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Unravelling the pre-Mesozoic history of Aar and Gotthard massifs (Central Alps) by isotopic dating – a review

by *Urs Schaltegger*[1]

Abstract

The Aar and Gotthard "massifs" in the Central Alps represent portions of pre-Mesozoic basement relatively weakly overprinted by Alpine metamorphism and deformation, and offer the possibility of reconstructing the Paleozoic and Proterozoic history of the Central Alpine realm. The oldest components in the basement of both massifs are Archean to Proterozoic in age and were incorporated as cores in detrital zircons of Pan-African age, which were discovered in high-grade meta-sediments. The same rocks also contain remnants of an ancient oceanic crust of Proterozoic age, the whole assemblage being formed in the accretionary wedge of the Caledonian subduction. Both Caledonian and Variscan metamorphic overprints are recorded by different chronometers (U–Pb, Sm–Nd) that point to ages of 460–470 Ma and 330–360 Ma, respectively, for the climax of the two metamorphic events. The Variscan orogenic cycle culminates in the intrusion of large volumes of mafic to acid, volcanic and magmatic rocks between 335 and 294 Ma, which were emplaced in the course of a late-orogenic transtensional regime. The isotopic systems of granitoid whole rocks and of minerals were severely disturbed during the Alpine orogenic cycle.

Keywords: Archean, metamorphic evolution, geochronology, Caledonian orogeny, Variscan orogeny, Aar massif, Gotthard massif.

Introduction

Today we look back to three decades of isotope geochemical research in the Central Alps. However, more than 60% of the accumulated data of Aar and Gotthard massifs (Tab. 1 and 2) originate from papers that appeared during the last ten years. The emphasis of isotopic dating has been on dating the Alpine mountain building processes and post-Alpine cooling uplift, using the K–Ar, Rb–Sr biotite, white mica and hornblende chronometers and the zircon, apatite fission track dating technique. Therefore the pre-Mesozoic data from both massifs are rather scarce compared to the wealth of information we have on the timing of Alpine metamorphism.

The unravelling of the pre-Mesozoic history of the Alpine realm is mainly hampered by the effects of the Alpine metamorphic overprint, blurring mutual relationships of mineral assemblages and mesoscopic structures that were formed during pre-Alpine events. As an exception, ARNOLD (1970a) described high-grade metamorphic mineral assemblages of Caledonian age in the Gotthard massif that partly survived the subsequent overprints. The age of this metamorphism was dated at 440–460 Ma by the Rb–Sr and U–Pb dating techniques (ARNOLD, 1970b; GRAUERT and ARNOLD, 1968). These Ordovician ages have remained unique for 20 years, until recent work confirmed the existence of an Ordovician ("Caledonian") overprint in the Central Alps.

Since the 1980ies, new techniques were applied to geological problems of the Alpine basement: Precise U–Pb dating and the determination of initial ε_{Nd} and ε_{Hf} values and mantle extraction model ages allow to estimate the age, proportion and nature of the different components that build the crust of central Europe. U–Pb single grain and ion-probe zircon dating were able to provide precise ages for magmatic and metamorphic events and to resolve the polymetamorphic history of metasedimentary rocks.

The aim of this paper is to compile all available pre-Mesozoic age data of the Aar and Gotthard massifs (Tab. 1 and 2) and to use these

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data for a synoptic chronological reconstruction of the two massifs for the respective time period. The renewed interest of Alpine geologists for this subject has led to the compilation of VON RAUMER and NEUBAUER (1993), which covers the whole Alpine realm. The present paper will therefore strictly focus on the problems of the two central Alpine massifs.

Late Variscan post-collisional magmatism and volcanism

AAR MASSIF

Both Aar and Gotthard massifs contain large bodies of late Variscan intrusives, the former comprises mainly granitoid rocks, diorites and syenites. For the Aar massif, three different magmatic suites can be distinguished on the basis of geochemical composition and age (PASTEELS, 1964; SCHALTEGGER, 1990a; SCHALTEGGER et al., 1991; SCHALTEGGER and CORFU, 1992; SCHALTEGGER, 1993; see Fig. 1):

(A) A shoshonitic-ultrapotassic suite at 334 ± 2.5 Ma, comprising the Giuv syenite, the granites and diorite of Val Punteglias; the Tödi granite at the eastern end of the Aar massif is dated at 325 ± 13 Ma (recalculated with new constants) by a K-feldspar-muscovite age of a crosscutting pegmatite and might belong to this group. (B) A high-K calc-alkaline suite at 309 ± 3 Ma, comprising the Düssi and Schöllenen diorites and the Voralp granite. (C) A calc-alkaline to subalkaline granitic suite, comprising granodiorites, granites and leucogranites of the Central Aar granite at 298 ± 2 Ma and the Gastern granite at 303 ± 4 Ma.

The intrusion ages of the three groups partly overlap within error limits, but, however, show a clear trend in age and geochemical composition. All mentioned intrusives are assumed to postdate Variscan collision and deformation and are therefore related to late-Variscan transtensional strike-slip tectonics (SCHALTEGGER et al., 1993). They show no Variscan solid-state deformation; group A is characterized by abundant magmatic flow textures, which are probably caused by synintrusive deformation and get less important with decreasing age.

GOTTHARD MASSIF

An older group of granites, granodiorites and diorites comprises the Gamsboden, Fibbia (301 ± 2 Ma; GUERROT and STEIGER, 1991; SERGEEV and STEIGER, 1993) and Cristallina-Medel intrusives. This group is thus coeval with group C of the Aar massif, but shows different geochemical characteristics and a higher degree of post-intrusive deformation. The more deformed character would imply that late Variscan deformation still was active in the Gotthard massif 300 Ma ago, whereas it had already ceased in the Aar massif. Additionally, a fourth group (D) is defined in the Gotthard massif (Fig. 1), younger than group C, comprising the Cacciola (292 ± 11 Ma; OBERLI et al., 1981), Rotondo, Tremola (295 ± 2 Ma; SERGEEV and STEIGER, 1993) and Winterhorn granites and the Sädelhorn diorite dike (293 +4/–5 Ma; BOSSART et al., 1986). This group consists of rocks that are nearly devoid of any deformation. The U–Pb zircon ages suggest that the Rb–Sr whole-rock isochron age of the Rotondo granite (269 Ma; JÄGER and NIGGLI, 1964; JÄGER, 1977) is lowered by a post-intrusive alteration event. This event is also responsible for the formation of microcline porphyroblasts with inclusions of zircons that yield $^{206}Pb/^{238}U$ ages around 270 Ma (SERGEEV and STEIGER, 1993).

The Mittagflue granite of the northern Aar massif has similar textural and geochemical characteristics and might be attributed to group D; its age of 296.5 ± 2.5 Ma is slightly younger than group C granites, but however, agrees with the age of the Central Aar granite within error limits. A sample of the northern border facies (Reuss valley) is dated at 292 ± 2 Ma, which might be significant, but lowering of the age by Alpine lead loss cannot be discarded (SCHALTEGGER and CORFU, 1992).

Volcanic rocks have only been dated in the Windgällen formation of the northern Aar massif (SCHENKER, 1986). This is a sequence of volcaniclastic rocks, containing ignimbrites and subvolcanic granitoids that are dated at 299 ± 2 Ma (SCHALTEGGER et al., 1993).

GEOTECTONIC ENVIRONMENT

The whole sequence of syenites, diorites and granites in the Aar and Gotthard massifs was suggested to build up a magmatic arc formed during Andean-type subduction at a late stage of the Variscan collision (FINGER and STEYRER, 1990). Other hypotheses invoke melting during late-orogenic crustal relaxation due to decompression and remobilization of lower crust and lithospheric mantle by the rising asthenosphere (GRAF, 1992).

Initial ε_{Hf} data suggest that the influence of a crustal component decreased in the course of the evolution from group A to C rocks in the Aar

Tab. 1 Compilation of isotopic age determinations of late Variscan magmatic rocks from Aar and Gotthard massifs.

Late Variscan volcanism and magmatism		
Gotthard massif		
Acquacalda, granodiorite gneiss	305/328±30 Ma; concordant U-Pb zircon ages (1)	Grünenfelder (1963)
Cacciola granite	292±11 Ma; U-Pb zircon upper intercept age	Oberli et al. (1981)
Fibbia gneiss	390±60 Ma; $^{207}Pb/^{206}Pb$ age (1)	Grünenfelder (1962)
	300±2 Ma; U-Pb zircon age	Sergeev and Steiger (1993)
Gamsboden gneiss	300±50 Ma; $^{207}Pb/^{206}Pb$ age (1)	Grünenfelder (1962)
	301±2 Ma; single zircon U-Pb age	Guerrot and Steiger (1991)
		Sergeev and Steiger (1993)
Medels granite	303±20 Ma; U-Pb zircon age	Grünenfelder (1962)
Rotondo granite	140/140/170 Ma; discordant U-Pb zircon age (1)	Grünenfelder and Hafner (1962)
	272 Ma; Rb-Sr wr age (2)	Jäger and Niggli (1964)
	269±11 Ma; revised Rb-Sr wr age (3)	Jäger (1977)
Sädelhorn diorite	293-5/+4 Ma; U-Pb zircon upper intercept age	Bossart et al. (1986)
Tremola granite	295±2 Ma; concordant U-Pb zircon age	Sergeev and Steiger (1993)
Aar massif		
Central Aar granite:		
Central Aar granite s. l.	292±2 Ma; Rb-Sr wr age, Sr_i=0.7050	Schaltegger (1990)
(Reuss valley)	298±3 Ma; zircon U-Pb upper intercept age	Schaltegger and von Quadt (1990)
	297±2 Ma; concordant zircon U-Pb age	Schaltegger and Corfu (1992)
Northern border facies	298±7 Ma; zircon U-Pb upper intercept age	Schaltegger and von Quadt (1990)
Central Aar granite s.str.	286 Ma; Rb-Sr wr age (3)	Wüthrich (1965)
(Grimsel)	285±25 Ma; zircon $^{207}Pb/^{206}Pb$ age (1)	Pasteels (1964)
	297±15 Ma; Rb-Sr wr age, Sr_i=0.7049	Schaltegger (1990)
	299±2 Ma; concordant U-Pb zircon age	Schaltegger and Corfu (1992)
	291±10 Ma; Rb-Sr wr age, Sr_i=0.7045	Marquer (1987)
	100, 110 Ma; Rb-Sr reference lines on small wr samples across mylonite zones, Sr_i=0.708-0.723	Marquer (1987)
Grimsel granodiorite	315±25 Ma; $^{207}Pb/^{206}Pb$ age (1)	Pasteels (1964)
	298±6 Ma; U-Pb zircon upper intercept age	Schaltegger and von Quadt (1990)
	299±2 Ma; concordant U-Pb titanite age	Schaltegger and Corfu (1992)
Mittagflue granite	235±90, 350±45; zircon $^{207}Pb/^{206}Pb$ ages (1)	Pasteels (1964)
	230±8 Ma; Rb-Sr wr age, Sr_i=0.7450	Schaltegger (1990)
	296.5±2.5 Ma; concordant U-Pb zircon age	Schaltegger and Corfu (1992)
Kessiturm aplite	254±8 Ma; Rb-Sr wr age, Sr_i=0.7221	Schaltegger (1990)
Aplite dikes	251±5 Ma; Rb-Sr wr age, Sr_i=0.7095	Schaltegger (1990)
	250 Ma; Rb-Sr wr reference line	Marquer (1987)
Düssi diorite	308±2 Ma; concordant zircon U-Pb age	Schaltegger and Corfu (1992)
Gastern granite	303±4 Ma; concordant U-Pb zircon age	Schaltegger (1993)
Habkern granite	310±60 Ma; $^{207}Pb/^{206}Pb$ age (1)	Pasteels (1964)
Schöllenen diorite	316±27 Ma; U-Pb zircon upper intercept age	Schaltegger and von Quadt (1990)
	310±3 Ma; concordant titanite U-Pb age	Schaltegger and Corfu (1992)
Shoshonitic-ultrapotassic series:		
Giuv syenite, Punteglias	334±2.5 Ma; U-Pb zircon upper intercept age	Schaltegger and Corfu (1992)
granite and diorites	332±2 Ma; concordant titanite U-Pb age	Schaltegger and Corfu (1992)
	332±1.5 Ma; U-Pb mineral isochron	Schaltegger and Corfu (1992)
Tödi granite; pegmatite	325±14 Ma; Mus-Kfs Rb-Sr age (3)	Wüthrich (1965)
Voralp granite	309±2 Ma; concordant zircon U-Pb age	Schaltegger and Corfu (1992)
Windgällen ignimbrite and porphyry	299±2 Ma; concordant zircon U-Pb age	Schaltegger et al. (1993)

Abbreviations: Sr_i=initial $^{87}Sr/^{86}Sr$; wr=whole rock; (1) Old constants for ^{235}U, ^{238}U, $^{235}U/^{238}U$; (2) Old constants for ^{87}Rb, $^{88}Sr/^{87}Sr$ and $^{88}Sr/^{86}Sr$ common; (3) Recalculated with new constants.

Tab. 2 Compilation of isotopic age determinations from basement rocks of Aar and Gotthard massifs.

Basements units			
Gotthard massif			
Giubine series	fine-grained two-mica gneisses	ca. 410 and 1550 Ma intercept ages; U-Pb zircon discordia (1) 258±31 Ma (Sr_i=0.7152) Rb-Sr isochron (1); 247± 58 Ma if recalculated using Ludwig (1988) (3) 276±90 Ma; $^{238}U/^{206}Pb$ wr isochron	Nunes and Steiger (1974)
Gurschengneis unit	biotite-plagioclase gneiss	514/600/932 Ma; discordant U-Pb zircon data (1)	Grünenfelder et al. (1964)
	kyanite-sillimanite gneiss	438, 1586 Ma intercept ages of U-Pb zircon discordia (1)	Grauert and Arnold (1968)
	quartz-diorite	450-465 Ma; slightly discordant U-Pb zircon data (1)	Grauert and Arnold (1968)
	ultramafic lens	450±5 Ma; concordant U-Pb zircon age (1)	Grauert and Arnold (1968)
	meta-gabbro	450-870 Ma discordia (no error); zircon U-Pb ionprobe data of magmatic zircons; 468 Ma lower intercept age, 1.27, 2.45, 2.67 3.17 Ga upper intercept ages; within-grain discordias of xenocrystic zircons (ionprobe data).	Gebauer (1990)
		461±25 Ma; Sm-Nd garnet-wr age	Gebauer et al. (1988)
		465±5, 296±19 Ma; U-Pb zircon intercept ages	Oberli et al. (1993 a, b)
Prato series	fine-grained two-mica gneisses	ca. 330 and 1700 Ma intercept ages; U-Pb zircon discordia	Nunes and Steiger (1974)
Sorescia gneiss	fine-grained two-mica gneisses	ca. 410 and 1550 Ma intercept ages; U-Pb zircon discordia (together with rocks of the Giubine series)	Nunes and Steiger (1974)
Streifengneis unit	biotite-muscovite-K-feldspar-gneiss, orthogneiss	485±20/520±25/560±30 Ma; discordant zircon U-Pb data (1)	Grünenfelder et al. (1964)
		421±17 Ma; Rb-Sr wr isochron, Sr_i=0.7137 (2); 436±17 Ma (3)	Arnold (1970b)
		approximate age of >440 Ma; single-grain zircon U-Pb ages	Bossart et al. (1986)
		439±5 Ma; U-Pb single-grain zircon age	Sergeev and Steiger (1993)
Tavetsch massif	pegmatite	365±21 Ma; common Sr-muscovite Rb-Sr model age (2)	Arnold and Jäger (1965)
Aar massif			
Erstfeld gneiss zone	migmatitic biotite gneiss	456±2 Ma; concordant zircon U-Pb age	Schaltegger (1992, 1993)
		312±10 Ma; K-Ar and Rb-Sr biotite ages	Schaltegger (1986), Wüthrich (1965)
	pegmatites	285-305 Ma; common-Sr - muscovite Rb-Sr model ages (2)	Wüthrich (1965)
	meta-psammite	452±5 Ma; concordant single zircon U-Pb age	Schaltegger (1993)
		330±3 Ma; rutile $^{238}U/^{206}Pb$ age	Schaltegger (1993)
		0.62, 2.5 Ga intercept ages of zircon U-Pb discordia	Schaltegger (1992, 1993)
	garnet amphibolite	330±3 Ma; zircon $^{238}U/^{206}Pb$ age	Schaltegger (1992, 1993)
	amphibolites and hornblendefelses	200-870 Ma; K-Ar hornblende ages	Schaltegger (1984)
Guttannen zone	biotite-sericite gneiss	discordant zircon U-Pb ages of ca. 390 Ma	Schaltegger (1993)
	aplite granite	234±26/208±26 Ma; Rb-Sr wr ages	Abrecht and Schaltegger (1988)
Innertkirchen-Lauterbrunnen Crystalline complex	cordierite-(pinite)-migmatite	445±2 Ma; concordant zircon U-Pb age	Schaltegger (1992, 1993)
		discordant U-Pb zircon data; upper intercept ages ca. 2 Ga	Gulson and Rutishauser (1974)

Abbreviations: as in Tab. 1

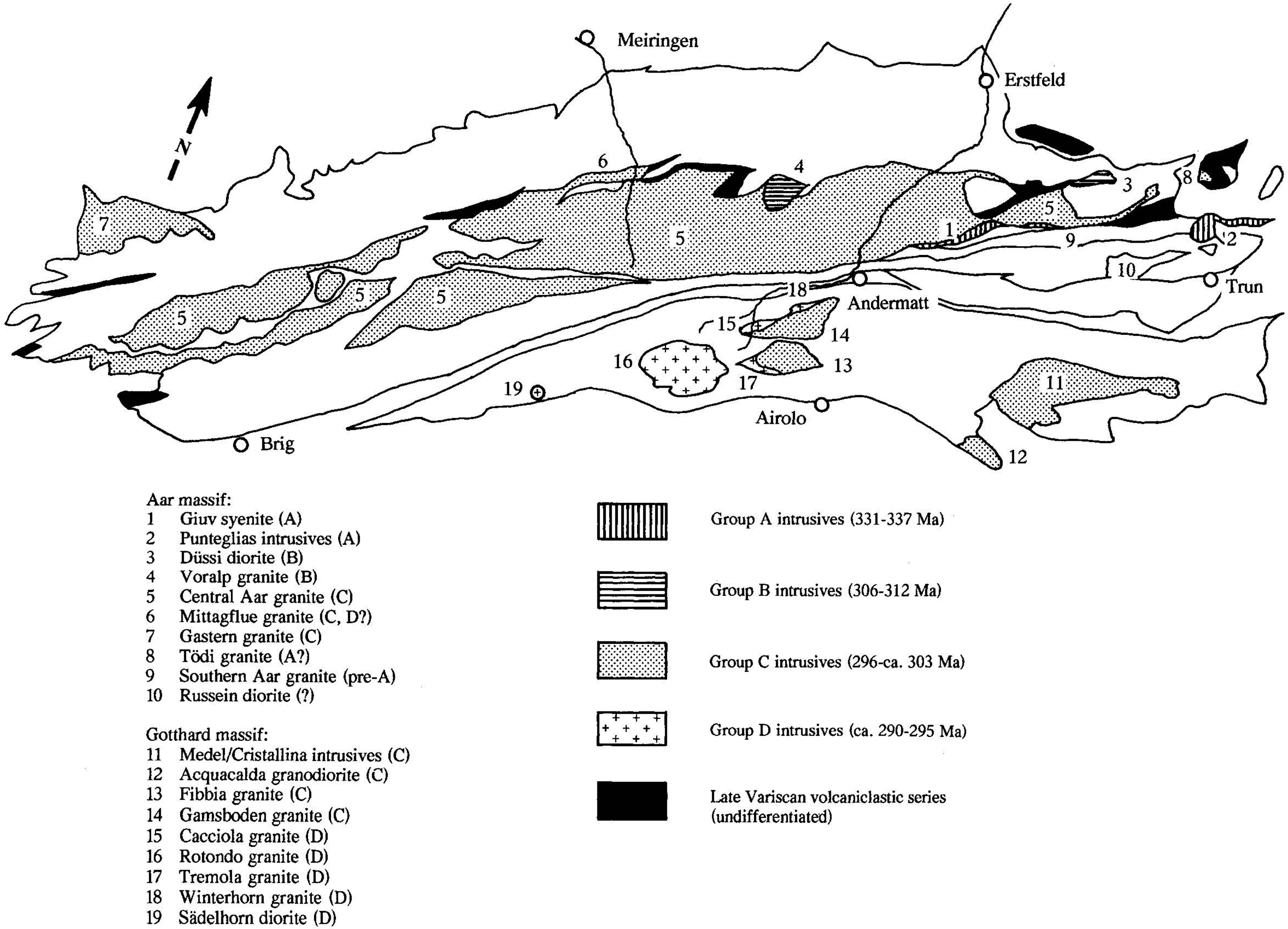

Fig. 1 Schematic map of the Aar and Gotthard massifs with the sequence of late Variscan magmatic rocks.

massif: the members of group A have ε_{Hf} of 0 to –8, whereas most group C granites lie in the range of +1 to +3.5 (SCHALTEGGER and CORFU, 1992), which is in line with initial Sr isotopic ratios around 0.705 (SCHALTEGGER, 1990b). A predominantly mantle-derived source for these granitoids is also indicated by the lack of inherited lead in the zircons. The northern border facies of the Central Aar granite shows differing isotopic characteristics with ε_{Hf} of –2.2 and contains inherited crustal zircons (SCHALTEGGER and CORFU, 1992). Addition of juvenile mantle material to the Variscan crust is also documented by coeval magmatism of the Penninic domain, showing initial Sr ratios of 0.705 (GULSON, 1973; HÄNNY et al., 1975).

The Gamsboden, Fibbia (both group C) and Sädelhorn intrusives (group D) have initial ε_{Nd} of –3 to –5 (BOSSART et al., 1986; GUERROT and STEIGER, 1991), which argues for considerable crustal contamination of these melts. The late Variscan magmatism in the Gotthard massif might therefore be generally more crust-contaminated than its counterpart in the Aar massif.

Variscan metamorphism

The Variscan metamorphism was the last major thermal event in the area of Aar and Gotthard massifs and reset all mineral systems (K–Ar, Rb–Sr of micas and hornblende), which then were again overprinted by Alpine metamorphism.

The Variscan ages we dispose of are (1) mineral cooling ages, (2) ages from late Variscan intrusives and (3) lower intercept ages of multiply disturbed U–Pb discordias that have to be interpreted with greatest caution. We, therefore, do not have exact time constraints for the climax of Variscan metamorphism. The cooling to 300 ± 50 °C is dated by the K–Ar and Rb–Sr systems of biotite at 312 ± 10 Ma (WÜTHRICH, 1965; SCHALTEGGER, 1986) along the northern border of the Aar massif and is most likely undisturbed by the intrusion of the late Variscan granites. A constraint for a minimum age of the thermal peak is a $^{206}Pb/^{238}U$ zircon age of 330 ± 3 Ma of a mafic rock from the Susten area (Aar massif; SCHALTEGGER, 1993), which is thought to date zircon growth in the course of retrograde mineral reactions. This age coincides with a rutile $^{206}Pb/^{238}U$ age of 330 Ma from a metasediment of the same region (SCHALTEGGER, 1993) and with a lower intercept age of around 330 Ma of a zircon U–Pb discordia from the Prato series (southern Gotthard massif; NUNES and STEIGER, 1974). An age of 365 ± 21 Ma (old constants; ARNOLD and JÄGER, 1965) is reported of pegmatite muscovite from the Tavetsch massif. These ages suggest an age of 330–360 Ma for the climax of Variscan metamorphism.

There are no isotopic evidences for a Variscan high pressure event in both massifs. Garnet-amphibolites that are interpreted as retrograded eclogites are ascribed to the Caledonian metamorphic cycle (ABRECHT et al., 1991). Variscan high pressure rocks are described and dated from other Alpine external massifs (Argentera, Belledonne; PAQUETTE et al., 1989), from Massif Central and Vosges (see O'BRIEN et al., 1990 for a review). Aar and Gotthard massifs may have another P-T-time path for Variscan metamorphism than other Variscan massifs in central Europe, or may represent a shallower crustal section of the Variscan orogen. The age determinations of Argentera, Belledonne and Massif Central eclogites, however, were carried out using zircon fractions for U–Pb dating, which possibly suffered complex and polyepisodic lead loss.

The Variscan metamorphic overprint is of variable degree in different parts of the Aar and Gotthard massifs: The rocks of the Erstfeld zone in the northern Aar massif equilibrated at amphibolite facies conditions, which is dated at a Caledonian age of 456 ± 2 Ma (SCHALTEGGER, 1993). Later metamorphic overprints (Variscan, Alpine) only left mineral assemblages in greenschist facies; the Variscan metamorphic overprint did therefore not exceed greenschist facies conditions in this northernmost zone. Data from more southern units of the Aar massif (SCHALTEGGER, 1993) and from the Gotthard massif (NUNES and STEIGER, 1974; ARNOLD, 1970a) suggest a stronger Variscan metamorphic overprint in amphibolite facies. The existence of a late Variscan deformation phase has been proposed by OBERHÄNSLI et al. (1988). If we assume that the contrasting state of deformation of the Gotthard massif granites is due to this late Variscan deformation phase, and not to differential response to Alpine stress, the age of this deformation is limited by the intrusions of the group C and group D granites (301 and 294 Ma), respectively.

Alpine-Variscan intermediate ages

Most K–Ar and Rb–Sr mineral systems in the Central Alps yield Alpine ages between 35 and 14 Ma. Along the northern border of the Aar massif, a transitional zone with biotite ages intermediate between Variscan (ca. 310 Ma) and Alpine (ca. 25 Ma) ages occurs. The degree of resetting of the isotopic systems was governed by a variety of parameters, including fluid/rock ratio and chemical composition, thus causing widely scattering age data (DEMPSTER, 1986) that are considerably below the Variscan cooling age of 312 ± 10 Ma (WÜTHRICH, 1965; SCHALTEGGER, 1986).

Alpine metamorphism or Mesozoic hydrothermal events affected the Rb–Sr whole-rock systems of granitoid rocks, causing point-scattering and lowering of the age by rotating the isochron. This is the case for the Rotondo granite (JÄGER and NIGGLI, 1964; SERGEEV and STEIGER, 1993) and metasediments of the Giubine series (NUNES and STEIGER, 1974), lowered by ca. 8 and 25% of their original age, respectively. SCHALTEGGER (1990b) obtained Rb–Sr whole-rock ages of 297 to 230 Ma for several members of the 298 Ma old Central Aar granite (leucocratic Central Aar and Mittagflue granites, aplite stocks and dikes) and an age of 208 ± 26 Ma for an aplitic granite within the Aar massif basement (ABRECHT and SCHALTEGGER, 1988). Small-scale Rb–Sr whole-rock isochrons across mylonite zones of the 298 Ma old Grimsel granodiorite yield fictitious ages of ca. 100 to 110 Ma (MARQUER, 1987) that are tentatively interpreted as the result of mineral transformations in an Alpine shear zone, which only attained partial equilibrium.

U–Pb analyses of zircon fractions are biased in most cases by Alpine metamorphic lead loss; U-rich zircons of usually small grain size are prone to Alpine lead loss and are responsible for the discordance in late Variscan intrusives of the Aar (SCHALTEGGER and QUADT; 1990) and Gotthard massifs (GRÜNENFELDER and HAFNER, 1962; GRÜNENFELDER, 1963).

Caledonian metamorphism

AAR MASSIF

Caledonian ages were recently found in the Aar massif: a layered migmatitic gneiss from the Erstfeld zone yields a concordant U–Pb zircon age of 456 ± 2 Ma (SCHALTEGGER, 1993). The rocks of the Aar massif occur in amphibolite facies and show no or only minor relics of an earlier granulite facies metamorphism. Caledonian regional metamorphism seems to be followed by a slightly younger thermal event at around 445 Ma (SCHALTEGGER, 1993), which causes in situ melting of large areas of the Innertkirchen-Lauterbrunnen Complex and of small pegmatoid pods within the Erstfeld zone. This thermal event coincides in age with the intrusion of the Streifengneis in the Gotthard massif.

From the Aar massif, no relics of eclogitic mineral assemblages were reported up to now. Garnet amphibolites from the Susten pass (SCHALTEGGER, 1984, 1986) that may be interpreted as meta-eclogites are equilibrated in amphibolite facies and did originally not contain zircon. Only Variscan greenschist facies metamorphism caused the crystallization of new zircon at 330 ± 3 Ma in these rocks due to the complete decomposition of Zr-bearing pyroxene (SCHALTEGGER, 1993).

GOTTHARD MASSIF

ARNOLD (1970a) reported the occurrence of granulite-facies mineral assemblages in paragneisses that are intruded by a 439 ± 5 Ma old granite, the so-called Streifengneis (SERGEEV and STEIGER, 1993; ARNOLD, 1970b), and concluded that the granulite-facies metamorphism must be of pre-Caledonian or Caledonian age. The latter is corroborated by several concordant and near-concordant U–Pb zircon ages between 450 and 470 Ma (GRAUERT and ARNOLD, 1968). The data of NUNES and STEIGER (1974) argue for a strong Caledonian metamorphic overprint, too, although they are disturbed by the Variscan event. A precise U–Pb zircon age of 465 ± 5 Ma from an island arc meta-gabbro (OBERLI et al., 1993 a, b) most likely dates the climax of Caledonian high-P-T metamorphism.

Beside the granulite-facies relics, occurrences of eclogites are reported from the Gotthard massif (ABRECHT et al., 1991), which were re-equilibrated under granulite- to amphibolite-facies conditions. A preliminary Sm–Nd garnet-whole rock age of 461 ± 25 Ma (GEBAUER et al., 1988) does not allow precise time constraints neither for the eclogitic nor the granulitic phase. Ion probe zircon U–Pb age determinations yielded lower intercept ages of 460 and 468 Ma (no error estimate), interpreted as the age of Caledonian metamorphic overprint of a ca. 870 Ma (no error estimate) old protolith (GEBAUER, 1990). This age is either thought to date the eclogitic or granulitic stage of Caledonian metamorphism.

The Streifengneis (Gotthard massif) is the only known Caledonian intrusion in the area of interest. It is a crust-derived granite, indicated by inheritance of old crustal lead in the zircons (GRÜNENFELDER et al., 1964) and a relatively high initial $^{87}Sr/^{86}Sr$ ratio of 0.714 (ARNOLD, 1970b). The Rb–Sr whole-rock age of 436 ± 17 Ma (ARNOLD, 1970b) and the U–Pb age of 439 ± 5 Ma (SERGEEV and STEIGER, 1993) date the intrusion of this late Caledonian granite. It crosscuts all deformational features of Caledonian age; its gneissification and Schlingen tectonics involving the granite and its country rocks are therefore assumed to be of Variscan age (MERCOLLI et al., this volume).

Summarizing, the Caledonian metamorphism in the Aar and Gotthard massifs was caused by collisional tectonics and subduction. A high-pressure eclogitic event was followed by high-temperature metamorphism in an age range of 460–470 Ma. After a granulitic stage, extensive partial melting occurred in metasedimentary and orthogenic rocks of the Aar and Gotthard massifs and formed migmatites. Magmatic activity is coeval or slightly younger and comprises crust-derived protoliths, like the Streifengneis or other orthogneisses of the Penninic realm (ALLÈGRE et al., 1974; STEIGER et al., 1993). Caledonian granitoids with predominantly juvenile (mantle) components seem to be rare (see IIZUMI et al., 1986).

Pre-Ordovician ages and isotopic constraints for the crustal evolution

The Aar and Gotthard massifs, as well as the crystalline cores of the Penninic and Austroalpine nappes, comprise metasedimentary sequences of flyschoid character that yield Proterozoic to Archean upper intercept ages for zircon U–Pb analyses. Inheritance of similar age is also found in migmatites (Innertkirchen-Lauterbrunnen Complex), orthogneisses (Streifengeis) and Variscan granites (Gamsboden, Fibbia, Gastern, Southern Aar granites). Ion probe U–Pb point ages in metasedimentary zircons scatter between 0.45 and 3.8 Ga for Central European metasediments (GEBAUER et al., 1989) and indicate that the upper intercept ages obtained by dating single grains and fractions might be a mixture of Proterozoic to Archean zircon growth zones. The inherited zircons, represented by old cores, were probably subjected to combined Pan-African, Caledonian and Variscan lead loss and zircon overgrowth, which results in highly complex and zoned zircon individuals.

It was demonstrated for many European Paleozoic sediments and metasediments that the inherited cores are enclosed in Pan-African detrital zircons, deposited in Late Precambrian to Early Cambrian sedimentary basins (GEBAUER et al., 1989; GEBAUER and GRÜNENFELDER, 1977). Detrital zircons of Pan-African age have recently been reported from Iberia (550–700 Ma; SCHÄFER et al., 1993), from the Gotthard massif (ca. 600 Ma; GEBAUER and QUADT, 1991) and from the Aar massif (ca. 620 Ma; SCHALTEGGER, 1993). The Pan-African zircon detritus is thought to be derived from either the Pentevrian microplate or the W-African craton on the Gondwana mainland. A Gondwana origin is also indicated by the lack of ca. 1 Ga old detritus dating the Grenville event, which is not present on the Gondwana continent.

Polymetamorphic basalts and gabbros that are enclosed in metasediments of the Gotthard massif basement may be divided into two groups: (1) An older group of meta-P or N-MOR basalts, peridotites and gabbros, and (2) a younger group of metagabbros and cumulitic ultramafics, probably generated in an island arc setting (PFEIFER et al., 1993). The first type shows an affinity to MOR basalts of the southern Penninic Ticino and Simplon areas, which have a crystallization age of around 0.9 to 1.0 Ga (STILLE and TATSUMOTO, 1985; SCHENK-WENGER and STILLE, 1990). For the second type, only a minimum crystallization age of 465–473 Ma may be inferred from zircon U–Pb age determinations (OBERLI et al., 1990 a, b), probably dating post-intrusive high-grade metamorphism. Intrusion ages around 500 Ma have also been found for MOR basalts from the Penninic basement (STILLE and TATSUMOTO, 1985) and the Tauern Window (VON QUADT, 1992). The crystallization ages of these MOR volcanics are in excess of the depositional age of the host metasedimentary rocks. The intimate relationship of metasediments and mafic-ultramafic rocks of different age and origin is thought to be the result of tectonic mélange in the accretionary wedge of an active continental margin of late Paleozoic age.

The isotope geochemical composition of mafic intrusives in the Alpine realm is thought to be representative for the evolution of a subcontinental mantle segment that has been geochemically enriched ca. 0.7 to 0.9 Ga ago (STILLE and SCHALTEGGER, work in progress). Partial melts of this mantle, variably contaminated by crustal material, are the most likely sources for most Caledonian, Variscan and Alpine intrusives in the Alpine realm. Nd and Hf T_{DM} model ages of granites from the Alpine basement scatter between 1.0 and 1.6 Ga, with a maximum around 1.5–1.6 Ga (SCHALTEGGER and CORFU, 1992; STEIGER and DEPAOLO, 1986; STILLE and STEIGER, 1991), a value that has also been found for Mesozoic to Tertiary marine deposits (STILLE and FISCHER, 1990).

Conclusions

The present data allow to draw the evolution of the Central Alpine Aar and Gotthard massifs from Archean source rocks until the last metamorphic overprint of Alpine age. Many periods of this protracted evolution remain, however, insufficiently investigated: The age or age distribution of the source material is known from a few ion-probe U–Pb spot ages from zircons that are not in agreement with conventionally obtained upper intercept ages. This discrepancy can readily be explained by mixing zircons from different provenances and with different histories, but, however, our ideas on age, composition and paleo-geographic position of potential source regions need to be refined.

There are no independent constraints for the existence of a Pan-African metamorphism in the Central Alps; U–Pb zircon ages of Central European sediments suggest a late Precambrian sedimentation age, which argues for a detrital origin of the Pan-African zircons. No Precambrian autochthonous crust has yet been determined in the Central Alps; more work on metasedimentary rocks and their mafic to ultramafic inclusions is needed to constrain or discard the existence of a Pan-African metamorphism and to explain the occurrence and the genesis of older mafic-ultramafic magmatic/volcanic suites within these metasedimentary sequences.

The existence of Variscan and Caledonian metamorphism is demonstrated by U–Pb zircon dating; we, however, lack detailed studies to determine the P-T-t paths of the two orogenic events. For the Caledonian orogenic cycle, the existence of an eclogitic stage is well accepted, but the precise age of this eclogite metamorphism remains unclear. Combining microstructural, petrological and geochemical information with high-precision geochronology of different geochronometers (zircon, titanite, garnet) from rocks that were shielded from the influence of later metamorphic events would allow to gain new evidence on the timing of the Variscan and Caledonian metamorphic overprints.

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