodies. The samples YR1 are close to GP, whereas Rh is different.

The peak of the elongation in OH expressed graphically (Fig. 5a) is less than 2.0, the value which is according to Poldervaart (1956) characteristic of zircons with abraded surface from sedimentary rocks. However, if sediments were metamorphosed the elongation also increased and this is documented by a second maximum on the diagrams while the original maximum is decreased. In our case the curve has only one maximum immediately below the value 2.0 with no indication of the second one (fig. 5a).

The proportion of crystals with lack of crystallographic faces varies about 20 %. Thus zircons with a good crystallographic shape are in predominance.

More than by their habitus the crystals differ by their crystallographic typology. This is closely connected with the petrology of the enclosing rocks. In the Pupin's diagram (fig. 8) the granite OH belonging to the Older Intrusive Complex occurs in the field of granodiorite, monzogranite to monzonites. It is outside the field of cordierite presence in igneous rocks in contrast to the younger granites (YIC) whose projections fall well into the field of cordierite – bearing granites. This strongly favours the idea that the granites of the YIC were affected by sedimentary source more than the granite of the OIC. However, the anomalous position of the sample YR2 is apparent from the diagram.

The importance of individual crystal faces on zircons is in agreement with the petrological nature. From it also the genesis can be deduced. According to the diagram proposed by Pupin (1980) the earliest of the granites the OH (Older Intrusive Complex) granite is close to the rocks of mantle derivation with a small admixture (fig. 8) of crustal material while the Rh and GP are entirely of the mantle origin. In the granites of the Younger Intrusive Complex the crustal material is predominant and it is manifested also by the presence of Al minerals. The YR2 sample has a transitional nature.

This can be further supported by the study of the internal structure of zircons mainly in initial stages of their development. This method is little known but even less is known about the initial development of zircons as given by Poldervaart (1956) on the basis of the study of elongation coefficients. Hoppe (1962) postulates that zircon crystallizing from the granitic melts developed only in metamict form very finely zonal. The question of the crystallization of the transparent zircon is considered as disputable and he thinks that transparent zircons originated under different conditions that metamict zircons and also in a different rock environment. He considers therefore the earlier clear stages of zircons in the Eibenstock Massif as earlier relics (Altbestand) belonging to a gneiss subjected to granitization. The crystallization in the YIC (Ore Mountain Granite) was very weak, insignificant with a share of "Altbestand".

If we apply this line of reasoning, we can assign the crystallization in the granitic environment with the fifth and fourth zone (Pl. 1, column d, OH, crystals 3, 4, YM crystal 1, 5, YR1B crystal 1, 2 etc.). The thickiest third zone would represent granitization (metamorphic) stage with a nucleus whereby the sedimentary transport occurred on its boundary with the second zone. This intepretation would be supported by distortion of its boundary (Pl. 1, OH, column d – crystal 4., column e – crystal 3, YM, column d, crystal 3, 5, YR2, column d, crystal 4, 6, YR1A, column d, crystal 2 – 5, column e, crystal 1, YR1B, column d, crystal 3, 4, column e, crystal 1) which does not correspond to the interpretation of an abbraded grain (YR1B, column d, crystal 3) which are missing on the grains studied. Such intepretation is more appropriate for the foreign crystals (GP, column f) or their nuclei (Rh, column f, crystal 1, YR1B, column f, crystals 1 and 2).

If we attribute the distortion of the zircon crystals formed by the zones 1 and 2 to abbrasion, then the source rock subjected to denudation might have been of relatively mafic composition like diorite. The zone 3 might correspond to the stage of metamorphism above 900 °C which is the optimum temperature for the zircon growth. During changing conditions the growth of zircons continued in granitic melts (zone 4 and 5).

This theory, however, does not explain well the uniform structure of most zircon crystals in the granites studied which suggests more probably a continuous evolution line as developed by Bowen for igneous rocks. A similar development can be observed in all the samples examined including the specimens of the granite porphyry (GP) and the rhyolite (Rh). In the last two rocks the boundary between the zone 3 and 4 is missing. We can observe some local differences e.g. the more repeated growth into the length (Pl. 1. GP, column d, crystal 4) or the occurrence of the (001) face on the surface of the zone 2 (Pl. 1, GP, column d, crystal 3).

Conclusions

The study of the zircon crystals indicate a considerable genetic unity of magmatites in or associated with the Krušné hory/Erzgebirge granite batholith which concerns common sources and magmatic development.

Zircons from the granite of the Older Intrusive Complex differ from the younger granites (YIC), Teplice rhyolite and granite porphyry by their smaller elongation. Zircon crystals from the granite porphyry of the Eastern Krušné hory are different from zircons in the microgranites (YM) associated with the Western pluton. Thus these rocks cannot be equivalent in their genetic position as indicated in some geological mapping (1:200 000, sheet Karlovy Vary, Geological Survey Prague). The zircons in the granite porphyry belong in all their features to the development of the rhyolite.

Zircon crystals in their internal structure lack any distinct evidence for the sedimentary stage of evolution which would be preserved as their nuclei. On the contrary the populations bear the features of zircons which can be correlated with some stages of the development of the mafic rocks (columns a – c). Thus the continuous development of the granites from the mafic rocks is used as a preferred explanation by the first author (Kodymová).

As the petrochemical and petrological evidence is strongly in favour of the sedimentary source of the granite (Štemprok 1986, 1993, Tischendorf and Förster 1990) it can be also postulated that the early stages of the growth of zircon crystal were obscured by sedimentary recycling and/or by metamorphism (Štemprok).

The granites of the Younger Intrusive Complex belong to the crustal granites according to the Pupin's classification whereas the OIC granite examined falls well into the group of granites of mixed crustal and mantle origin. The anomalous sample of the YR2 granite occurs in an intermediate position. Rhyolite belongs to alkaline extrusive rocks of the anorogenic position which well agrees also with the geotectonic position derived from the major element oxide chemistry.

The zircon typology reveals a considerable time interval mainly for the origin in the YIC granites which might have terminated in the postsolidus stage as indicated by the low temperature of the origin of some crystals in association with topaz. The assemblages of the opaque accessory minerals confirms early classification of the granites of both the intrusive complexes with the ilmenite series granites (Ishihara 1977). S–type classification essentially of the YIC granites (Štemprok 1986) supports the idea of the crustal origin of the granites based on zircon typology.

Translated by the authors

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Typologie a vnitřní stavba zirkonů žul krušnohorského batholitu a na něj vázaného rhyolitu a žulového porfyru

Byly studovány základní znaky (barva, rozměry a vnitřní stavba) a typologie akcesorického zirkonu v magmatitech variského krušnohorského žulového plutonu z našeho území. Ke studiu byly vybrány charakteristické vzorky žul z profilu Karlovy Vary– Březová (žula staršího intruzivního komplexu OH, porfyrický mikrogranit "žulový porfyr" YM, žula mladšího intruzivního komplexu YR a žuly z Karlových Varů (YR1A a YR1B), dále rhyolit (Rh) a žulový porfyr (GP) z východních Krušných hor.

Všechny pozorované zirkony ukazují na značnou genetickou shodu studovaných magmatitů. Zirkony ze žuly staršího intruzivního komplexu se liší od pozdějších žul a také od žulového porfyru a rhyolitu menším protažením. Zirkony ze žulového porfyru z východních Krušných hor jsou odlišné od zirkonů porfyrických mikrogranitů západních Krušných hor a proto nelze tyto mikrogranity geneticky spojovat s porfyrickým magmatismem východních Krušných hor. Ve své vnitřní stavbě nemají zirkonové krystaly jednoznačný důkaz o sedimentárním cyklu, kterým by prošly. Je však možné že tento vývoj byl zakryt opakovanou sedimentární recyklací nebo metamorfózou. Podle Pupinovy klasifikace patří zirkony žul mladšího intruzivního komplexu skupině korových žul, zatím co zirkony žul staršího intruzivního komplexu patří do skupiny žul smíšeného korového a plášťového původu. Zirkony z rhyolitů ukazují na příslušnost k alkalickým extruzivním horninám anorogenické pozice. Vnitřní stavba zirkonů je charakterizována vývojem pěti zón, které lze do určité míry ve studovaných horninách vzájemně korelovat. Existence dlouhodobého růstu je dokumentována zejména v žulách mladšího intruzivního komplexu, kde růst končil v období vývoje žuly v postsolidovém stadiu. Asociace opakních akcesorických minerálů potvrzuje příslušnost granitů k ilmenitové sérii žul podle Ishihary (1977).