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Metagranitoids and associated metasediments as indicators for the pre-Alpine magmatic and metamorphic evolution of the western Austroalpine Ötztal Basement (Kaunertal, Tirol)

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Abstract

Metagranitoids associated with metasediments are common in the Ötztal crystalline basement which is part of the Austroalpine tectonic unit of the Eastern Alps. The two main orthogneiss types, muscovite- and biotite-bearing metagranites (type 1) and mainly biotite-bearing metagranodiorites and metatonalites (type 2), were investigated together with the associated metasediments in the Kaunertal–Langtaufers area using geochemical and geochronological methods. A Sm–Nd errorchron, derived using data for ten type 1 metagranites, result in an "age" of 494 ± 73 Ma. An apatite whole-rock two-point isochron for one of these samples yields an age of 455 ± 8 Ma. Rubidium-Sr whole-rock ages are highly variable, and range from 470 Ma to 309 Ma. The broad scatter is probably caused by partial resetting of this isotope system during Caledonian and/or Variscan metamorphic events. Rubidium-Sr white mica ages also show a very large range. In few cases, near-Caledonian ages in muscovite cores have been preserved, whereas the majority of the micas has been reset, or recrystallized, during the Variscan tectonometamorphic evolution. Three Sm–Nd garnet whole-rock ages from micaschists range from 343 ± 1 to 331 ± 1 Ma and indicate a medium to high grade metamorphism of the metasedimentary host rocks of the orthogneisses at that time.

The mean ε_{Nd}^{490} values of the micaschists at the time of supposed magmatic crystallization of the metagranitoids (490 Ma) are –9.1 ± 1.1 and are significantly lower than those of the orthogneisses. For the two orthogneiss types 1 and 2 the mean ε_{Nd} values are –4.8 ± 0.5 and –7.6 ± 0.5, respectively. The negative ε_{Nd} values are compatible with a crustal source of the metagranitoids, but at least some mantle contribution is indicated for the type 1 orthogneisses by the shift to less negative values compared to the metasediments. Different degrees of fractionation for the two orthogneiss types are evident from major, minor and trace element correlation with CaO and from chondrite normalized REE patterns. Metagranites (type 1) are highly differentiated due to fractionation of plagioclase, K-feldspar and an accessory phase compatible for REE, whereas at least K-feldspar fractionation is absent in metagranodiorites and -tonalites (type 2).

The magmatic protoliths of the orthogneisses from the Austroalpine continental crust of the Ötztal basement were formed during an episode of intense crustal melting, possibly in the early Ordovician which is consistent with data on the metamorphic evolution in other Variscan and Alpine terranes of central and western Europe.

Keywords: Austroalpine unit, Ötztal Alps, orthogneisses, geochemistry, isotope geology, geochronology, crustal melting, fractionation, metamorphic events.

Introduction

Within the Eastern Alps the main tectonic units (Austroalpine units) comprise rocks from the continent south of the Alpine collision zone. Within these Austroalpine units medium- to high-grade metamorphic rocks are most abundant and are referred to as the crystalline basement. The Aus-

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troalpine crystalline basement consists of prominent metasedimentary and subordinate metaigneous rocks. Sm–Nd crustal residence ages of metasediments typically range from 1.4 to 1.7 Ga (THÖNI, unpublished data) and indicate a complex geologic history accompanied by numerous orogenic events. This study is restricted to metagranitoids which occur in distinct tectonic units of the Austroalpine. The polymetamorphic Ötztal and Silvretta units are typical examples of abundant metagranitoids in a matrix of quartzofeldspatic metasediments. Within the Ötztal block, the Kaunertal area was selected for detailed geochemical investigation of metagranitoids and neighbouring metasediments in order to constrain tectonic setting and age of magmatic and metamorphic processes within this part of the Austroalpine basement.

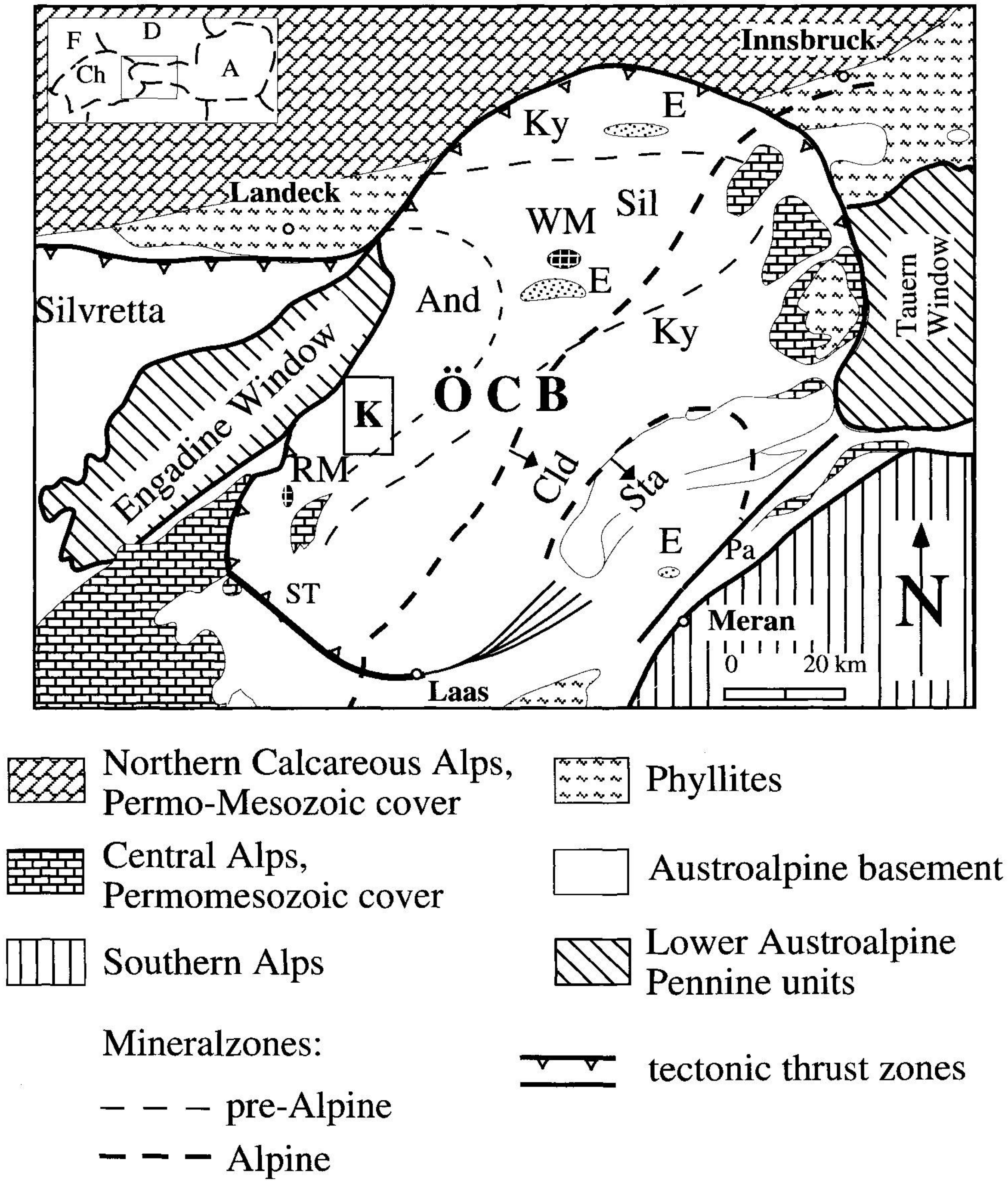

Fig. 1 Tectonic sketch map of the Ötztal crystalline basement (**ÖCB**). Ky: Pre-Alpine Kyanite; And: Pre-Alpine Andalusite; Sil: Pre-Alpine Sillimanite; Cld: Alpine Chloritoid; Sta: Alpine Staurolite; WM: Winnebach migmatite; RM: Reschen migmatite; E: Eclogite; ST: Schlinig thrust; Pa: Passeier-Jaufen thrust; K: Area of investigation.

Geological setting

The Ötztal crystalline basement represents a tectonically isolated Austroalpine thrust block (Fig. 1). It rests on Penninic units to the east and west, is thrusted against Austroalpine sediments to the north and is separated from underlying Austroalpine basement sheets by the Schlinig thrust plane at its southern rim (SCHMID and HAAS, 1989). The lithology comprises 1) typical paragneisses which are rarely migmatized and, less commonly, micaschists and metacarbonates, and 2) orthogneisses and amphibolites and, less commonly, metagabbros and eclogites. The structural pattern is dominated by an E–W-trending schistosity in the northern half of the block and megascale folding around steep axes in the southern part. The mineral assemblages are dominantly of amphibolite-facies grade, but relictic occurrences of eclogites are known since HEZNER (1903) from the central Ötztal area and have been studied in detail by MILLER (1970). Using Sm–Nd dating this metamorphism of eclogite- to amphibolite-facies grade in the northern and central Ötztal block is attributed to the Variscan orogeny. MILLER and THÖNI (1995) presented ages of 520–530 Ma based on magmatic plagioclase-clinopyroxene pairs from gabbros. These ages were interpreted as crystallization ages of the magmatic protoliths of these metabasites, whereas the high-P metamorphism was dated at c. 350–360 Ma based on metamorphic garnets. GEBAUER and SÖLLNER (1993), on the other hand, determined ages of 481 ± 9 and 336 ± 14 Ma, respectively, for the two events of interest, using conventional U–Pb and SHRIMP analysis of zircons from the metabasites. Further geochronological and petrological data indicate a Cretaceous Alpine metamorphic event (c. 100 Ma; THÖNI, 1981), with an increasing grade from very low to high grade conditions from northwest to southeast in the Ötztal block, where again eclogites are preserved within predominantly amphibolite-facies rocks. However, these eclogites are attributed to the Alpine evolution of the basement (HOINKES et al., 1991). The study area is situated in the westernmost Ötztal block, which was overprinted by only low grade Alpine metamorphism and is therefore well suited to investigate the pre-Alpine history of the Austroalpine basement.

Geology and petrography of the study area

The Kaunertal intersects the E–W trending structures and a complete geologic section across the main lithologies is exposed (Fig. 2). Numerous orthogneiss bodies, locally accompanied by amphibolites which contain relictic eclogite assemblages, are intercalated with paragneisses and micaschists. Orthogneisses either form concordant layers of several kilometers in length or resemble stocks of several kilometers in diameter. All orthogneiss bodies have the same metamorphic fabric as the neighbouring metasediments. Contact metamorphic phenomena are not observed. The micaschists of the upper Kaunertal–Langtaufers area are known for their low variance KFMASH-assemblages as they may contain kyanite, fibrolite and andalusite within the same sample in addition to staurolite, garnet, biotite, muscovite and quartz (PURTSCHELLER, 1969). In recent petrologic investigations TROPPER and HOINKES (1996) proposed a continuous clock-wise pT-evolution during one single metamorphic episode crossing subsequently the stability-fields of the three Al_2SiO_5-polymorphs during pressure release. Temperature peak conditions were calculated as c. 630 °C at maximum pressures of 0.7 GPa. During pressure release garnets have been partly or completely replaced by a biotite and fibrolite intergrowth. Application of geothermobarometric methods to these replacement textures indicated pressure- and temperature-conditions of 530 to 630 °C and 0.35 to 0.57 GPa for this retrogressive stage of metamorphism (TROPPER and HOINKES, 1996). Potassium-Ar ages of muscovite and biotite and Rb–Sr ages of biotite from metagranitoids of the study area range from 273 to 305 Ma and are interpreted as cooling ages (THÖNI, 1981). Hence a Variscan metamorphic overprint is demonstrated to have occurred also for this part of the Ötztal crystalline basement. However, the knowledge of the pre-Variscan evolution of the metagranitoids in terms of magma formation and intrusion as well as postmagmatic metamorphism is still poor.

Petrography of metagranitoids

In terms of the mineral assemblages three groups of metagranitoids are distinguished: a group of two mica-bearing (type 1), a group of only biotite-bearing (type 2) and a group of hornblende-bearing (type 3) orthogneisses.

Type 1 is a biotite- and muscovite-bearing leuco- to mesocratic orthogneiss and typically has a stock-like occurrence of 5 to 12 km^2 in size (Fig. 2). Crosscutting aplitic dikes composed of albite, quartz and garnet are typical structural features. Weakly foliated biotite-free leucocratic varieties, which lack augen-texture, may occur at the margins of type 1 orthogneisses. In contrast, a pronounced schistosity is outlined by laths of K-

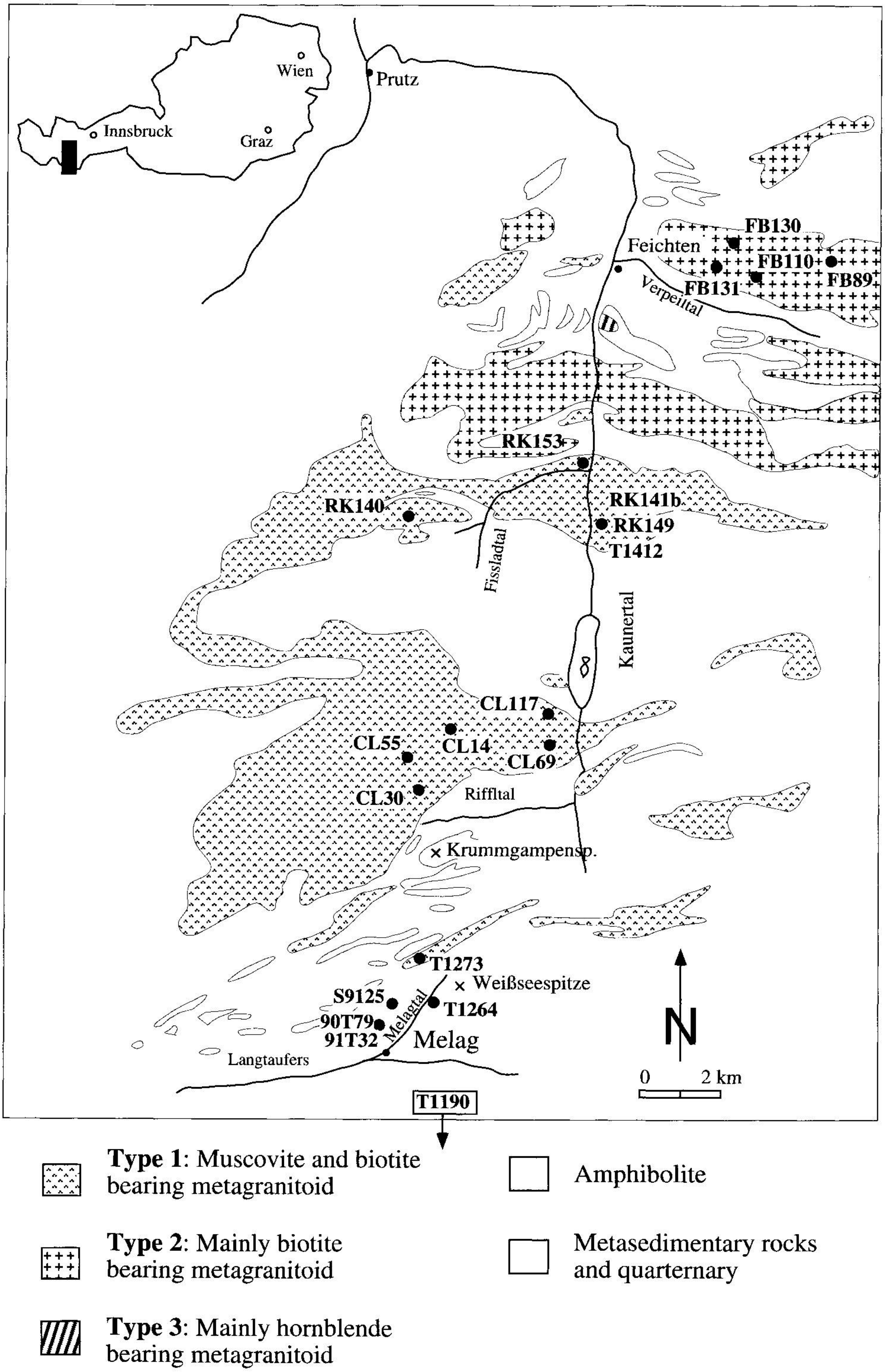

Fig. 2 Geological sketch map of the study area (Kaunertal–Langtaufers) showing sample locations.

feldspar megacrysts, which are several cm in size in the central part. In addition the schistosity is defined by quartz ribbons and elongated muscovite- and biotite-rich aggregates. The dominant mineral assemblage is quartz + K-feldspar + plagioclase + muscovite + biotite with accessory garnet, apatite, zircon, epidote, ilmenite, monazite and titanite. Muscovite is typically rimmed by secondary fine-grained, pale green phengite.

Type 2 orthogneisses are mainly biotite-bearing mesocratic rocks (virtually muscovite-free) and occur as separate highly stretched bodies which are 3 to 10 km in length (Fig. 2). They always exhibit up to 200 m wide transition zones to the surrounding metasedimentary rocks. These zones are characterized by bands of orthogneisses with metasedimentary rocks and aplites. The mineral assemblage is quartz + plagioclase + K-feldspar + biotite with accessory garnet, zircon, apatite, titanite, epidote, allanite, rutile, ilmenite and rarely molybdenite. Some varieties of type 2 orthogneisses contain either hornblende and biotite or hornblende only. Other biotite-bearing orthogneisses in the northern Ötztal block, situated outside the study area, were examined by EICHHORN (1991, unpubl. M. Sc. thesis). His geochemical data are used for comparison.

Type 3 is a hornblende-bearing orthogneiss and occurs in the study area as a weakly foliated body which is about hundred meters in diameter. It is enclosed by amphibolites. According to its location the type 3 orthogneiss is termed Tieftal-orthogneiss. The mineral assemblage comprises quartz, albite, microcline and hornblende. In addition to hornblende, clinopyroxene or biotite may occur. Common accessory minerals are titanite, zircon, apatite, allanite and rarely magnetite, molybdenite and fluorite. A detailed description and interpretation of this small metagranitoid is already published by BERNHARD et al. (1996). It is interpreted as the granitic differentiation product of a tholeiitic basic magma which was formed 485 Ma ago (single zircon Pb evaporation and Sm–Nd sphene whole-rock dating) in course of an Early Paleozoic rifting process.

In this contribution, we are therefore mainly dealing with the geochemical and petrological characteristics of the two dominant orthogneiss-types 1 and 2 which are discussed in comparison to the Tieftal orthogneiss.

ZIRCON TYPOLOGY

Zircons of type 1 and 2 orthogneisses exhibit oscillatory growth zoning and may contain relictic cores which are usually absent in type 3 orthogneisses. Zircons of type 1 and especially type 2 orthogneisses are characterized by a broad range of shapes (Fig. 3). In contrast type 3 has specific shapes dominated by (101)-pyramids and (100)-prisms. Zircons with (211)-pyramids and (100)-prisms are typical of type 2 orthogneisses only. Zircons of type 1 orthogneisses are characterized by a combination of (101)-pyramids and (110)-prisms (Fig. 3). In terms of zircon types, type 1 and 2 orthogneisses are similar and clearly separated from type 3.

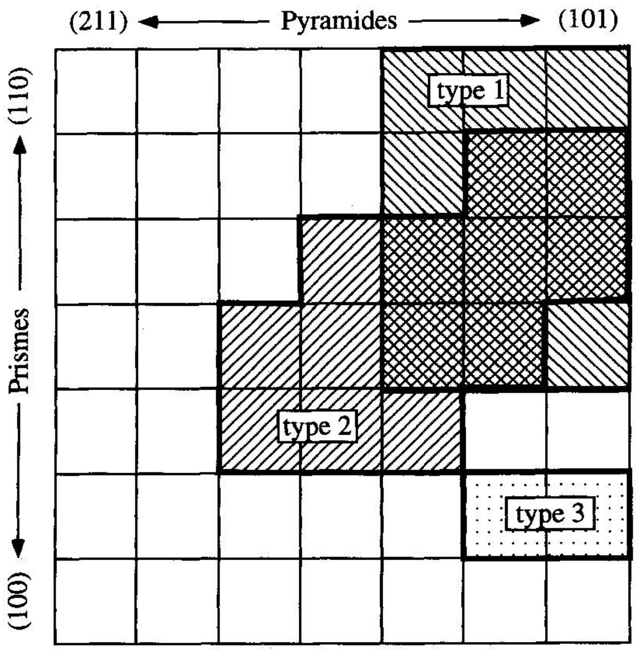

Fig. 3 Morphology of the zircons of the different metagranitoid types after PUPIN (1980).

Major-, minor- and trace element geochemistry

Representative chemical compositions of the two types of metagranitoids are presented in table 1 (Appendix). According to the chemical classification scheme of DE LA ROCHE et al. (1980) type 1 and the Tieftal orthogneisses are granites, whereas type 2 gneisses are mainly granodiorites and locally tonalites. Type 1 and 2 orthogneisses are calc-alkaline granitoids (IRVINE and BARAGER, 1971), whereas the small Tieftal body cannot be classified due to its high degree of differentiation.

Correlation diagrams of selected major and minor elements against CaO show significant differences between the three types of orthogneisses (Fig. 4). As typical for granitoids metagranodiorites and -tonalites (type 2 orthogneisses) are higher in CaO but lower in $Na_2O + K_2O$ and SiO_2 than metagranites (type 1 and 3 orthogneisses). In addition some crucial differences are observed:

– Higher P_2O_5-contents in type 1 orthogneisses distinguish them from type 2 and 3.

– Significantly higher Zr- and Y-contents are observed in type 3 compared to type 1 and 2 orthogneisses.

– The negative correlation of Ba with CaO in type 2 orthogneisses compared to a positive correlation in type 1 clearly distinguishes these two types.

A geochemical distinction between the three

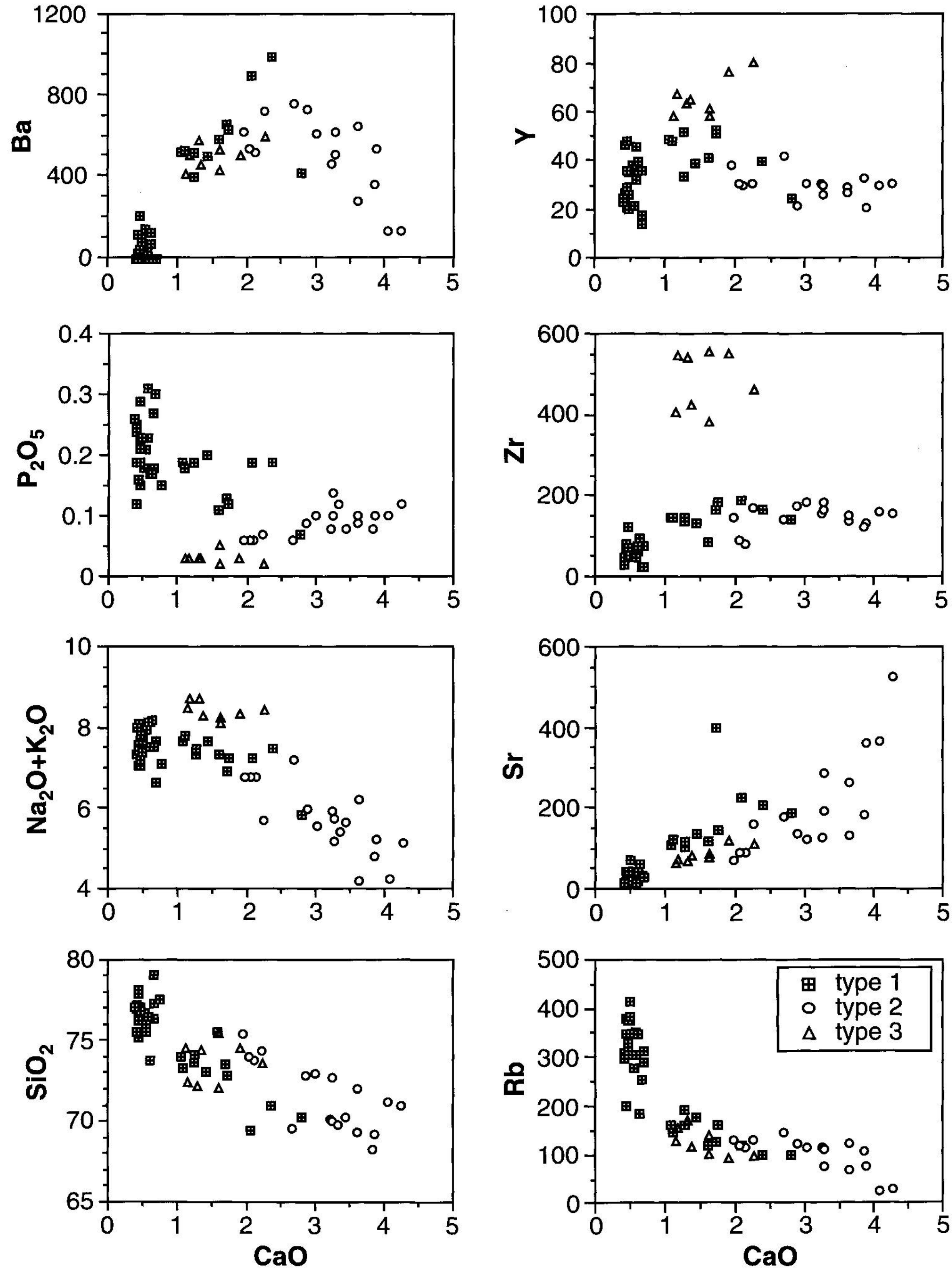

Fig. 4 Variation diagrams of selected major, minor and trace elements versus CaO for the three types of metagranitoids.

orthogneiss types implying differences in degree of fractionation is additionally supported using the discrimination diagram of WAHLEN et al. (1987) (Fig. 5). Discrimination in terms of (Na_2O + K_2O/CaO) and (Zr + Nb + Ce + Y) clearly separates the Tieftal orthogneiss (type 3) from type 1 and 2 orthogneiss compositions due to its high total (Zr + Nb + Ce + Y)-amounts. Type 1 metagranites may be divided into two groups, one with low (Na_2O + K_2O)/CaO-ratios and one with high (Na_2O + K_2O)/CaO-ratios, the latter being represented mainly by the biotite-free leucocratic border zones. Type 2 compositions are less variable and plot exclusively in the field of low (Na_2O + K_2O)/CaO-ratios.

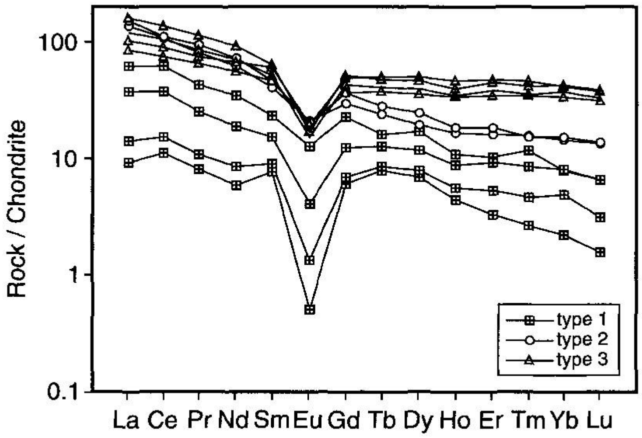

Fig. 5 Chondrite-normalized REE-patterns of the metagranitoids.

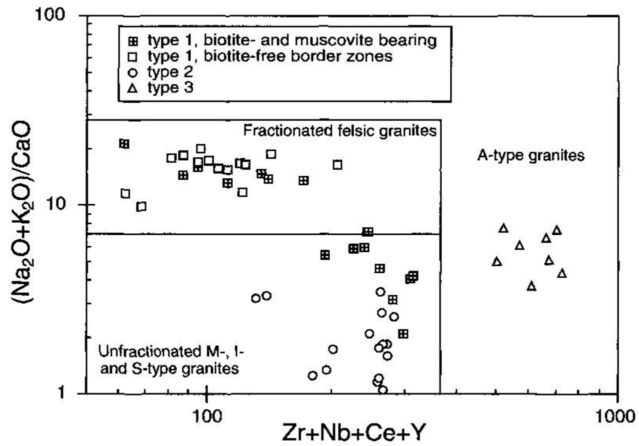

Fig. 6 Discrimination of the metagranitoids according to WHALEN et al. (1987).

The REE-patterns are rather flat for all three types of orthogneisses with a decreasing abundance of the heavy REE and a pronounced negative Eu-anomaly (Fig. 6). However, the slope and the $(La/Yb)_N$-ratios differ between the three orthogneiss-types: The muscovite- and biotite-bearing orthogneisses (type 1) have the lowest total REE concentrations and intermediate but highly variable $(La/Yb)_N$-ratios ranging from 8.0 to 3.8. The Eu-anomaly increases significantly with decreasing total REE amount. The biotite-bearing orthogneisses (type 2) contain moderate amounts of REE and are characterized by the highest $(La/Yb)_N$-ratios of about 10. The Tieftal metagranite (type 3) contains the highest amounts of REE and the lowest $(La/Yb)_N$-ratios varying between 3.7 and 2.4.

Isotope geochemistry and geochronology

The Rb–Sr, Ar–Ar, Sm–Nd and oxygen isotope systems were used to obtain geochemical and geochronological information about the different orthogneiss types and enclosing metasediments.

RUBIDIUM-STRONTIUM, ARGON-ARGON AND OXYGEN ISOTOPE SYSTEMS

Rb and Sr concentrations and isotope ratios were analyzed using whole-rock samples (several kilograms in weight) of type 1 and 2 and white mica concentrates of different grain size fractions of type 1 orthogneisses (Tab. 2). 27 whole-rock samples of type 1 orthogneisses of the western Ötztal basement yield a Rb–Sr errorchron age of 435 ± 11 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7105 ± 12 (Fig. 7). This initial ratio is rather similar to the value of 0.7099, obtained from five Tieftal-orthogneiss (Typ 3) samples, which resulted in an age of 411 ± 9 Ma (BERNHARD et al., 1996). Recalculation of the isotope data of six type 2 orthogneiss samples shown in table 2 result in an errorchron age of 384 ± 26 Ma and an initial ratio of

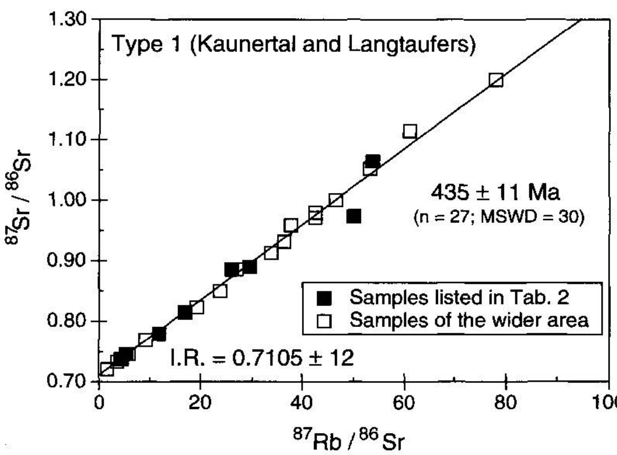

Fig. 7 Rb–Sr whole-rock errorchron of 27 type 1 metagranites (mainly literature data, see text).

0.7114. The initial $^{87}Sr/^{86}Sr$ ratios are rather similar for the three types of orthogneisses and possibly indicative of postmagmatic alteration processes.

Due to the highly radiogenic nature ($^{87}Rb/^{86}Sr$ ratios of 50 or higher) of some of the orthogneiss samples, model ages (using an initial $^{87}Sr/^{86}Sr$ ratio of 0.710), ranging between 474 Ma and less than 400 Ma, can be calculated for individual whole rock samples (LICHEM, 1993; KAINDL, 1994; SCHWEIGL, 1993, unpupl. M. Sc. theses). In addition, a whole rock age of 443 ± 5 Ma with an initial ratio of 0.710 was calculated by THÖNI (1986) using 47 literature data from the wider area of the Ötztal basement.

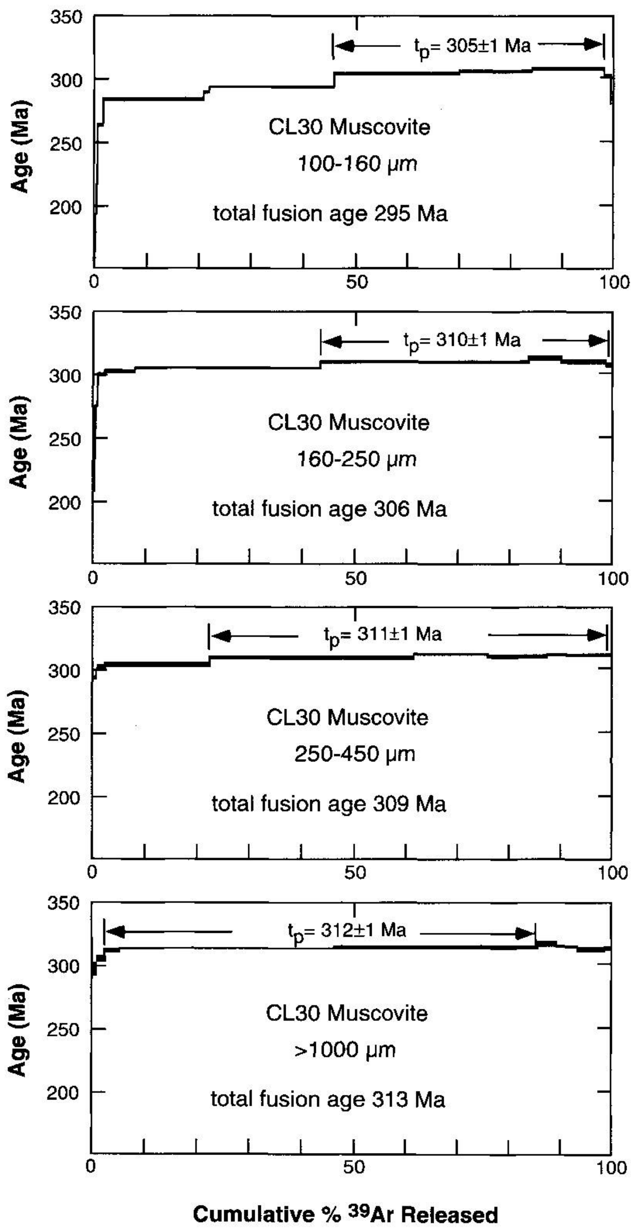

Fig. 8 $^{40}Ar/^{39}Ar$ age spectra of muscovite from different grain size fractions of sample Cl 30.

Mineral age data on orthogneisses obtained during this study mostly confirm the well known Variscan cooling ages. Rb–Sr white mica ages from different grain size fractions up to 450 µm in the type 1 gneiss sample CL30 range between 310 ± 2 and 315 ± 3 Ma (Tab. 2). From the coarsest grain size fraction of > 1000 µm, which represents the least – altered cores of the cm-sized muscovites in this sample, a pre-Variscan Rb–Sr mica age of 435 ± 8 Ma was obtained (Tab. 2). This age is close to a number of pre-Variscan white mica ages ranging up to 461 ± 4 and 474 ± 9 Ma which were recently reported from the Winnebach migmatite of the central Ötztal basement (CHOWANETZ, 1990) as well as from pegmatites near Reschen Pass (SCHWEIGL, 1995). $^{40}Ar/^{39}Ar$-dating of the same grain size fractions of white mica from sample CL30 resulted in well defined plateau ages ranging from 305 ± 1 to 312 ± 1 Ma (Tab. 2, Fig. 8).

Oxygen isotope compositions of type 1 orthogneisses range from $\delta^{18}O$ = 7.2 to 9.9‰, whereas type 2, biotite-bearing, metagranodiorites show partly much lower values down to 4.7‰ (Tab. 2). For comparison, the range in $\delta^{18}O$ for the mantle-derived Tieftal gneiss is 5.0–6.6‰ (BERNHARD 1994, unpubl. M. Sc. thesis).

SAMARIUM-NEODYMIUM ISOTOPE SYSTEM

Ten type 1 and five type 2 whole-rock samples and one apatite concentrate from the type 1 orthogneiss sample RK149 were analyzed for Sm and Nd isotopes.

The ten type 1 whole-rock samples result in an errorchron-age of 494 ± 73 Ma with an ε_{Nd}^{490} of –4.8 ± 0.7 (Fig. 9). The spread in $^{147}Sm/^{144}Nd$ for these ten type 1 orthogneisses is fairly large, ranging from 0.14 to 0.26 (Tab. 3). This may tentatively be interpreted as being related to fractionation of LREE-rich phases, such as monazite or allanite. The apatite-whole-rock age of sample RK149 is 455 ± 8 Ma. All these data overlap within the limits of analytical errors with those obtained for the type 3 Tieftal orthogneiss by BERNHARD et al. (1996). In this case the Sm–Nd regression age of three whole-rock samples is 470 ± 28 Ma, and 487 ± 5 Ma for a magmatic titanite-whole-rock pair.

ε_{Nd}^{490} values are negative for both orthogneiss types (1 and 2) and range from –3.9 to –8.3 (Tab. 3), whereas, in contrast, type 3 has a positive initial ε_{Nd}^{t} value of +1.5 (BERNHARD et al., 1996). If taken separately, the range of ε_{Nd} calculated for an age of 490 Ma for type 2 orthogneisses is –6.0 to –8.3 (with the exception of sample BEG12 from the northern Ötztal), whereas a range of –3.9 to

–5.8 for 10 type 1 orthogneisses (Tab. 3) results in a less negative mean value of –4.8 ± 0.5 at 490 Ma. Thus, the mantle contribution to the type 1 and 2 granitoid melts is, in any case, minor, however it is higher in type 1 than in type 2 orthogneisses, if only the information derived from Nd isotopes is considered.

ε_{Nd}^{490} values of five metapelites of the study area were calculated for comparison and range from –7.2 to –9.8 (mean: –9.1 ± 1.1, Tab. 3). These values are somewhat lower or overlapping with type 2, but significantly different from type 1 and 3 orthogneisses. Depleted mantle model ages for the same micaschist samples range from 1.57 to 1.70 Ga (Tab. 3). In three out of the five metapelite-samples garnets were dated by the Sm–Nd method resulting in ages of 331 ± 3, 335 ± 4 and

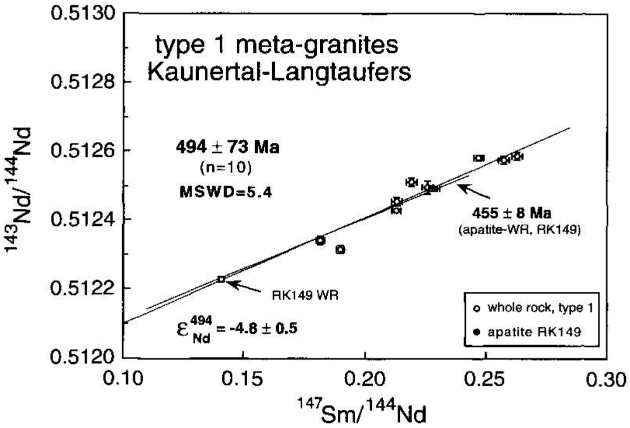

Fig. 9 Sm–Nd whole-rock errorchron of ten type 1 metagranites and a mineral-whole rock isochron from sample RK 149.

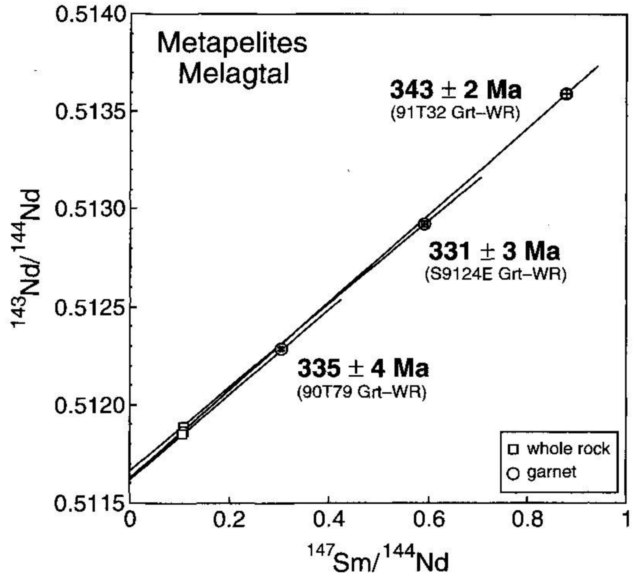

Fig. 10 Three Sm–Nd garnet whole-rock isochrons obtained from metapelites with varying degree of replacement of the garnet by biotite and fibrolite.

343 ± 2 Ma (Fig. 10). All dates stem from garnets which are partly replaced by fibrolite and biotite intergrowth to a varying extent, due to pressure release in course of Variscan metamorphism (SCHWEIGL, 1995; TROPPER and HOINKES, 1996).

Metamorphic conditions of metagranitoids

Metagranitoids are usually the least suitable lithologies for geothermobarometric considerations. However, two-mica metagranites provide at least some possibilities to constrain P and T. Type 1 orthogneisses contain the metamorphic assemblage muscovite + biotite + K-feldspar + quartz. The celadonite substitution in muscovite as part of this assemblage is pressure sensitive and was experimentally investigated by VELDE (1965) and MASSONNE and SCHREYER (1987). It was shown above that the mineral assemblages of the orthogneisses were mainly formed during Variscan metamorphism. Pre-Variscan ages are rarely documented and the Alpine event was to weak to disturb the isotope systems of higher retentive minerals significantly. However, type 1 orthogneisses contain two generations of muscovites: Millimeter-sized (Variscan) sheets (with rare pre-Variscan cores) are overgrown by µm-sized (probably Alpine) flakes (Fig. 11). The Si-content in the formula based on 11 oxygens is significantly different for these two generations: It varies from 3.15 to 3.19 for the pre-Alpine muscovites compared to a range from 3.31 to 3.52 for the younger

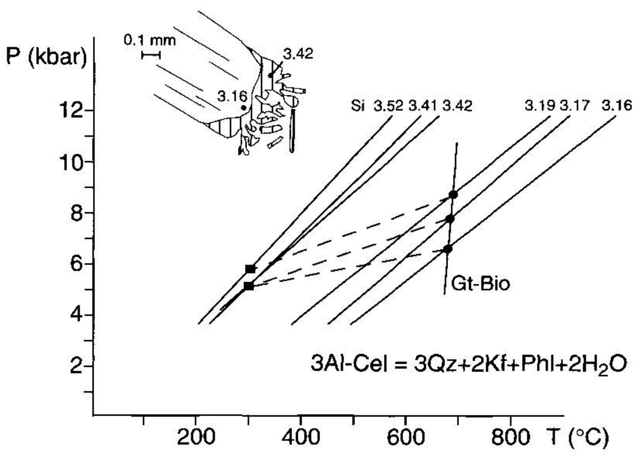

Fig. 11 PT diagram showing the positions of the assemblage phengitic white mica + biotite + K-feldspar + quartz with different degrees of celadonite substitution indicated by the number of Si per 11 oxygens. The reactions were calculated with the Geocalc software (BERMAN, 1988) and activity models for muscovite according to MASSONNE (pers. comm.). Inserted is a sketch of the microscopic appearance of the two generations of white mica.

generation. Using these data, pressure conditions of 0.65 to 0.85 GPa are derived for the Variscan metamorphism at maximum temperatures of 630 °C, as deduced from adjacent metapelites (Fig. 11). This result is consistent with pressures of 0.7 GPa derived from the metapelites (TROPPER and HOINKES, 1996).

Interpretation and discussion

One special feature of the Ötztal crystalline basement is the wide spread occurrence of a variety of orthogneisses embedded in paragneisses and micaschists. The mean crustal residence age of the host rocks is Middle Proterozoic (Sm–Nd DM model ages), whereas the magmatic rocks have Early Paleozoic magmatic emplacement ages. Compared to the mantel-derived type 3 metagranite from the Tieftal (BERNHARD et al., 1996), a crustal origin is likely for the two dominant orthogneiss types based on geochemical data. The relictic cores in zircons, the REE-patterns with high La/Yb-ratios and the strongly negative ε_{Nd}-values are indicative for a crustal source. These indications are more pronounced in type 2 than type 1 orthogneisses. For instance, the significantly less negative ε_{Nd}^{490} values of –4.8 ± 0.5 of type 1 orthogneisses than those of the metapelitic host rocks at 490 Ma (mean ε_{Nd} for 5 samples: –9.1 ± 1.1) may indicate a minor contribution of components more strongly depleted in LIL elements to the type 1 precursor magmas. On the other hand, a significant mantle contribution to the magmas of type 2 protoliths is more likely than for type 1 which is indicated by the oxygen isotope data ($\delta^{18}O$-values for type 1 and 2 gneisses are +7.2 ± 9.9‰ and +4.7 ± 9.3‰, respectively). From the similarities in ε_{Nd} values of metapelites and type 2 gneisses it seems possible that these two rock-types were derived from the same protolith, possibly represented by old, intermediate (meta)igneous rocks. The significantly less negative ε_{Nd} value of type 1 gneisses excludes a genetic link of the two orthogneiss types.

In addition, the two orthogneiss types are clearly distinguished by differences in degree and style of fractionation. Intense fractionation is indicated for the muscovite- and biotite-bearing type 1 orthogneisses by the (1) decreasing Ba-content, (2) increasing Eu-anomaly and (3) increasing Sm/Nd ratio with decreasing REE concentration. (1) and (2) can be explained by plagioclase and K-feldspar fractionation, whereas (3) may be due to the fractionation of accessory mineral phases more compatible for LREE, possibly monazite (MILLER and MITTLEFEHLDT, 1982; LIEW and McCULLOCH, 1985). The strong enrichment of P_2O_5 in the highly evolved varieties of type 1 orthogneisses is probably a consequence of the low CaO content which inhibits the precipitation of apatite during magmatic crystallization. In addition, the high $(Na_2O + K_2O)/CaO$-ratios classify type 1 and, in particular, their leucocratic border zones as fractionated granites (WHALEN et al., 1987). Type 2 orthogneisses on the other hand are classified as unfractionated granites which exhibit also a different style of differentiation. This is indicated by increasing Ba with decreasing CaO, probably due to plagioclase fractionation and lack of K-feldspar fractionation.

The geochronological results support in general the well documented Caledonian Rb–Sr ages of the metagranitoids which were usually interpreted as magmatic ages in the literature (THÖNI, 1986; BORSI et al., 1979). Also the age relations as derived from the data presented in this paper are, within error, not significantly different from each other. Most Rb–Sr whole rock model ages from type 1 orthogneisses cover a range from 420 to 470 Ma, whereas mean regression ages of such Rb–Sr whole rock data arrays are represented by errorchrons around 440 Ma. The $^{87}Sr/^{86}Sr$ initial values of such errorchrons are close to 0.710, and could as such point to a S-type origin of the melts. Because of the large analytical error of ± 73 Ma for the Sm–Nd regression line of type 1 orthogneisses (Fig. 9), it is undetermined, whether the 494 Ma date is closer to the age of magmatic emplacement and whether the Rb–Sr ages signal some later event, e.g. metamorphic resetting. In such a case, the "true" $^{87}Sr/^{86}Sr$ initial would have been considerably lower than 0.710, again indicating minor mantle contributions to the magma. This notion is also supported by the results of the Tieftal orthogneiss (BERNHARD et al., 1996). In this special case, a clearly mantle derived protolith has a relatively high $^{87}Sr/^{86}Sr$ initial ratio of 0.709, and an unrealistically young Rb–Sr whole rock isochron age of 417 ± 9 Ma was obtained. This is interpreted as being not a primary age but to reflect the influence of alteration processes. The crystallization age of the Tieftal protolith is well constrained at 487 ± 5 Ma by a Sm–Nd magmatic titanite-whole-rock age and Pb–Pb single zircon evaporation ages close to 485 Ma (BERNHARD et al., 1996).

The Sm–Nd apatite-whole-rock age of 455 Ma from a type 1 orthogneiss probably constrains the time of metamorphic recrystallization. In one case this Caledonian metamorphism is still recorded by the Rb–Sr system in cores of large white mica sheets with an age of 435 ± 8 Ma. This date is close to the ages reported for white micas from migmatites and pegmatites with Rb–Sr ages of up to 461 ± 4 (CHOWANETZ, 1990) and 474 ± 9 Ma (SCHWEIGL, 1995). The age of the migmatization, which preferably is observed in the vicinity of large metagranitoid bodies, is dated in case of the Winnebach migmatite (Fig. 1). Application of the conventional U/Pb-zircon and the single zircon Pb/Pb-evaporation method resulted in 490 ± 8 Ma and 484 ± 6 Ma respectively (KLÖTZLI-CHOWANETZ et al., this volume). These data indicate intense magmatic activity during the Ordovician which probably caused high temperature metamorphism of the intruded crustal rocks of unknown metamorphic grade at that time. The vast majority of white micas of the investigated orthogneisses were reset during the Variscan event. K–Ar and Rb–Sr ages from biotites and white micas in the range of 320 to 270 Ma may probably be related to slow Variscan cooling, although, in some cases very weak Alpine influence (partial Sr and Ar loss in biotite) may not be ruled out. In addition to these ages THÖNI (1986) and SCHWEIGL (1995) reported an older group of Rb–Sr ages which range from 354 Ma to 372 Ma and were derived using coarse-grained white mica out of weakly deformed orthogneisses and pegmatites from the southern part of the study area and to the west of it. Since these ages are similar to mineral-whole-rock ages of eclogites from the central Ötztal (MILLER and THÖNI, 1995), it is argued that these ages probably record the time of higher pressure conditions during earlier steps of Variscan evolution, not being reset during subsequent, exhumation-related sillimanite-andalusite grade low-P metamorphism. The Sm–Nd ages of 343, 335 and 331 Ma from garnets of the orthogneiss-hosting metapelites in the investigated area, which were partly replaced by fibrolite and biotite during pressure release, are interpreted to date the temperature climax following the Variscan pressure peak. There is no need to interpret the metapelite garnet Sm–Nd ages as cooling ages, since it is well demonstrated by petrological data that Variscan peak metamorphic conditions hardly exceeded 600–650 °C (TROPPER and HOINKES, 1996), even if the low closure temperature of MEZGER et al. (1992) determined for the Sm–Nd system in garnet is taken into consideration.

Conclusions

The dominant orthogneiss bodies of the Kaunertal area are represented by muscovite- and biotite-bearing metagranites and biotite-bearing metagranodiorites and -tonalites. Their evolution can be reconstructed by means of geochemical, geochronological and petrological methods from the nature of the protolith to the age of magmatic crystallization and subsequent metamorphic overprints. The following petrogenetic evolution is proposed:

(1) REE-patterns and ε_{Nd}-values clearly indicate a crustal-source dominated protolith for both orthogneiss types. Fractionation processes for the two mica orthogneisses are indicated by major and minor element variation diagrams and REE-distribution. Type 2 orthogneisses are much less fractionated.

(2) A Sm–Nd errorchron age of 494 ± 73 Ma for the type 1 metagranitoids is tentatively interpreted to date the time of magmatic crystallization.

(3) One Sm–Nd apatite-whole-rock age as well as Rb–Sr whole-rock model ages in the range of 420 to 470 Ma are taken as rough indicators for a Caledonian metamorphism, which reset the primary magmatic Rb–Sr ages, thus resulting in higher (crustal type) Sr "initial" ratios. In one case, relictic cores of white micas from type 1 orthogneisses have preserved a Caledonian Rb–Sr age of 435 ± 8 Ma.

(4) The Variscan overprint reached T = 600–650 °C at p = 0.5–0.7 GPa during the final stages and lead to almost complete resetting of the mica ages. The majority of Rb–Sr mica ages of ≤ 320 Ma represents cooling ages, whereas Rb–Sr white mica ages in the range of 354–372 Ma are interpreted to record the Variscan P-peak in the gneiss-micaschist association.

(5) The metapelitic host rocks of the orthogneiss bodies, although representing the metamorphic product of Proterozoic sediments with at least earlymost Cambrian to Late Proterozoic sedimentation ages, give evidence for only one intense metamorphic event which is of Variscan age. Samarium-Nd dating of garnets, showing different grade of breakdown reactions due to pressure release after the Variscan P-peak, results in ages of 343 to 331 Ma.

The two orthogneiss types investigated in this study from the Kaunertal area are ubiquitous in the whole Ötztal block. Our conclusions about the magmatic and metamorphic evolution of the muscovite- and biotite-bearing metagranites and the mainly biotite-bearing metagranodiorites and -tonalites should therefore be valid for the whole Ötztal basement.

In summary, the evolution from the magmatic stage to the actual metamorphic rock is as follows: In the early Ordovician acidic melts, mainly derived from crustal sources, but with varying degree of minor mantle contribution and varying differentiation intruded the basement and were subsequently metamorphosed in course of the Caledonian event. During the Variscan orogenic processes they obtained, together with their metasedimentary host rocks, their present mineral assemblages and fabric at crustal depth of about 20–25 km at the final stages of this evolution. Finally, they suffered a weak metamorphic overprint during Early Alpine times which, however, did not significantly disturb the isotope systems.

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Appendix

ANALYTICAL METHODS

For quantitative geochemical analyses standard XRF, microprobe and ICP-MS-procedures were used, partly with the aid of commercial labs. The ARL-SEMQ electron microprobe of the senior authors Institute was used to analyze major and minor elements from fused rock pellets according to the method described by HOINKES (1978). Trace elements, except the REE, were determined on pressed powder pellets by XRF in the Institute of Petrology at the University of Vienna using a PHILIPS PW 2400 instrument. Data reduction followed the unpublished computer program "TRACES" written by Petrakakis and Nagel. REE, U, Th and F were analyzed at the commercial laboratory XRAL in Don Mills, Ontario, Canada using ICP-MS and a specific ion electrode technique for F. Techniques applied for Rb–Sr and Sm–Nd isotope analyses closely followed the procedure described by THÖNI (1986) and MILLER and THÖNI (1995). Sm and Nd concentrations and Nd and Sr isotope ratios were determined on a FINNIGAN MAT 262 multicollector thermal ionization mass spectrometer in the Laboratory of Geochronology at the University of Vienna. In the same laboratory a VG MICROMASS M30 machine was used to determine the Sr and Rb concentrations and isotope ratios. Maximum errors for the $^{147}Sm/^{144}Nd$ and $^{87}Rb/^{86}Sr$ ratios are ± 1%. The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios for the La Jolla and NBS987 international standards during the course of this work were 0.511847 ± 10 and 0.71023 ± 1, respectively. The following parameters were used for the calculation of depleted mantle (DM) model ages: $^{143}Nd/^{144}Nd = 0.513114$, $^{147}Sm/^{144}Nd = 0.222$ (FAURE, 1986). For the calculation of Rb–Sr model ages an initial $^{87}Sr/^{86}Sr$ ratio of 0.710 was used. Isochron calculation followed the method of YORK (1969). Measurement of argon isotope compositions of irradiated white mica concentrates during stepwise heating from 550 to 1540 °C were obtained in the Institute of Mineralogy and Petrography, University of Lausanne. Irradiation of the samples was done with the TRIGA reactor in Denver, Colorado, with an intensity of 20 MWh. The $^{40}Ar/^{39}Ar$ plateaux were calculated after COSCA et al. (1991).

Chemical compositions of minerals were obtained by an ARL-SEMQ electronmicroprobe using 15 kV accelerating voltage and 20 nA on brass. Mineral standards and empirical matrix correction procedures after BENCE and ALBEE (1968) were applied.

Tab. 1 Representative major, minor, trace and rare earth element analyses of selected type 1 and 2 metagranitoids.

Sample	RK149	Type 1 RK153	FB110	Type 2 FB89
Major elements (wt%)				
SiO_2	73.62	76.01	68.51	68.56
TiO_2	0.28	0.05	0.47	0.37
Al_2O_3	14.07	13.61	14.52	15.57
Fe_2O_3*	2.43	1.29	4.21	3.64
MnO	0.03	0.03	0.06	0.06
MgO	0.39	n.d.	1.17	0.80
CaO	1.23	0.46	3.13	2.63
Na_2O	2.92	2.77	2.66	3.02
K_2O	4.38	4.56	3.14	4.08
P_2O_5	0.19	0.23	0.08	0.06
L.O.I.	0.79	0.94	0.64	0.96
Total	100.33	99.95	98.56	99.75
A/CNK	1.24	1.32	1.08	1.10
Trace and rare earth elements (ppm)				
Ni	11	9	11	8
V	29	3	83	46
Cu	15	< 4	6	< 4
Pb	16	8	23	26
Zn	59	79	42	47
Rb	194	381	113	145
Ba	401	< 3	456	758
Sr	105	69	126	175
Ga	22	26	17	18
Nb	10	15	10	10
Zr	145	51	152	141
Y	34	20	30	41
La	15.4	2.3	33.2	37.5
Ce	39.8	7.1	68.6	70.4
Pr	4.1	0.8	7.8	9.0
Nd	16.6	2.8	29.3	34.7
Sm	3.6	1.2	6.3	7.2
Eu	0.75	0.03	1.21	1.18
Gd	4.7	1.3	6.1	7.4
Tb	0.6	0.3	0.9	1.1
Dy	4.3	1.8	5.0	6.2
Ho	0.62	0.25	0.94	1.06
Er	1.7	0.6	2.7	3.1
Tm	0.3	0.1	0.4	0.4
Yb	1.3	0.4	2.3	2.5

*: Total Fe as Fe_2O_3
n.d.: not detected
A/CNK = molar $Al_2O_3/(CaO + Na_2O + K_2O)$

Tab. 2 Rb–Sr and Ar–Ar data of metagranitoids for whole rocks (WR) and minerals.

Sample	Locality/ Fraction	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$\pm 2\sigma_m$	Mineral – WR age	$^{40}Ar/^{39}Ar$ Total gas age (Ma)	$^{40}Ar/^{39}Ar$ Plateau age (Ma)	$\pm 2\sigma$	Gas released (%)	$\delta^{18}O$ (‰)
Muscovite- and biotite-bearing metagranites (type 1)												
RK140 WR		297.9	17.7	50.07	0.97312	19						8.1
RK141 WR		306.7	17.2	53.69	1.06425	7						9.2
RK149 WR		197.5	105.4	5.46	0.74526	10						7.2
RK153 WR		378.4	66.0	16.82	0.81523	7						9.0
CL14 WR		350.9	35.2	29.5	0.88962	8						9.9
CL30 WR		320.9	36.5	25.9	0.88540	9						9.3
CL30 w. mica	80–160 μm	979.4	7.4	465.2	2.82923	850	310 ± 2	296	305	1	52.2	
CL30 w. mica	160–250 μm	1037.3	6.0	655.8	3.71353	200	315 ± 3	306	306	1	56.7	
CL30 w. mica	250–450 μm	974.0	4.5	872.7	4.635	30	311 ± 2	309	311	1	77.6	
CL30 w. mica	> 1000 μm	973.0	7.7	474.3	3.6665	50	435 ± 8	313	313	1	83.6	
CL30 biotite		1445	4.34	1588.4	7.247	30	286 ± 3					9.8
CL55 WR		164.3	106.1	4.5	0.73695	10						9.3
CL69 WR		190.2	46.5	11.9	0.77944	7						
Mainly biotite-bearing metagranitoids (type 2)												
FB89 WR	Schweikert	147.8	169.4	2.54	0.72630	6						9.3
FB110 WR	Schweikert	116.4	120.5	2.81	0.72559	7						6.9
FB130B WR	Schweikert	64.8	255.1	0.737	0.71545	5						6.2
FB131 WR	Schweikert	114.3	184.6	1.80	0.72111	5						
FB130A WR	Schweikert	28.1	342.2	0.239	0.71266	5						
FB130C WR	Schweikert	28.9	633.3	0.132	0.71213	5						4.7

Tab. 3 Sm–Nd data of metagranitoids and metapelites for whole rocks (WR) and minerals.

Sample	Locality	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\pm 2\sigma_m$	ε^{0}_{Nd}	ε^{490}_{Nd}	T^{Nd}_{DM}	Mineral WR age
Muscovite- and biotite-bearing metagranites (type I)									Ga	Ma
RK149 WR	Kaunertal	5.22	22.53	0.1402	0.512227	± 9	−8.0	−4.5		
RK149 apatite	Kaunertal	76.59	202.7	0.2284	0.512490	± 7				455 ± 8Ma
RK140 WR	Kaunertal	1.36	3.12	0.2627	0.512584	± 11	−1.1	−5.2		
RK141B WR	Kaunertal	1.23	2.89	0.2567	0.512572	± 14	−1.3	−5.1		
RK153 WR	Kaunertal	1.48	3.62	0.2467	0.512581	± 8	−1.1	−4.3		
T1412 WR	Kaunertal	4.22	13.46	0.1893	0.512315	± 12	−6.3	−5.8		
T1190/1 WR	Langtaufers	0.88	2.35	0.2255	0.512496	± 19	−2.7	−4.6		
T1190/2 WR	Langtaufers	1.08	2.97	0.2187	0.512511	± 12	−2.6	−3.9		
T1273 WR	Weisseejoch	1.79	5.09	0.2128	0.512453	± 12	−3.6	−4.6		
CL30-KA WR	Kaunertal	2.60	8.67	0.1810	0.512339	± 12	−5.8	−4.9		
CL117 WR	Kaunertal	2.32	6.61	0.2124	0.512428	± 4	−4.1	−5.1		
Mainly biotite-bearing metagranitoids (type 2)										
FB110B WR	Kaunertal	7.26	29.97	0.1464	0.512072	± 10	−11.0	−7.9		
FB130C WR	Kaunertal	5.78	29.54	0.1182	0.512075	± 3	−11.0	−6.0		
BEA2 WR	Hocheder	6.75	31.35	0.1310	0.512003	± 4	−12.4	−8.2		
BEA7 WR	Hocheder	5.93	29.61	0.1211	0.511968	± 10	−13.1	−8.3		
BEG12 WR	Hocheder	3.82	14.67	0.1574	0.512305	± 6	−6.5	−4.0		
Metapelites										
S9124D WR	Melagtal	11.15	58.90	0.1144	0.512006	± 10	−12.3	−7.2	1.57	
S9124D garnet	Melagtal	2.13	6.53	0.1974	0.512077	± 8				
S9124E WR	Melagtal	10.08	55.53	0.1097	0.511888	± 10	−14.6	−9.2	1.66	
S9124E garnet	Melagtal	1.86	1.91	0.5906	0.512929	± 14				331 ± 3
90T79 WR	Melagtal	8.09	45.89	0.1065	0.511849	± 7	−15.4	−9.8	1.67	
90T79 garnet	Melagtal	2.55	5.05	0.3052	0.512285	± 8				335 ± 4
91T32 WR	Melagtal	9.08	49.71	0.1104	0.511866	± 10	−15.1	−9.7	1.70	
91T32 garnet	Melagtal	3.47	2.57	0.8149	0.513450	± 20				343 ± 2
T1264 WR	Melagtal	7.21	40.02	0.1089	0.511872	± 4	−14.9	−9.5	1.67	