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Resolving complex geological histories by zircon dating: A discussion of case studies from the Bohemian Massif and the Eastern Alps

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Die Auflösung komplexer geologischer Entwicklungsgeschichten mittels Zirkondatierung: Eine Diskussion von Beispielen aus der Böhmischen Masse und den Ostalpen

Zusammenfassung

Mittels vier Beispielen aus dem Bereich der Böhmischen Masse und der Ostalpen wird dargestellt, wie die U-Pb- und Pb-Pb-Datierung von Zirkon zur Lösung geochronologischer Probleme eingesetzt werden kann. Anhand der Altersdaten vom Rastenberger Granodiorit wird die komplexe zeitliche Entwicklung von Magmatiten des Südböhmischen Plutons dargestellt. Nach einer mehrphasigen prävariszischen Entwicklung der Protolithgesteine läßt sich im variszischen Zyklus eine mindestens zweiphasige oberkarbone magmatische Entwicklung der Plutonite belegen. Die polymetamorphe Entwicklung zweier Metamorphite aus dem oberostalpinen Ötztal-Stubai-Kristallin (Winnebach Migmatit, Tieftal Orthogneis) wird aufgezeigt. Die Anatexis im Winnebach Gebiet sowie die magmatische Bildung der Tieftal Orthogneise erfolgen gleichzeitig im Unter Ordovizium. Beide Ereignisse deuten auf eine beginnende altpaläozoische Krustenausdünnung im Oberostalpin hin. Das letzte Beispiel diskutiert die Datierung ostalpiner Quarzphyllitkomplexe. Aus der Datierung detritischer Zirkone werden maximale und minimale Sedimentationsalter abgeleitet. Diese machen deutlich, daß bezüglich der stratigraphischen Stellung und Reichweite der Quarzphyllitkomplexe noch große Unsicherheiten bestehen.

Abstract

Using four case studies from the Bohemian Massif and the Eastern Alps the application of U-Pb- and Pb-Pb-dating of zircon is demonstrated. In order to illustrate the complex evolution of granitoids age data obtained for the Rastenberg granodiorite (South Bohemian Pluton, Bohemian Massif) is discussed as a first example. Here, after a multi-phase pre-Variscan evolution of the granitoid protoliths, there is evidence for a two-step magmatic evolution during the Variscan magmatic cycle in the Carboniferous. The history of two rock units from the Upper Austroalpine Ötztal-Stubai crystalline complex (Winnebach migmatite and Tieftal orthogneiss) is documented next. The anatexis in the Winnebach area is shown to be of Early Ordovician age. It occurred contemporaneously to the magmatic formation of the Tieftal orthogneiss body. Both events are attributed to the beginning of Early Palaeozoic crustal thinning in the Upper Austroalpine realm. The last example focuses on conflicting age data from different Austroalpine quartzphyllite complexes. From detrital zircon dating maximum and minimum sedimentation ages are derived. These demonstrate that there exist strong ambiguities concerning the stratigraphic age of the investigated quartzphyllite complexes.

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1. Introduction

When examining rocks s.l. in geosciences several basic and fundamental questions can be asked. One of them certainly is: When…?

A number of dating methods are used at present to tackle this question, all of which may provide different geochronological information. They range from the dating of magmatic crystal growth at highest temperatures with the uranium-lead system in zircon (U-Pb) to the dating of the cooling of the investigated rock below a specific temperature, the so called closing temperature, by the argon-argon (Ar-Ar) method in micas and fission track dating (FT) of zircon and apatite. By applying different geochronological methods to different minerals and rocks a quantification of processes such as magmatic evolution, metamorphism, and subsequent cooling can be possible. By combining these data with information from structural geology, petrology, and sedimentology the evolution of a rock can more or less be completely unravelled.

But since many rocks have complex geological histories, the dating of multi-crystal or whole-rock samples is often not very enlightening. This sort of samples tends to form a more or less intricate mixture of single mineral grains with different "entrapped" age information which cannot easily be interpreted in a geologically meaningful sense. The dating of single crystals, or even of domains within a single grain, is thus very desirable. Some modern geochronological methods do allow single mineral grain dating and thus greatly enhance the possibilities of age data interpretation.

The present contribution summarises geochronological data from four different case studies, as gained by single zircon U-Pb, Pb-Pb dating and zircon typology examinations. The first study is devoted to the dating of a complex magmatic system in a granitoid of the South Bohemian Pluton (Rastenberg granodiorite). Two studies deal with geochronological aspects of polymetamorphic rocks in the Upper Austroalpine Ötztal-Stubai crystalline basement (Winnebach migmatite area, Tieftal orthogneiss). The last example discusses the dating of almost unfossiliferous meta-sediments which cannot stratigraphically be dated directly. Their sedimentation age has to be bracketed by other suitable approaches such as youngest magmatic ages of detrital zircons (i.e. maximum age of sedimentation) or maximum ages for metamorphic overprinting (i.e. minimum age of sedimentation). Application of the technique is demonstrated by using single zircon Pb-Pb age data of Austroalpine and Southalpine quartzphyllite complexes.

Data from all presented case studies were published previously and the interested reader is referred to the respective publications. Except for the last example diagnostic zircon typologies and obtained age data are illustrated by appropriate figures.

2. Analytical Techniques

The analytical techniques applied in the presented studies comprise standard heavy mineral separation, zircon typology investigations using microscopy, cathodoluminescence and back-scattered electron imaging, conventional single-grain and multi-grain zircon U-Pb geochronology, and single zircon evaporation geochronology. Further details of the techniques can be found in PARRISH et al. (1987), KLÖTZLI (1997), and references therein. Additional methods applied are Rb-Sr and Sm-Nd geochronology and geochemical investigations. Unless stated otherwise all errors quoted are at the 2σ-level (approx. 95% confidence interval).

On the figures zircon designations are as follows: Indication of zircon typology of a certain zircon type or age group always designates the subgroup of the mean typology of the respective zircon type. Subscript "a" denotes air abrasion of multigrain fractions.

For the typology plots field shading corresponds to relative subgroup abundance. Black shading indicates maximum abundance of > 30% of the specific subgroup. Grey shading accordingly indicates lower abundance.

3. Dating rocks of the South Bohemian Pluton: The Rastenberg granodiorite

The Rastenberg-type granodiorite forms a separate intrusion to the east of the large composite South Bohemian Pluton. It was intruded into the nappe system of the Moldanubian basement sequence (Monotonous Series, Dobra gneiss, and Varied Series). Except for a weak syn- to post-magmatic low strain deformation no post-intrusive tectonic or metamorphic overprinting is present.

The aim of the discussed study (KLÖTZLI & PARRISH, 1996) was to precisely date the time of intrusion of the Rastenberg granodiorite. Tight time constraints on the magmatic history of the pluton should allow conclusions about minimum ages for Variscan nappe stacking and metamorphic overprinting. Also, protolith ages of assimilated rocks should provide additional information about the age distribution and composition of the lower to middle pre-Variscan crust.

Typological investigations show two distinguishable zircon populations (Figs. 1 and 2):

– long prismatic crystals of mean subtype S24, often with cores (e.g. A, B of Fig. 1);

– short prismatic crystals with tabular habit of mean subtype S4, no cores (e.g. C, D of Fig. 1).

Geochronological investigations reveal at least four different zircon-forming events (Fig. 3, 4).

Evaporation Pb-Pb ages older than 1206 Ma (KLÖTZLI & PARRISH, 1996) are interpreted as being derived from inherited cores. The ages must be interpreted as minimum age estimates for magmatic or metamorphic zircon growth during the Proterozoic and/or Archean. It cannot be decided whether

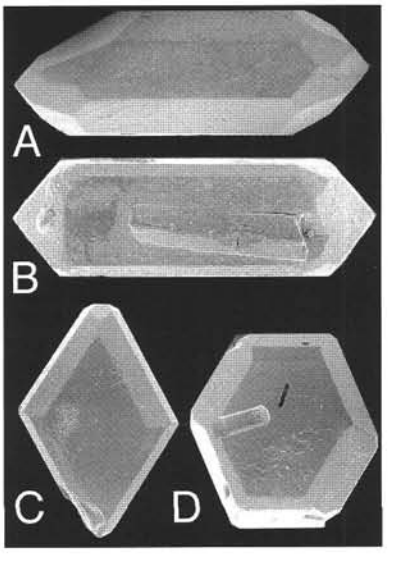


Fig. 1
SEM images of typical zircons from the Rastenberg granodiorite. A, B: Zircons with mean typology of subgroup S24. They often contain inherited cores which are overgrown during the ~ 350 Ma magmatic event. Corroded edges and overgrowths are attributed to the 338 Ma intrusion event. C, D: Zircons with mean typology of subgroup S4. These zircons exhibit a very characteristic tabular habit and never contain cores. Their growth is attributed to the 338 Ma intrusion event. Note: c-axis of all four crystals is horizontal. Adapted from KLÖTZLI and PARRISH (1996).

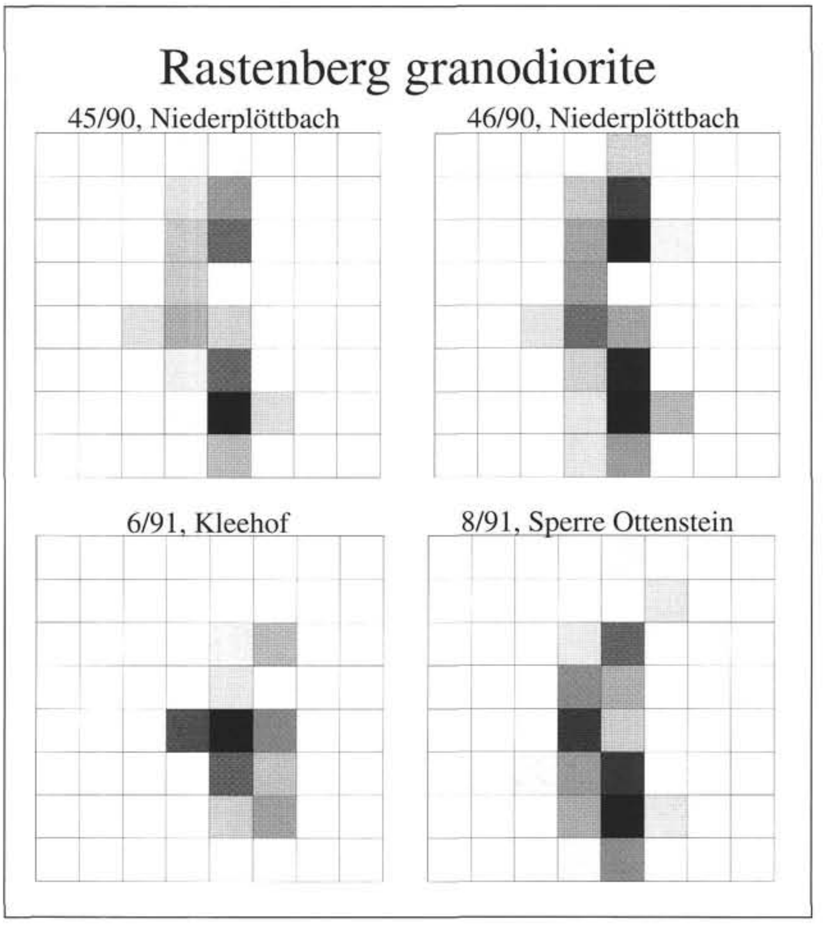


Fig. 2
Zircon typology diagrams of four samples from the Rastenberg granodiorite. The elongated zircons (i.e. A, B of Fig. 1) plot in the lower half of the diagram, the tabular zircons in the upper half, respectively (i.e. C, D of Fig. 1). Note the marked bimodality in zircon typology in sample 45/90 and 46/90 from the central part of the intrusion. This bimodality is less pronounced in the S and E part of the pluton (samples 6/91 and 8/91). Adapted from KLÖTZLI and PARRISH (1996).

these old zircons belong to distinct Proterozoic or older rocks or whether they are derived from metasedimentary (basement-) sequences. Zircon ages higher than 1700 Ma are well known from all over the Bohemian Massif and prove the existence of heterogeneous Proterozoic crust reworked into the Variscan realm of Central Europe. The upper intercept age of 2005 Ma (Fig. 4) is interpreted as a minimum mean age for this Early Proterozoic crust (KLÖTZLI & PARRISH, 1996).

It is remarkable that no zircons originating from the adjacent 1380 Ma old Dobra gneiss could be found (GEBAUER & FRIEDL, 1994). Instead, most inherited zircons seem to have been assimilated from the Monotonous Series W of the pluton.

The Vendian ages at 623 ± 22 Ma (Figs. 3 and 4) are interpreted as minimum age estimates for a Cadomian (Pan-African) magmatic or metamorphic event. Core typology, the limited scatter in age distribution, and $^{208}Pb/^{206}Pb$ systematics suggest that the reworked Cadomian protoliths were magmatic in origin. Cadomian ages of magmatic and metamorphic rocks are widespread in the Bohemian Massif, especially in the Moravo-Silesian zone where the intense Variscan overprint of the Moldanubian zone is missing (KLÖTZLI et al., 1999a).

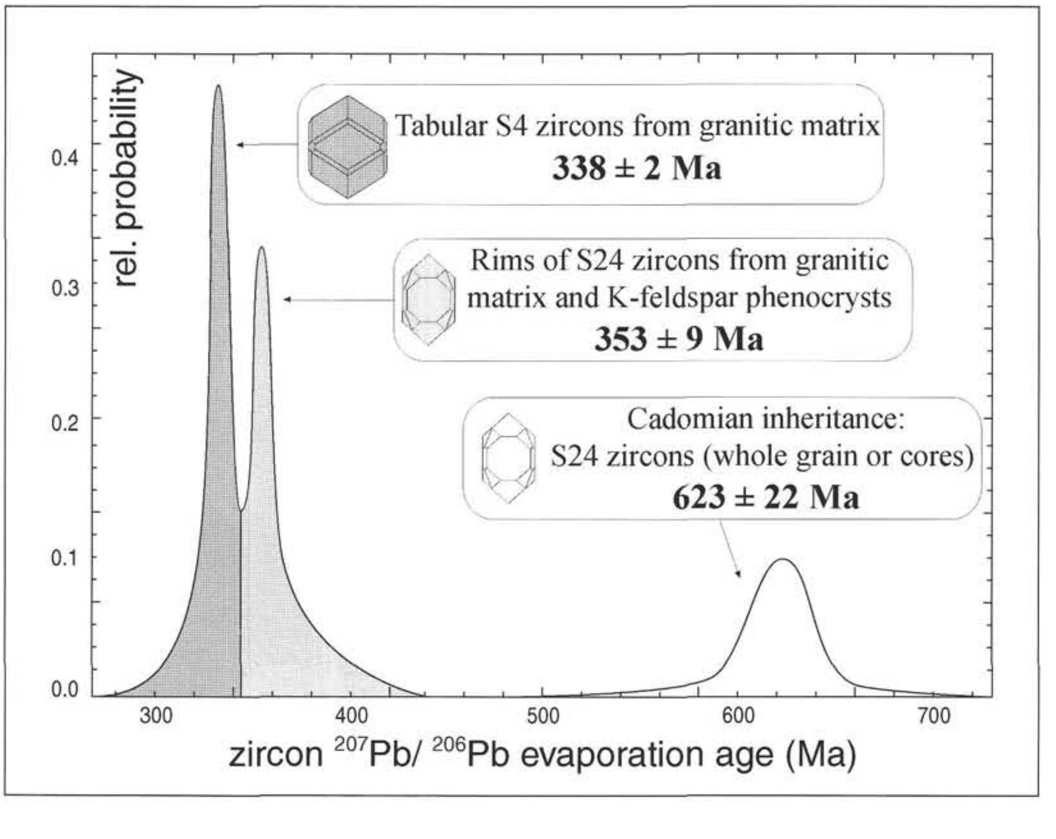


Fig. 3
Probability density distribution plot of the single zircon evaporation ages from the Rastenberg granodiorite. Both zircon forming events around 338 Ma and 353 Ma result in prominent peaks in the relative probability distribution. The peak at 623 Ma corresponds to a major inherited component in the granodiorite. Note the lack of any inheritance between 623 Ma and 353 Ma. This is strong evidence for the complete absence of any "Caledonian" or Early Variscan inherited zircons. Erratic inherited ages > 700 Ma are not shown. 20 zircons were analysed. Adapted from KLÖTZLI and PARRISH (1996).

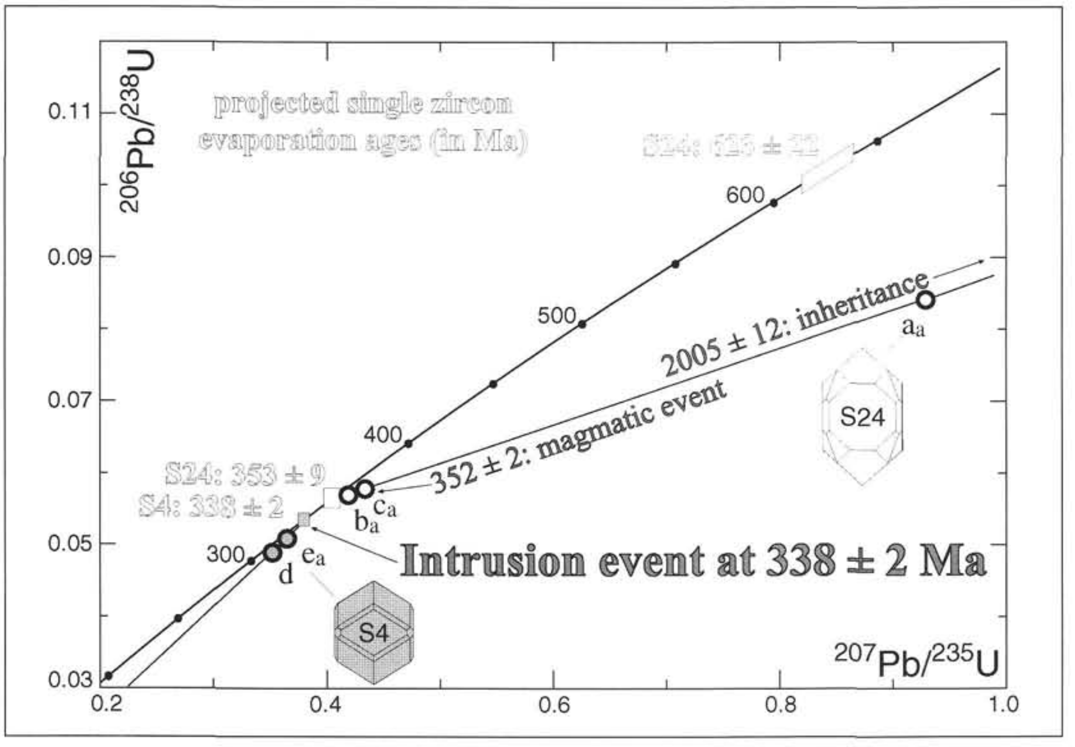


Fig. 4
U-Pb concordia diagram showing conventional U-Pb age data from the Rastenberg *granodiorite*. Data points for conventional analyses (circles) are much bigger than the actual 2σ-error. For comparison the mean $^{207}Pb/^{206}Pb$ evaporation age values for the postulated age groups are plotted on the concordia although the data points are not necessarily concordant (rectangles, cf. Fig. 3). The width of the rectangles parallel to the concordia corresponds to the respective 2σ-standard-errors of the mean age values of the postulated age groups. Adapted from KLÖTZLI and PARRISH (1996).

Yellowish, long prismatic S24 zircons (Figs. 1 and 4, fractions b_a and c_a) exhibit a very high degree of discordance. This provides evidence for overprinting during a high-temperature event which led to a practically complete lead loss and severe overgrowth of the zircons of fractions b_a and c_a, and to a lesser extent of fraction a_a (colourless, clear). The lower intercept age of a discordia through the S24 zircons (fractions a_a, b_a, and c_a) is 352 ± 2 Ma (Fig. 4). Together with the mean Pb-Pb evaporation age of 353 ± 9 (Fig. 3, also from S24 zircons) this Early Visean age is interpreted as the time of zircon formation in the granodiorite magma during a first magmatic event prior to the actual intrusion event.

The Later Visean ages of 338 ± 2 Ma found by evaporation analyses of S4 zircons and overgrowths of S24 zircons (Figs. 1 and 3) and as upper intercept of the discordia through zircon fractions d, e_a, and the origin (Fig. 4) are interpreted as dating the time of intrusion or, alternatively, subsequent high-T cooling of the granodiorite. A similar intrusion age of 340 ± 8 Ma (HOLUB et al., 1997) has been reported for the Trebic massif in the Czech Republic. With respect to tectonic position and geochemistry this pluton shows close resemblance to the Rastenberg granodiorite. The, within error, identity of both intrusion ages additionally stresses this similarity.

Of special geochronological and petrological interest is the fact, that no tabular S4 zircons have been found as inclusions within large K-feldspar phenocrysts. Therefore, the growth of these K-feldspars crystals seems to have taken place during or shortly after the first postulated magmatic stage around 353 Ma, but not at 338 Ma. This and additional textural evidence, i.e. the observed resorption of K-feldspar phenocrysts in the finer-grained matrix of the granodiorite, furthermore supports the model of a two-stage magmatic evolution of the Rastenberg granodiorite.

The lower intercept of 352 ± 2 Ma could also be interpreted as resulting from secondary lead loss during the 338 Ma event from zircons originally located on a discordia with a lower intercept age > 352 Ma and an upper intercept of > 2005 Ma. In this case, the age estimate of 352 ± 2 Ma would be geologically meaningless. However, a two-stage magmatic evolution, as proposed for the Rastenberg granodiorite, can also be found in the large Weinsberg granite body (KLÖTZLI, 1993, KLÖTZLI & KOLLER, 1998, KLÖTZLI et al., 1999a) and in possible equivalents of the Moldanubian granitoids in the Mecsek Mountains of South Hungary (KLÖTZLI et al., 1999b).

A younger upper intercept age of 328 ± 10 Ma from long prismatic zircons is reported by FRIEDL et al. (1993). Two evaporation Pb-Pb ages (330 ± 12 Ma and 324 ± 20 Ma, KLÖTZLI & PARRISH, 1996) from the same locality also seem to be younger than the average of 338 ± 2 Ma observed in other samples of the pluton. The sample comes from the eastern most part of the Rastenberg granodiorite pluton, near the border zone to the Dobra gneiss. This border zone is marked by the occurrence of fine-grained granites and aplites which were intruded into the Rastenberg granodiorite and Dobra gneiss. Thus a possible explanation for the occurrence of the younger ages could be, that the late- to post-magmatic intrusions of fine-grained granites and aplites have led to a reheating and/or a slower cooling of the eastern part of the Rastenberg granodiorite thus leading to the observed younger ages.

3.1 Concluding remarks

The Visean intrusion age of 338 ± 2 Ma found for the Rastenberg granodiorite provides a minimum age estimate for Variscan nappe stacking and metamorphism in this part of the Moldanubian zone. This is in line with the average post high-T-metamorphism mineral cooling ages clustering around 340 Ma in the SE Bohemian Massif (PETRAKAKIS, 1997, KLÖTZLI et al., 1999a).

Only Cadomian and no Caledonian (Early Palaeozoic) zircons could be found within the investigated rocks. This suggests a different provenance of the pre-Variscan basement suites of the Rastenberg granodiorite and of the higher parts of the Moldanubian nappe pile (Gföhl gneiss and granulites) than proposed for the western part of the Bohemian Massif (Regensburger Wald, Bavaria) and for the Sudetes (KLÖTZLI et al., 1999a).

4. Migmatite formation in the Winnebach area, Ötztal-Stubai basement

Partial anatexis of biotit-plagioclase-paragneisses is known from several localities within the Ötztal-Stubai crystalline complex. One of these migmatite areas, the "Winnebach"-migmatite (Gries, Ötztal), has since long attracted much attention. But despite a number of investigations dealing with the geochronological aspects of migmatite formation only ambiguous age data for the migmatisation event in this part of the complex have yet been obtained. Because of unclear field relations, the anatexis was attributed to the Variscan orogenic cycle (HOINKES et al., 1972). Subsequent Rb-Sr white mica analysis from the central part of the migmatite give a clearly pre-Variscan minimum age of 461 ± 4 Ma for the migmatisation (CHOWANETZ, 1991). As this central part shows only very minor post-anatectic structural overprint, this age is thought to represent cooling shortly after the migmatisation. SÖLLNER & HANSEN (1987), on the other hand, report conventional U-Pb zircon data that point to a complex multi-stage Pb-loss scenario with all data points plotting below a postulated "Pan-African" discordia (lower intercept at 670 Ma and upper intercept at 2275 Ma). The assumed lower intercept age of 670 Ma was believed to represent the age of the anatexis.

In the presented case study (KLÖTZLI-CHOWANETZ et al., 1997), two different samples were investigated. 1) Neosome from the central migmatite probably representing the highest degree of melting and 2) paragneiss from the vicinity of the migmatite as non-migmatic reference material. Primarily, a zircon typology study comparing the zircon populations of the migmatite with those of the adjacent paragneiss was expected to allow a discrimination of anatectic zircon growth and polyphase metamorphic growth. Except for one zircon type, all populations exhibit polyphase crystal growth and do not show any specific mode of occurrence (Fig. 5).

Measured by single grain evaporation these zircon populations document three growth events with mean Pb-Pb ages of 480 – 490 Ma, ~ 560 Ma, and ~ 635 Ma (Fig. 6). However, since these ages are found both within the migmatite and the paragneiss, none of them can be directly assigned to the migmatisation.

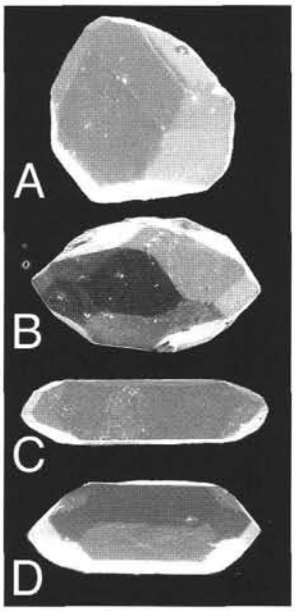


Fig. 5
SEM images of typical zircons from the Winnebach migmatite area. A: clear, colourless, inclusion free, polyfaced zircon with spherical shape. This growth type is typical for highest metamorphic temperature conditions/anatectic melting and has only developed in the migmatite. B: clear, colourless, very short prismatic, mean typology subgroup S13; C: clear, colourless to slightly pink, mean typology subgroup L2; D: clear, colourless to slightly pink, mean typology subgroup S7. Adapted from KLÖTZLI-CHOWANETZ et al. (1997).

One population of spherical, clear and colourless zircons is found to be characteristic for the migmatite only. These anatec-tically grown zircons yield a concordant U-Pb age of 490 ± 9 Ma (Fig. 7).

Presently available textural and structural data indicate that post-anatectic overprinting of the Winnebach migmatite area is of lower amphibolite-facies grade (HOINKES et al., 1997). Therefore, the Early Ordovician zircon ages of 490 ± 9 Ma are interpreted to directly date the time of anatexis. This interpretation is in line with the muscovite ages around 460 Ma (CHOWANETZ, 1991) for the post-migmatic cooling.

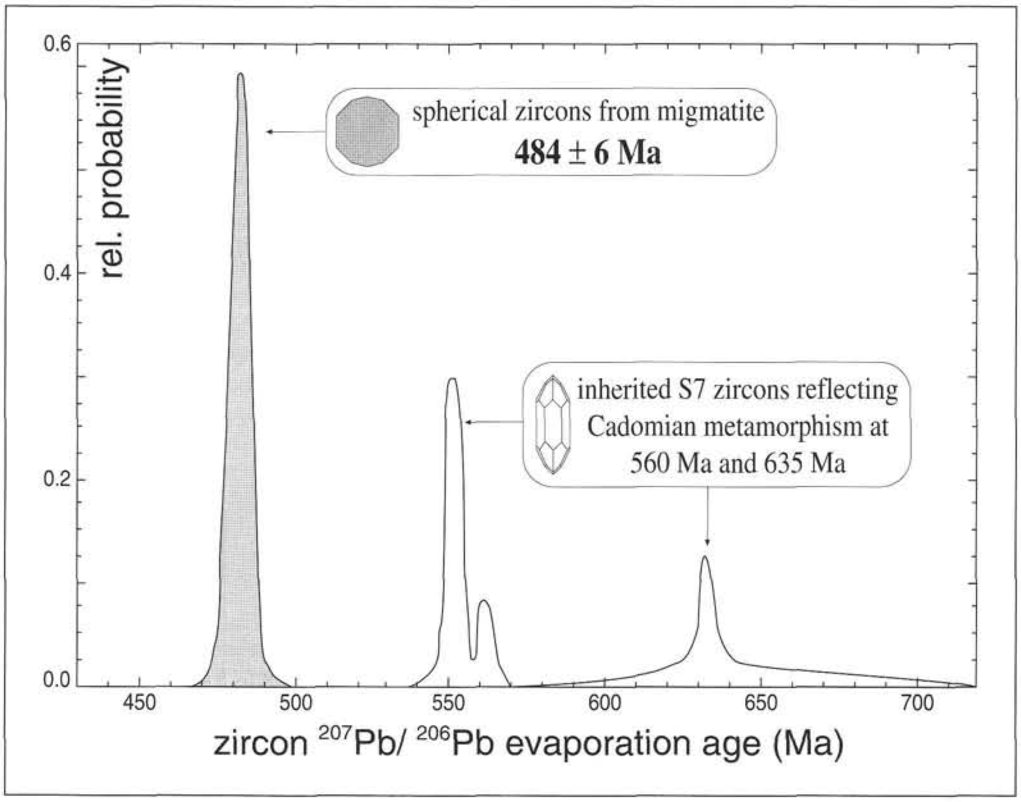


Fig. 6
Probability density distribution plot of the single zircon evaporation ages from the Winnebach area. Ages interpreted to reflect the growth of spherical zircons attributed to the anatectic event around 484 ± 6 Ma form a very sharp peak in the probability distribution. There is no evidence for a prolonged metamorphic event in the Ordovician nor for a zircon forming event in the Later Palaeozoic. Ages > 500 Ma are attributed to Cadomian metamorphic events (see Fig. 7). Erratic inherited ages > 700 Ma are not shown. Ten zircons were analysed. Adapted from KLÖTZLI-CHOWANETZ et al. (1997).

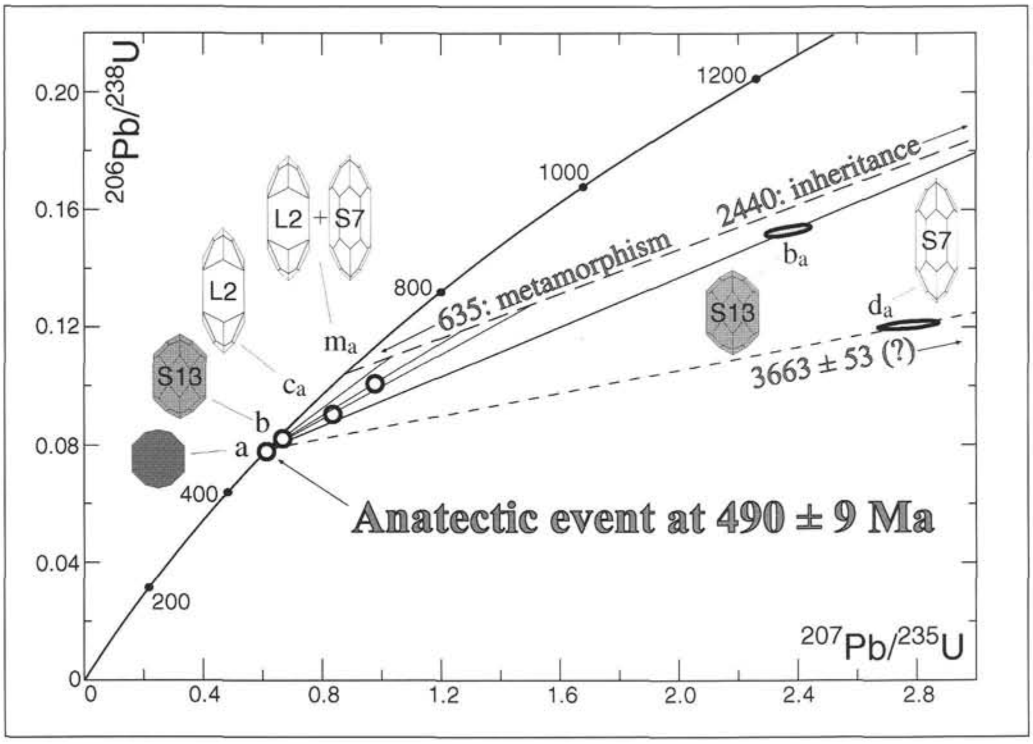


Fig. 7
Concordia diagram of U-Pb zircon data from the Winnebach migmatite. Fraction a yields a concordant Early Ordovician age of 490 ± 9 Ma, which is interpreted to represent the age of anatexis. The fractions b, b_a, c_a, and m_a have been affected by at least two episodes of lead loss prior to the Ordovician high-temperature event. Fraction d_a seems to be derived from a source older than b, b_a, c_a and the mixed fraction m_a. The discordia from 635 Ma to 2440 Ma has been drawn considering the single zircon evaporation results. Data points for fractions a, b, b_a, c_a, and m_a (circles) are far bigger than actual 2σ-error. For fractions b_a and b_a the 2σ-error ellipse is shown. Adapted from KLÖTZLI-CHOWANETZ et al. (1997).

The high-T metamorphism and anatexis is contemporaneous to an extended magmatism related to crustal extension in the Ötztal crystalline complex, also leading to the intrusion of rocks now found as acid orthogneisses from S- to A-type affinity (see below).

4.1 Concluding remarks

Based on arguments from zircon typology, U-Pb, and Pb-Pb dating, crustal extension related anatexis in the central Ötztal crystalline complex took place during the Early Ordovician at 490 ± 9 Ma. Prior to this event the zircons from the paragneisses were subjected to additional, Cambrian and older, recrystallisation and growth events.

Variscan and Alpine metamorphic imprinting has not been recorded in the zircon isotope data of the investigated rocks.

5. Dating the magmatic formation of a polymetamorphic felsic gneiss: The Tieftal hedenbergite-hornblende-biotite gneiss (Kaunertal)

Polymetamorphic felsic rocks with magmatic precursors are widespread in the Ötztal crystalline basement. Numerous geo-chronological studies have been made on these rocks, including zircon U-Pb dating and Rb-Sr whole rock and mica dating. Zircon ages are in the range of 540 to 455 Ma (HOINKES et al., 1997) for different gneiss types, but an interpretation is not straight-forward because of large amounts of inherited zircons and severe lead loss during subsequent metamorphic events. Rb-Sr whole rock isochron ages vary from 480 to 420 Ma and are rarely as high as 583 Ma (HOINKES et al., 1997), but their interpretation as magmatic crystallisation ages is hampered by the possible partial to complete resetting of the Rb-Sr whole rock system during metamorphic overprinting (BERNHARD et al., 1996).

A multi-method approach was applied therefore to derive the age and origin of an orthogneiss body located in the central Kaunertal, western Ötztal crystalline complex (BERNHARD et al., 1996). The so-called Tieftal orthogneiss body is an internally differentiated, polymetamorphosed intrusion, embedded in metabasites of tholeiitic composition. It belongs to the group 3 granitoids of HOINKES et al. (1997). It comprises leucocratic hedenbergite-hornblende-, hornblende- and biotite-hornblende-gneisses, and various xenoliths. A relictic magmatic mineral assemblage comprises the accessories titanite, zircon, allanite, fluorite, molybdenite and magnetite. Magmatic T-P conditions are assumed to be 660°C – 880°C and <= 5 kbar (BERNHARD, 1994).

Zircon typology studies reveal only one dominant zircon type clustering around the subgroup P5. No zircon xenocrysts could be identified (Fig. 8).

Single zircon evaporation dating of two samples and Sm-Nd *dating of relictic magmatic titanite resulted in ages of* 487 ± 7, 484 ± 3 and 487 ± 5 Ma, respectively (Fig. 9, 10).

The mean of 485 ± 3 Ma is interpreted as the best estimate for the primary crystallisation age of the Tieftal orthogneiss body. Rb-Sr whole rock dating of five samples results in a well defined regression line, corresponding to an age of 411 ± 9 Ma. This age value clearly documents partial resetting of the whole rock Rb-Sr system during post-magmatic metamorphic overprint.

Inherited zircon cores are dated at 523 ± 4 Ma, 532 ± 2 Ma, and ~2600 Ma. The two Cambrian ages are in the age range found for the gabbroic precursor rocks of the eclogite from the central Ötztal (MILLER & THÖNI, 1995). Thus there seems to be a temporal connection between the MORB-type rocks of the central Ötztal and the Tieftal gneisses, but exact relationships are not yet resolved. Similar ages for Cambrian magmatism are also found in the Silvretta crystalline basement (MÜLLER et al., 1996, SCHALTEGGER et al., 1997).

Geochemical data suggest a possible mantle derivation of the Tieftal meta-igneous rocks. Most probably, the gneiss precursors have originated through magmatic fractionation processes from protoliths of the accompanying tholeiitic metabasites. The more primitive isotopic composition of metabasites and early Proterozoic and Cadomian inheritance in Tief-

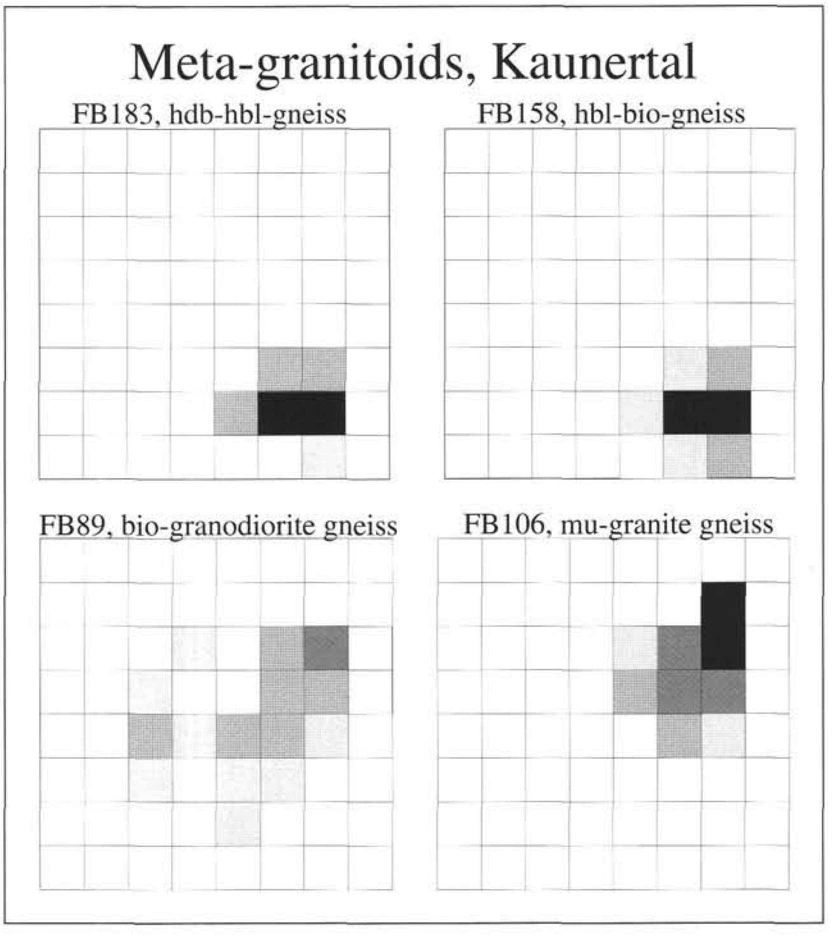


Fig. 8
Zircon typology diagrams of different meta-granitoids in the vicinity of Tieftal. The zircons from the hedenbergite-hornblende-biotite gneiss exhibit a concise typology subgroup distribution (upper diagrams). For comparison type 1 and type 2 meta-granitoids are shown in the lower diagrams. They exhibit a broad range of typologies which do not overlap with the subgroup distribution of the Tieftal gneisses. The mean typology subgroup of P5 of these Tieftal gneisses is characteristic for zircons having grown in a high temperature, alkali-rich magma. Thus, the mean single zircon evaporation age of 484 ± 3 Ma is attributed to the magmatic protolith formation and not to subsequent metamorphism. Adapted from BERNHARD (1994).

tal gneiss zircons suggest some involvement of older crustal rocks, too. The amount of crustal contamination can be calculated to be in the range of 10 – 40% (BERNHARD, 1994).

5.1 Concluding remarks

The Tieftal gneisses are interpreted together with their accompanying metabasites as remnants of an advanced stage of Early Ordovician rifting and incipient formation of new oceanic crust. Ordovician rifting in the Tieftal area is contemporaneous with the anatexis in the Winnebach area. Based on zircon inheritance a temporal or genetic relation seems to exist between the Tieftal meta-igneous rocks and a proposed Cambrian rifting documented in the central Ötztal and the Silvretta crystalline basement series.

The study demonstrates the concordance of zircon Pb-Pb ages and Sm-Nd whole-rock and titanite age data. Both isotopic systems were not influenced by post-magmatic events. In contrast, the whole rock Rb-Sr systematics were severely disturbed during metamorphism.

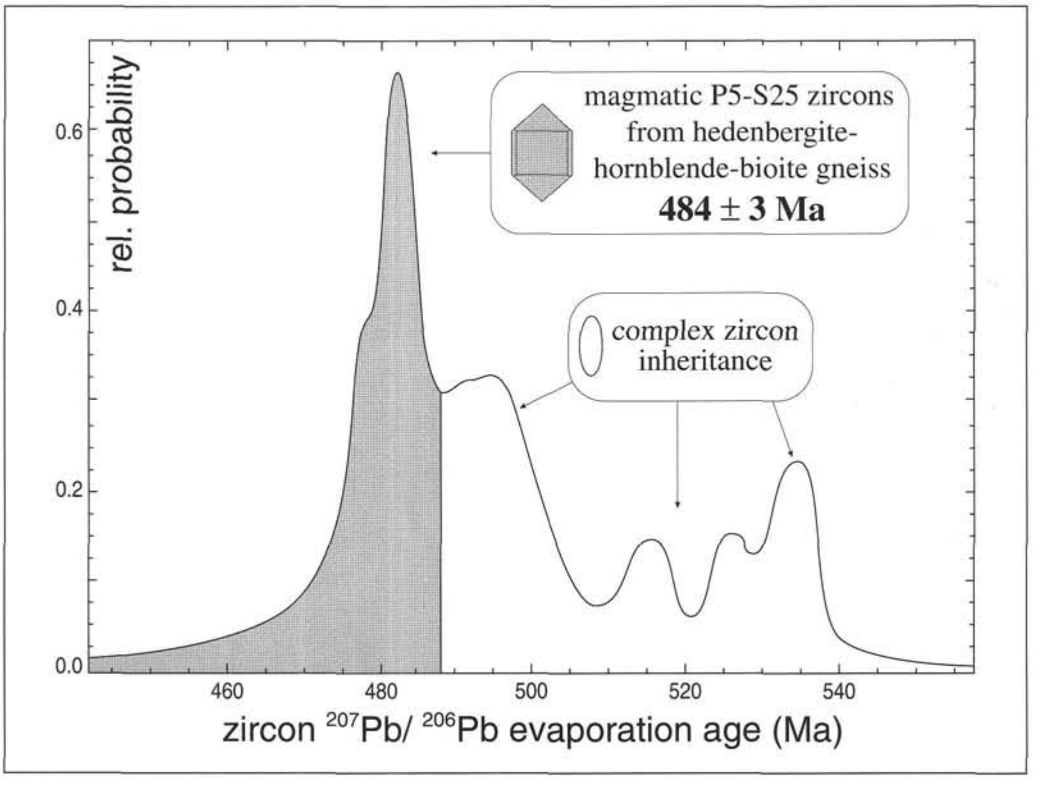


Fig. 9
Probability density distribution plot of the single zircon evaporation ages from the Tieftal hedenbergite-hornblende-biotite gneiss. Magmatic zircon growth around 484 ± 3 Ma is indicated by a not very prominent peak in the probability distribution. The observed complex inheritance results in a continuum of peaks. Only with the additional age information from Sm-Nd investigations, the zircon evaporation age distribution can be properly interpreted (see Fig. 10 and text). Erratic inherited ages > 550 Ma are not shown. Eight zircons were analysed. Adapted from BERNHARD et al. (1996).

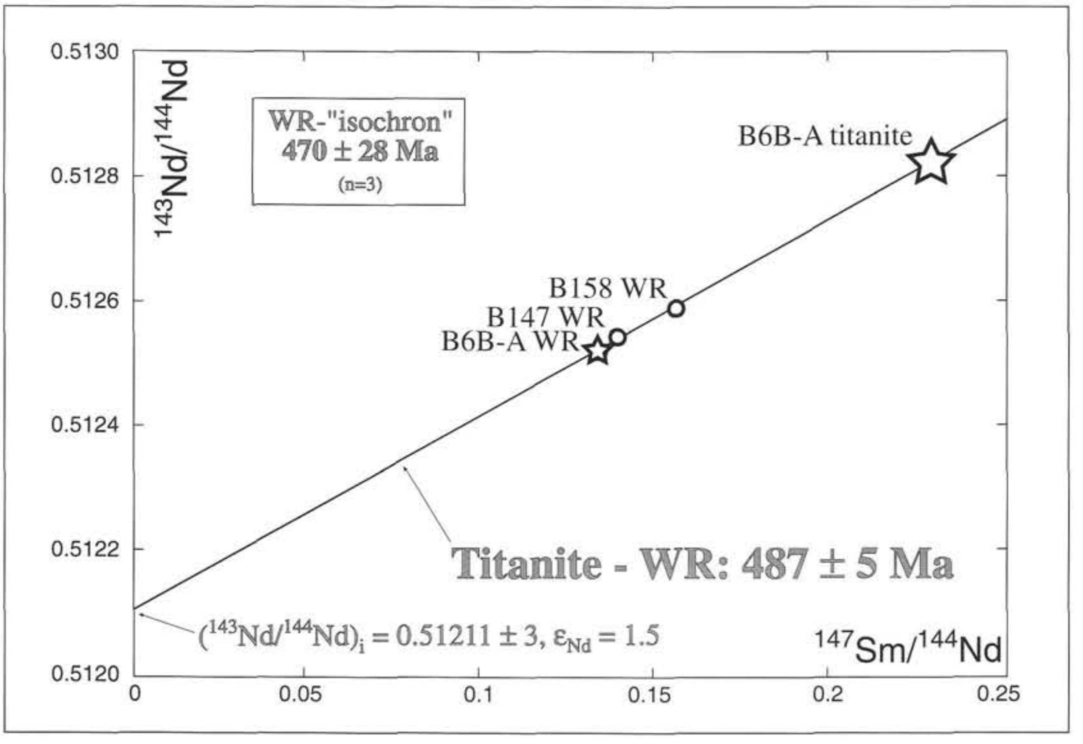


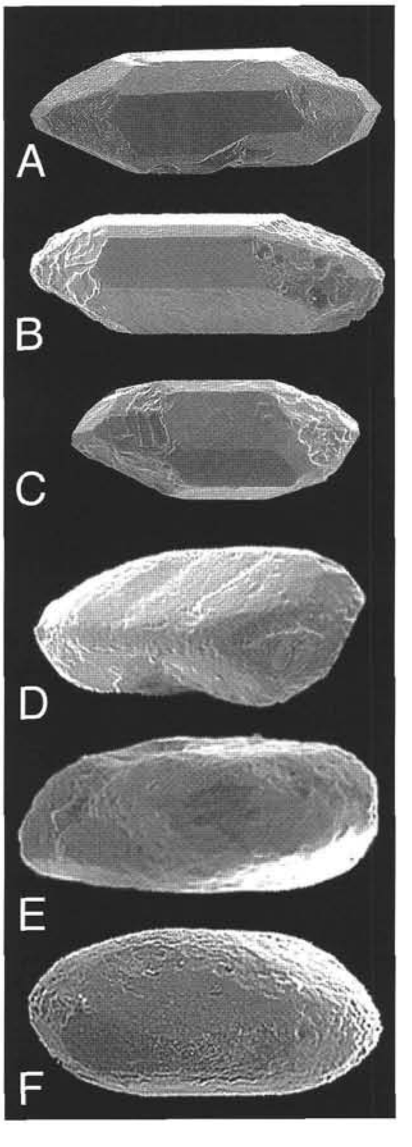
Fig. 10
Sm-Nd isochron plot of the Tieftal hedenbergite-hornblende-biotite gneiss. Three whole-rock samples and one titanite sample were investigated. The titanite – whole-rock age is 487 ± 5 Ma, whereas the three whole-rock samples define an "age" of 470 ± 28 Ma. Both ages are identical within error. Adapted from BERNHARD et al. (1996).

6. Maximum sedimentation ages of quartzphyllite complexes of the Eastern Alps

The widespread Austroalpine and Southalpine quartzphyllite complexes are normally interpreted as the infilling of an Early Ordovician (ca. 510 Ma) to Early Carboniferous (ca. 320 Ma) basin (Fig. 11). This basin may have initially formed as a back-arc basin on a Late Cadomian metamorphic crust during the Ordovician. These phyllitic complexes consist of a monotonous series of mainly meta-pelitic rocks with interbedded mafic and, more subordinate, acidic volcanics as well as carbonates and coarse-grained detrital sediments (SASSI et al., 1994). All complexes were overprinted by at least one pre-Permian low-pressure greenschist-facies metamorphism. Alpine overprinting, where present, is of variable intensity. Scarce fossil records, mostly conodonts and acritarchs, have given rise to a partly resolved stratigraphy of incomplete known sections. Ages from Ordovician to Early Carboniferous are reported (SCHÖNLAUB, 1979, SASSI et al., 1994). However except for some ages reported for the volcanic sequences (Ordovician to Silurian), no unequivocal absolute age data for the time of sedimentation is provided for most of these complexes. Scarce K-Ar and Rb-Sr ages on mica generally date the post-Variscan cooling.

In order to establish more exact time constraints on possible maximum sedimentation ages, the following approach was used (RIZZO et al., 1998): The youngest concordant magmatic or metamorphic age found for a given detrital zircon suite defines a maximum sedimentation age for the sampled sediment layer. If the zircon is not of true detrital origin but stems from a syn-sedimentary volcanic rock (ash flow, tuff), the age probably directly reflects the sedimentation age. On the other hand, older zircon ages are interpreted as representing minimum formation ages of the hinterland. These ages thereby provide valuable additional information about the age structure of the recycled crust. They also allow the tentative correlation of the otherwise unrelatable quartzphyllite complexes.

Fig. 11
SEM images of typical zircons from Austroalpine quartzphyllites. Only idiomorphic zircons (examples A, B, and C) with the least amount of rounding were used for Pb-Pb dating. Strongly rounded zircons (examples D, E, and F) are only shown for comparison.



In a preliminary study detrital zircon populations from five different quartzphyllite complexes from the Eastern and Southern Alps were investigated by SEM and individually dated. Fig. 11 shows examples of typical detrital zircons found in the quartzphyllites. Fig. 12 summarises the age data.

For a sample from the Thurntal quartzphyllite of Eastern Tyrol the youngest magmatic age determined is 598 ± 19 Ma (latest Precambrian / earliest Cambrian). For a sample derived from probably stratigraphically higher levels extrusion ages for meta-andesitic volcanics are in the range of 514 ± 16 Ma (Late Cambrian – Early Ordovician, KLÖTZLI, unpublished). At the moment, there is no additional evidence for Ordovician or younger sedimentation and/or magmatic ages for this quartzphyllite complex. Based on these age data a possible parallelisation with Ordovician Blasseneck-type porphyroids and porphyroids of other quartzphyllite complexes does not seem to be justified.

For a sample from the Gailtal quartzphyllite the youngest magmatic age found, i.e. the maximum sedimentation age, is 341 ± 24 Ma (Visean). Although this age is rather badly constrained again it is in some contrast to published biostratigraphic ages which are all either Silurian or Devonian (438 – 360 Ma, SCHÖNLAUB, 1979). A preliminary interpretation could be that the age range of sedimentation of at least some parts of the Gailtal quartzphyllite must be extended into the Variscan orogenic cycle probably with the accompanying erosion of Variscan granitoids. Therefore, the magmatic rocks formed during the Variscan should have already reached the surface in the Visean, implying a rapid exhumation shortly after their formation.

For samples from the Goldeck quartzphyllite, no definitive maximum age for the sedimentation can be provided. Badly defined youngest magmatic ages found are in the range of 270 – 280 Ma (Early Permian !), i.e. in the age range of post-Variscan cooling or Permian metamorphism. The significance of these ages is not yet clear. However, petrographic evidence seems to exclude a metamorphic overprint high enough for zircon recrystallisation or growth.

For comparison: In the quartzphyllite complex of Vetriolo (Southern Alps) only Early Proterozoic ages older than 1800 Ma were observed, which probably cannot directly be interpreted as maximum sedimentation ages. However, a possible interpretation is, that the sediment inventory of the Vetriolo complex stems from a Proterozoic basement which was not or only partly reworked during the Cadomian. This is a marked difference to the investigated Austroalpine complexes, were the presently available hinterland ages are always considerably younger and normally do comprise Cadomian rocks.

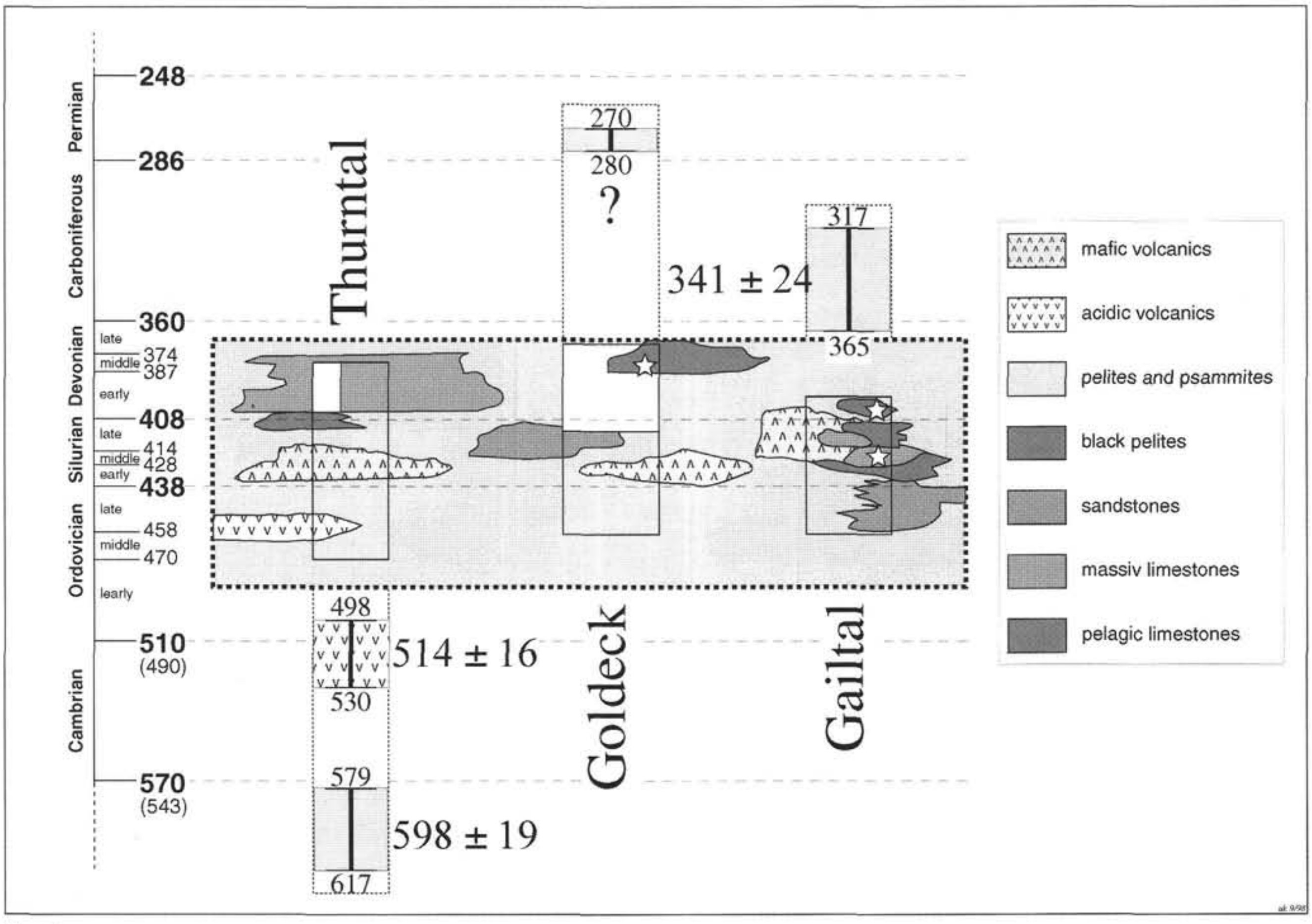


Fig. 12
Lithostratigraphic schemes of the investigated Austroalpine quartzphyllites. The represented rock types refer to the protoliths. In the Goldeck and Gailtal sections stars symbolise biostratigraphic age constraints. Ages on the stratigraphic column are recommended IUGS values (COWIE & BASSET, 1989). Bracketed ages for the Cambrian are new recommended values from BOWRING & ERWIN (1998). Single zircon Pb-Pb ages are shown as 2σ-age ranges for the respective quartzphyllite complex. Ages for the Gailtal and Goldeck complexes are from phyllitic rock samples. They are problematic as they indicate far younger maximum sedimentation ages or extended sedimentation age ranges than previously considered. Ages from the Thurntal complex are not necessarily in contradiction to published ages. They could represent some amount of sedimentary recycling, although the Cambrian age of 520-500 Ma stems from a concordant andesitic porphyroid layer. The dashed framed schematic profiles are redrawn from SASSI et al. (1994).

Maximum sedimentation ages for the quartzphyllite complex of Recoaro (Southern Alps) are in the range of 473 ± 21 Ma (Middle Ordovician). This is within error identical to Ordovician U-Pb zircon ages around 470 – 480 Ma derived from the volcanics of the Comelico complex (Meli & Klötzli, 1997) probably justifying a correlation of the Recoaro and Comelico complexes.

6.1 Concluding remarks

The presented preliminary single zircon age data have revealed one important fact. Published stratigraphic ages of the different quartzphyllite complexes probably have to be reviewed critically. But in order to come to a more complete and comprehensive picture, additional detailed geochronological investigations are needed.

7. Conclusions

The combination of zircon typology studies and U-Pb and Pb-Pb dating of zircon has proven to provide valuable information concerning genesis and evolution of complex magmatic and polymetamorphic rock series. All discussed case studies show the importance of preliminary zircon typology investigations. Only the recognition of different zircon types within one sample allows an appropriate analytical strategy and, possibly, subsequent parallelisation of age data and geological events.

For the South Bohemian Pluton the importance of the widespread reworking of Cadomian rocks into the Variscan granitoids is stressed. A two-stage magmatic evolution for the Carboniferous plutonites is proposed. The first stage comprises regional partial melting in the lower crust at around 355 – 350 Ma. Subsequently, individual intrusion events took place between 350 Ma and 320 Ma.

In the Upper Austroalpine basement series Early Ordovician crustal thinning is proposed on the basis of zircon age data. This finding is in some contrast to published Palaeozoic evolutionary schemes of the Austroalpine realm, but on the other hand, matches perfectly recent results from the Silvretta crystalline basement sequences. The inheritance of zircons derived from Cadomian rocks, as found also for the southern part of the Bohemian Massif, is widespread. This again points to the fact, that Cadomian rocks do form a substantial part of the pre-Variscan basement of the Eastern Alps.

The preliminary data for the Austroalpine quartzphyllite complexes are in contradiction to published stratigraphies. Therefore, more single zircon age data are needed in order to review critically the assumed sedimentation ages.

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