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Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution

by *Dieter Gebauer*[1]

Abstract

Modern geochronological data reveal a complex geodynamic evolution for the Western and Central Alps that differs significantly from models described previously. After rifting of the Variscan basement until the Triassic, formation of Jurassic oceanic crust is now documented reliably by an increasing amount of geochronological data. For the Piemont-Ligurian ocean ages of c. 160–166 Ma have been obtained so far. The U–Pb zircon data suggest that the oceanic crust was restricted to a narrow basin. This follows from the presence of inherited zircons of probable crustal origins in various magmatic and sedimentary members of the ophiolitic rocks.

SE directed subduction of continental crust of the Sesia-Lanzo Zone started 76 Ma ago and reached maximum burial under HP metamorphic conditions 65 Ma ago. This is clearly younger than the c. 100 Ma old orogeny in the Eastern Alps which led to west-directed imbrication of the Austroalpine nappes.

Further movement of the Gondwana-derived Apulian plate towards the NW, now also including the newly amalgamated Sesia-Lanzo crust, resulted in subduction of oceanic crust of the Piemont-Ligurian ocean. This reached HP and UHP peak metamorphic conditions c. 44 Ma ago.

The age of subduction of the Briançonnais is not yet precisely defined, but probably occurred in the time span 35–40 Ma. Subduction metamorphism up to UHP conditions was reached at c. 35 Ma in the the Internal Massifs (Dora-Maira, Monte Rosa) which, according to numerous authors, belong to the Briançonnais.

After closure of the Valais basin, European crust – of Gondwana affinity like the whole Western and Central Alps – was subducted and reached peak metamorphic conditions at c. 33 Ma. This is best documented in the Adula-Cima Lunga nappe. Mafic/ultramafic rock associations (e.g. at Alpe Arami and Cima di Gagnone) originated from greater depths and reached peak metamorphic conditions slightly earlier, at c. 35 Ma. Tectonic intermingling with rocks of the Adula-Cima Lunga continental crust took place during very rapid exhumation at c. 33 Ma. HP-UHP metamorphism was quasi synchronous in the Adula - Cima Lunga nappe and the Internal Massifs, which favours an alternative hypothesis assigning the Internal Massifs to the European margin. As for all other units mentioned before, thrusting must have been towards the NW.

Alpine magmatism started around 31.5 Ma (Bergell tonalite) and reached a maximum at c. 30 Ma. The last granitoids are c. 25 Ma old, e.g. the Novate granite and pegmatites/aplites in the southern steep belt. At least for the southern Lepontine Alps this magmatic and fluid activity led to reheating and to partial or complete resetting of many mineral ages. Depending on the individual exhumation history of the different tectonic units, cooling below c. 100 °C occurred between c. 25 Ma (Sesia-Lanzo Zone) and 1.4 Ma (Mont Blanc Massif).

Keywords: geochronology, Alpine orogeny, geodynamic evolution, Central Alps, Western Alps.

1. Introduction

Almost 40 years of geochronological work in the Western and Central Alps have resulted in a wealth of information relevant to the geodynamic evolution of the Alps and the continental crust on which they are built. In this review, dealing with the Alpine evolution since the Middle Jurassic, a selection had to be made in order to restrict this topic to the most relevant and reliable data. Naturally, such an attempt is subject to the individual judgement and prejudices of the author and therefore can only be as objective as individuals can be. Nevertheless, ongoing progress in analytical techniques, data interpretations and geological/petrological understanding has allowed

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geodynamic evolutions of orogens to be constrained much better today than only about 10 years ago. The Alps are a good example of this as major progress has been possible in the last few years that has drastically changed, modified and – as usual if things are understood better – led to a more complex and more detailed geodynamic view on the Alpine orogen. Many of the interpretations given below are also based on progress in other disciplines, especially petrology, structural geology and geophysics. Thus, we can now quantify parameters such as subduction and heating rates, exhumation and cooling rates, rates of mass and heat transfer or duration of deformation episodes much better than only several years ago. As a consequence of the new and much better constrained geochronological data, previous model parameters for heat and mass transfer need to be revised. This implies important consequences for the rheological properties of the lithosphere.

Considering specifically the geochronological data base, it must be born in mind that erroneously old ages may readily be obtained from mineral systems if excess radiogenic daughter products are present. This is a notorious problem for any of the different Ar-techniques, usually performed on white micas and hornblendes, and has been substantiated by numerous examples world-wide, especially over the last few years (e.g. KELLEY et al., 1994). In the case of Rb–Sr and Sm–Nd mineral dating, geologically meaningless ages may also be obtained. Disequilibrium within and amongst the analyzed minerals and their inclusions are the major causes for unsuccessful dating attempts (e.g. JAGOUTZ, 1994 or TILTON et al., 1995). Multigrain, or even single grain zircon dating has been known for a long time to give unreliable intercept ages – in our case lower intercept ages that are too old – if more than two zircon phases and/or zircon domains of different age are present in the analyzed fractions or within a dated single zircon grain (e.g. ALLÈGRE et al., 1974; GEBAUER and GRÜNENFELDER, 1979). Thus, SHRIMP-dating based on cathodoluminescence information for the "magmatic or metamorphic spot locations" to be selected, is one of the most powerful techniques for unravelling the expected complex histories of individual zircon grains. Although the analytical precision of SHRIMP-ages is generally smaller by about an order of magnitude when compared to the isotope dilution techniques, this is usually more than compensated by the fact that distinct zircon domains can be dated separately. Typically, at least two and up to four types of zircon domains of different ages occur in the Archean to Late Oligocene zircons of the Central and Western Alps. Mixing of ages can be avoided if concordancy of different domains can be demonstrated statistically. As a consequence, both accurate and detailed information can be obtained on the usually complex age history of zircon domains within one or more zircon crystals. The application of this technique has become particularly desirable considering the existing age dilemma caused by numerous contradictory geochronological results previously obtained in the Western and Central Alps.

In the following, major tectonometamorphic units within the Central and Western Alps are reviewed separately and a model of the geological evolution since the Middle Jurassic will be discussed. This model is largely based on SHRIMP-results obtained by the author and one of his Ph. D. students (Daniela Rubatto). Most of the data and/or results can be found in publications (GEBAUER, 1996; GEBAUER et al., 1997; RUBATTO et al., 1998), in extended and regular abstracts (e.g. GEBAUER et al., 1992a; GEBAUER, 1994; RUBATTO and GEBAUER, 1997; RUBATTO et al., 1995 and 1997; GEBAUER and RUBATTO, 1998) or in the Ph. D. Thesis of D. Rubatto (1998). Some publications are in review (RUBATTO et al.) or in preparation (RUBATTO and GEBAUER). As the few Alpine age data available for the Helvetic zone, the Prealps and the External Massifs are reported by FREY and FERREIRO MÄHLMANN (1999, this volume), they are omitted here.

2. The Lepontine area

Numerous geochronological data are available for the Lepontine and the Bergell Alps, key areas for the understanding of complex Alpine orogenic processes. As ascent, emplacement and exhumation of the Bergell intrusives took place during a sequence of important, post-nappe deformational stages (see e.g. BERGER et al., 1996 and references therein), the exact timing of these intrusions in relation to regional metamorphism is of special significance. Furthermore, comparisons with age data from other parts of the southern steep belt, particularly with data from the Adula-Cima Lunga nappe system are of special importance. This is so, as in its southern part, probably representing the southernmost part of the European continental margin, Alpine subduction of continental crust reached its maximum depth. The preservation of UHP mantle rocks within the Adula-Cima Lunga nappe system, cut by the Bergell intrusives (for details see e.g. SCHMID et al., 1996b), supplies important constraints for the calculation of exhumation- and cooling rates in this part of the Alps –

provided that reliable age data exist for the various stages of exhumation. Thus, this part of the Alps has always attracted many earth scientists and geochronological data have existed now for about 40 years.

2.1. THE BERGELL INTRUSIVES AND THEIR RELATIONSHIPS TO ALPINE METAMORPHISM AND DEFORMATION

The most reliable age data on the older part of this composite pluton, the tonalites, are U–Pb and Th–Pb data obtained on zircon and allanite giving 31.88 ± 0.09 Ma and 31.5 ± 0.35 Ma, respectively (VON BLANCKENBURG, 1992). Interestingly, K–Ar biotite and zircon fission track dating of a tonalite boulder within the oldest (Rupelian) part of the Gonfolite Group between Lago di Como and Lago Maggiore also gives ages of 31.8 Ma (GIGER, 1991). Based on textural evidence, this boulder was interpreted to be derived from shallow levels of the intrusion, implying that the tonalite was emplaced and solidified quasi simultaneously over a vertical distance of c. 20–25 km. Identical results were also obtained for the Sondrio pluton, Veltlin (GIGER, 1991). As the tonalite is generally regarded as syntectonic with respect to the post-nappe refolding episodes (e.g. PUSCHNIG, 1996), these data are also crucial for the timing of major deformation episodes. In a recent study, allanite and zircon ages were obtained from a sample taken at the western termination of the tonalite close to Bellinzona (OBERLI et al., 1996). Based on U–Pb and Th–Pb ages of zircon and allanite ranging from 32.0 Ma to c. 28 Ma, the authors suggested the possibility that this age range reflects the magmatic crystallisation history of the tonalite magma. However, if crystallization of the tonalite really lasted 4 Ma until c. 28 Ma, problems arise with the timing of both regional metamorphism and deformation as well as with the age of the post-tectonic granodiorite (c. 30 Ma) that is clearly not metamorphic.

A cumulitic gabbro enclosed in the tonalite gave "ages" between 31.3 Ma and 31.7 Ma (VON BLANCKENBURG, 1992) that are consistent with the 31.5 ± 0.35 Ma Th–Pb allanite age of the tonalite (VON BLANCKENBURG, 1992). Thus, this age may presently be the best estimate for the age of the tonalite. The discrepancy of the 31.88 ± 0.09 Ma zircon data of the tonalite with the very slightly younger zircon ages of the gabbro (31.3 Ma to 31.7 Ma) occurring within the tonalite may be explained with minor inherited Pb within zircon cores of the tonalite. Zircon cores do occur in the tonalites (VON BLANCKENBURG, 1992), especially in the much larger granodioritic part of the Bergell pluton. For the latter, the data set (U–Pb on titanite, thorite and an undefined Th–U phase as well as U–Pb and Th–Pb on allanite) is fortunately more homogeneous in that the average age of this post-tectonic rock can be given as 30.15 ± 0.21 Ma (see detailed compilation of literature data by HANSMANN, 1996). Also here pebbles of granodiorites from the Gonfolite group, derived from a subvolcanic provenance, yielded identical K–Ar biotite ages (GIGER, 1991) suggesting, as for the tonalite, rapid emplacement and solidification of the granodioritic magma.

As regards the post-magmatic cooling history of the pluton, a differentiation between its eastern part, emplaced into a depth of about 18 km, and its western part, intruded into a depth of about 27 km (REUSSER, 1987), has to be made. A second distinction has to be made between more or less synchronous cooling of the tonalite and its gneissic country-rocks in the western part of the intrusion and cooling histories of tonalite and granodiorite that are different from the country-rocks in the eastern part. Finally, the intrusion of the Novate granite around 25 Ma (KÖPPEL, pers. comm. 1996; GIGER, 1991), together with numerous 25 Ma to 29 Ma old granitic, aplitic and pegmatitic melts (GEBAUER, 1996; ROMER et al., 1996) observed throughout the southern steep belt, necessitates a further differentiation of the cooling history for areas outside the southern steep belt. These complications will be discussed in the next paragraphs.

2.2. LEPONTINE REGIONAL METAMORPHISM

Good approximations for the timing of the Lepontine temperature peak(s) are still scarce. A leucosome, probably formed by decompressional melting from a Variscan granite in the Alpe Arami area (Adula-Cima Lunga nappe), has been dated at 32.4 ± 1.1 Ma (GEBAUER, 1996). Similarly, metamorphic zircon domains from a country-rock gneiss of the Cima di Gagnone ultramafic/mafic HP-rocks yielded 33.0 ± 0.6 Ma (GEBAUER, 1996). Four quasi concordant titanite ages from the Melirolo augengneiss south of Bellinzona gave 32.8 ± 0.7 Ma (ROMER et al., 1996) assuming a correct common Pb correction via the analyzed K-feldspar. If this age is related to metamorphism and cooling of a Variscan protolith, it may approach the Alpine T-peak as detected by SHRIMP-dating in the southern steep belt and immediately to the N of it (Cima di Gagnone). Otherwise, it may be the age of the synmetamorphic, Alpine protolith of the augengneiss and thus be genetically related to the equally synmetamorphic tonalites with which it is in direct contact. Whatever interpretation is correct, the titanite age – although slightly uncertain due to uncertainties with the common lead correction – is in good agreement with the zircon domain data from the Alpe Arami and Cima di Gagnone areas. Thus, however one pools the data set, the T-peak in these areas is likely to be bracketed between 32.4 Ma and 33.0 Ma, i.e. around 32.7 ± 0.3 Ma (Fig. 1). Interestingly, K/Ar mica ages obtained on gneissic Central Alpine boulders with an "epi- to mesozonal, metamorphic overprint" within the Lombardian Gonfolites also do not exceed 33 Ma (GIGER, 1991).

In an approach to dating the Lepontine metamorphic peak, VANCE and O'NIONS (1992) dated garnet cores and rims using both the U–Pb and Rb–Sr techniques. Samples were from the western part of the Lepontine dome close to the staurolite isograd, i.e. the obtained ages were interpreted as dating metamorphic growth below the blocking temperature of the applied systems. For the garnet cores both techniques yielded concordant ages at 32.5 ± 1.4 Ma and 32.0 ± 1.9 Ma. For the garnet rims discordant data were obtained. Setting aside known problems concerning the dating of inclusions in garnet, these ages still agree with the more precise U–Pb ages discussed before. A 32–33 Ma age for the metamorphic climax within at least most of the Lepontine gneiss dome is therefore indicated. In the same paper VANCE and O'NIONS (1992) also published Sm–Nd data on garnets from the Castione quarry (southern steep belt NW of Bellinzona) that gave 26.7 ± 1.7 Ma, interpreted to reflect peak metamorphic conditions. Thus, this interpretation of the Sm–Nd data from Castione is not in agreement with the conclusions on the age of the Lepontine metamorphic peak as discussed above. An explanation, involving partial or complete resetting during a 25 Ma old thermal and fluid event, is given two paragraphs below.

Assuming the age of the Bergell tonalite to be 31.5 Ma (GIGER, 1991, VON BLANCKENBURG, 1992), it intruded c. 1 Ma after regional Alpine peak metamorphic conditions. This is in line with its post-nappe, but synmetamorphic setting, as derived from structural and petrological evidence. It coincides with a period of fast exhumation rates demonstrated by the existence of tonalite boulders in the Oligocene molasse sediments. Based on mineral ages of these tonalite boulders, cooling rates of c. 50 °C/Ma were calculated by GIGER (1991). Similarly, cooling rates around 50 °C/Ma and exhumation rates of 5–7 km/Ma (= 5–7 mm/a) were derived from zircon domain data for that time interval in the Alpe Arami and Cima di Gagnone areas within the Adula-Cima Lunga nappe (GEBAUER, 1996). This is of particular interest, as no other nappe of the Central Alps records such extreme subduction-related metamorphism.

The exhumation and cooling history after about 30 Ma, especially in the southern steep belt, is obscured by the emplacement of numerous granitic, aplitic and pegmatitic veins and concomitant fluid circulation that altered and reset many zircon rims within a variety of ultramafic to felsic rock types 25 Ma ago (GEBAUER, 1996). The Novate granite is the largest exposed representative of this magmatism but similar granitoid bodies, that fed the numerous granitoid veins, may well occur below the present erosion level. One pegmatite, c. 8 km NE of Bellinzona, has been dated at 25.1 ± 0.6 Ma (GEBAUER, 1996), while others may range up to 29 Ma (ROMER et al., 1996). It is very likely that not only zircon rims have been affected by thermal and fluid events, especially the 25 Ma old episode. This is expected to have a much greater effect on other mineral systems such as the K–Ar hornblende- and mica systems, Rb–Sr mica- as well as U–Pb monazite or Sm–Nd mineral systems. Thus, "ages" obtained by these techniques (e.g. KÖPPEL and GRÜNENFELDER, 1975 and 1978; DEUTSCH and STEIGER, 1985; VON BLANCKENBURG, 1990; VANCE and O'NIONS, 1992), frequently ranging from c. 28 Ma to 25 Ma, may well be partially or fully reset. Therefore, in contrast to previous interpretations, these ages are interpreted here to be unrelated to regional Alpine peak metamorphism in the southern steep belt. The fact that the c. 30 Ma old Bergell granodiorite, for example, does not show any signs of this apparently very young Lepontine peak metamorphism around 25–28 Ma, is in line with a regional metamorphic peak in the Lepontine that pre-dates the Bergell granodiorite. The same probably even holds true for the tonalite that postdates peak metamorphism by only about 1 Ma, explaining its high-grade metamorphic transformation in its deepest, westernmost part. Similar to many hornblende, white mica, monazite and garnet ages, biotites that usually give ages around 19 Ma for the southern steep belt (see e.g. compilations by HUNZIKER et al., 1992; HANSMANN, 1996) do, in a strict sense, not reflect undisturbed cooling after the regional Lepontine metamorphism, but are shifted to younger "ages". This is also true for the zircon, and to a minor degree for apatite fission track data, yielding c. 18 Ma and 11 Ma, respectively. Thus, cooling to the presently accepted annealing temperatures of c. 250 °C and c. 100 °C must also be disturbed and variably governed by the post-Lepontine reheating in the southern steep belt. A further, so far unexplained bias may be additionally introduced by a thermal event suggested, for example, by monazite ages around 21 Ma to the north of the southern steep belt (KÖPPEL and GRÜNENFELDER, 1975 and KÖPPEL, pers. comm.). Such young ages, also known from a white mica age of the Sion-Courmayeur Zone in the Rhone valley (MARKLEY et al., 1998), may result from reheating (± deformation) during extensional tectonics juxtaposing hotter footwall against cooler hanging wall rocks.

Exhumation and cooling of the eastern part of the Bergell intrusives is generally believed to have occurred before that of the western part. This is largely based on biotite K–Ar ages yielding c. 28 Ma (HUNZIKER et al., 1992; GIGER, 1991), i.e. ages about 9 Ma older than in the western part of the Bergell and the southern steep belt. Two arguments caution against this assumption: 1) The lack of a predominantly 25 Ma old reheating event after the Lepontine peak that reached only c. 450 °C and c. 6 kbar (GUNTLI and LINIGER, 1989) in this eastern part of the Bergell. 2) Identical ages of high-level tonalite and granodiorite in boulders and of the same rocks in place, suggest that both rocks crystallized quasi synchronously over a vertical distance of at least 9 km. The boulders occur in the lower part of the Chiasso Formation, deposited, according to modern stratigraphic time scales and BERNOULLI et al. (1993), 27–30 Ma ago. A more or less simultaneous crystallization of the Bergell intrusives over large vertical distances is in line with the petrological data of REUSSER (1987). As emplacement and crystallization probably happened during fast exhumation (see discussion above), exhumation and cooling started or continued more or less simultaneously, however, when viewed in an E–W profile, in different levels of the crust. Under these circumstances, upper greenschist facies peak conditions in the East do not necessarily have to be significantly older than upper amphibolite facies peak conditions in the western part of the tonalite, or in the southern steep belt in general. Depending on the hypothesis chosen for the cause of the Lepontine metamorphism (see FREY and FERREIRO MÄHLMANN, 1999, this volume), they may even be younger. However, this can not exceed c. 2.5 Ma, assuming a post-peak metamorphic crystallization of the granodiorite at 30.15 ± 0.21 Ma.

2.3. HP- AND UHP METAMORPHISM IN THE ADULA-CIMA LUNGA NAPPE SYSTEM

Numerous boudinaged peridotite and eclogite bodies occur in gneisses of the Alpine Adula-Cima Lunga nappe system. Thermo-barometric data (e.g. EVANS and TROMMSDORFF, 1978; HEINRICH, 1986) demonstrate a significant P and T increase towards South and low, i.e. subduction-related geothermal gradients. At Alpe Arami (AA) the peridotites seem to have undergone ultra-high pressure (UHP) metamorphism (35–42 kbar, 850–900 °C; BECKER, 1993 and references therein) while at Cima di Gagnone (CdG) this is arguable (EVANS and TROMMSDORFF, 1978; BECKER, 1993).

As seen in figure 1, the oldest Alpine stage, detected so far in only a few magmatic but also metamorphic domains within zircons of two garnet-pyroxenites and one eclogite at AA, give analytically indistinguishable ages at c. 43 ± 2 Ma (GEBAUER, 1996). Identical ages were also obtained from metamorphic zircon domains of a peridotite at CdG (GEBAUER, 1994). As at least the CdG rocks are very likely subduction-related – the low pressure protoliths of the eclogites are probably part of a Cambrian ophiolite suite (GEBAUER, 1994) – this Middle Eocene stage may be related to incipient melting and/or subsolidus re-equilibration at prograde HP or UHP conditions. The cause for prograde melting and/or subsolidus re-equilibration may be found in fluid percolation as a result of dehydration reactions within the subducting slab. For the AA pyroxenites, the presence of numerous inherited zircons of probable crustal origin argues for an enrichment of the mantle by crustal material. These locally enriched portions of the mantle may then preferentially melt intergranularly during prograde subduction metamorphism, especially if fluids from the dehydrating slab were present.

The best documented ages at AA, very probably related to HP-decompressional melting (T > 1000 °C and P > 30 kbar) of the mantle source, are 35.4 ± 0.5 Ma. They were obtained from predominantly magmatic zircon and zircon zones of the garnet-pyroxenites, the primary magmatic eclogites and one peridotite and imply, based on the data in figure 1, exhumation rates > 2 cm/a (GEBAUER, 1996). At CdG this age was found in metamorphic zircon domains in the grt-peridotite that do not show any undisturbed and concentric, oscillatory growth zoning (GEBAUER, 1994). This indicates that they did not precipitate freely within a melt. The same holds true for the magmatic, Cambrian zircons of the eclogite at CdG that not only contain metamorphic domains at 35 Ma, but also even younger ones at 30 Ma ± 1.5 Ma. The latter might have formed as a result of destabilization of pyroxene during amphibolite facies retrogression.

The Cambrian age of the low-pressure protoliths of the CdG eclogite is in good agreement with a 521 ± 8 Ma protolith age of an amphibolite at the Simano-Leventina nappe boundary near Biasca (GEBAUER, 1993 and 1994). This rock is also associated with ultramafic rocks (Loderio) and has a very similar geochemical signature to the corresponding CdG eclogites (SCHALTEGGER, pers. comm.). Thus, apart from the different mantle origins and depths of partial melting of the ultramafic rocks at AA and CdG, their protolith ages are also grossly different.

Tectonic intermingling of the cooling peridotite and its enclosed partial melting products with the felsic country-rocks at AA must have occurred during still rapid exhumation and cooling (c. 2 cm/a, resp. c. 67 °C/Ma) between 35.4 Ma and 32.4 Ma under probable granulite facies conditions (see Fig. 1). Identical age signatures at 33 Ma in zircon domains of both mafic/ultramafic and felsic country-rocks lead to this conclusion. Once the mantle- and crust-derived rocks at AA were tectonically juxtaposed, left mantle depths and reached levels of the continental crust, exhumation rates decreased considerably from about 2 cm/a to about 0.23–0.20 cm/a. Apparently, cooling rates have increased between 33.4–32.4 Ma to about 100 °C/Ma and then, after migmatization of the metagranitic country-rocks of the peridotite at 32.4 Ma, decreased to c. 40 °C/Ma. These changes of exhumation, and possibly also cooling rates, may have been caused by the introduction of the hotter ultramafic/mafic rock assemblage into cooler country-rocks, that were subducted to less extreme P-T conditions than the peridotites. Similarly to the peridotites, the country-rocks also partially melted during fast exhumation, but c. 3 Ma later than the peridotite and under considerably lower P-T conditions.

At CdG, the probable T-peak of Alpine metamorphism in the metasedimentary country rocks occurred at 33.0 ± 0.6 Ma, as at AA. This age was obtained within metamorphic zircon domains typical for granulite-facies conditions surrounding detrital zircon cores (GEBAUER, 1994).

A final pulse of reheating at 25.1 ± 0.6 Ma, not detected at CdG, is caused by considerable mag-

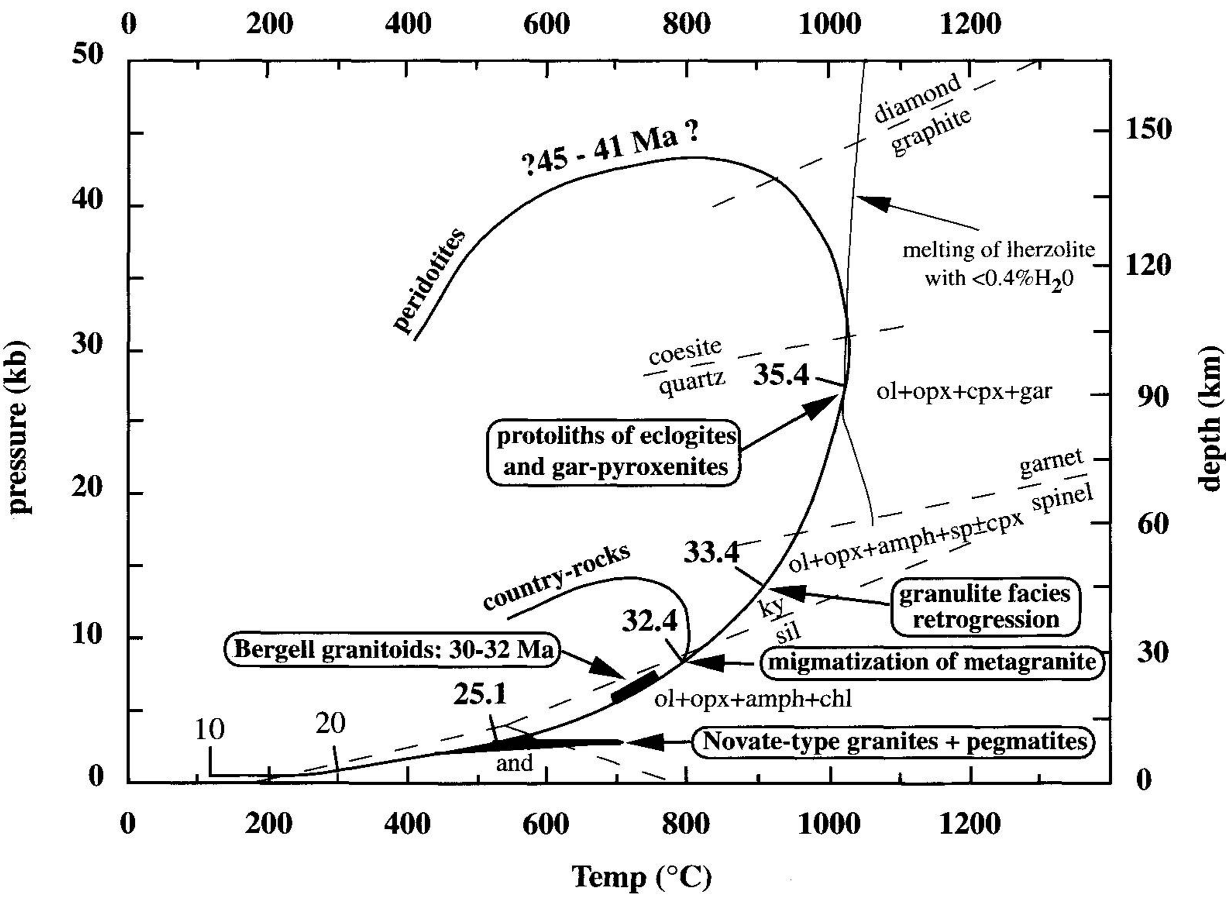

Fig. 1 P-T-t path for ultramafic/mafic as well as felsic rocks of the Alpe Arami area (southern steep belt within the Cima Lunga-Adula nappe system). Very similar paths exist also for ultramafic/mafic as well as felsic rocks of Cima di Gagnone, however at lower P-T conditions for the mafic/ultramafics (GEBAUER, 1994). For further explanation see text. From GEBAUER (1996).

matic and fluid activity after formation of the southern steep belt. It was determined by dating a late pegmatite that cut the subvertical structures of the gneisses of the southern steep belt and by numerous rims around zircons of granitic, mafic and ultramafic rocks (GEBAUER, 1996). This reheating event in the Upper Oligocene is probably also responsible for formation of sillimanite after andalusite (KLEIN, 1976). It is interesting to note here that, based on petrological data, reheating at similar depths (ca 10 km) was also described for the Internal Massifs of the Western Alps (BORGHI et al., 1996). Thus, many mineral ages, at least in and around the Lepontine gneiss dome, may have been partially or fully rejuvenated by this or even younger reheating and/or fluid circulation. This important point will be addressed in the final section of this paper.

Assuming subduction of the Lepontine gneisses into the mantle transition zone (DOBRZHINETSKAYA et al., 1996) and even assuming the improbable survival of these fluid-bearing rocks at temperatures of c. 1600 °K (Fig. 4 in DOBRZHINETSKAYA et al., 1996), the ultramafic/mafic as well as the buoyant country-rocks of AA rocks must have been exhumed from 400–670 km to c. 20 km depth within only about 2–3 Ma. It is important to note that, in contrast to their host rocks, zircons and their U–Pb systems can fully or partly survive at such extreme T-conditions (see e.g. GEBAUER, 1990). Thus, the 35 Ma old zircons and zircon domains in the garnet-peridotites, garnet-pyroxenites and eclogites would be expected to have formed close to the T-peak, i.e. within the transition zone. The apparently 2–3 Ma lasting exhumation from the transition zone is more than one order of magnitude faster than the already "blasphemously" fast, but consistent exhumation rates of c. 8 km/Ma (= 8 mm/a) that have also been detected recently in the Rhodope complex of northern Greece (GEBAUER and LIATI, 1997) or the Himalaya (> 13 km/Ma; SPENCER and GEBAUER, 1996). Recent P-T estimates for all of these areas, including AA, imply exhumation and cooling rates similar to those also found for the continental crust of the Dora-Maira Massif (c. 22 km/Ma and 85–100 °C/Ma), which was buried to depth of c. 130 km (GEBAUER et al., 1997 and below). Apart from other factors like U–Pb systematics in zircon, metamorphic new growth under granulite facies conditions, etc., the geochronological arguments do not support an origin of the AA peridotites in the mantle transition zone.

The Sm–Nd data of BECKER (1993) are of special interest for comparison with the ionprobe study as the analyzed rocks were also sampled at Alpe Arami and Cima di Gagnone. The best concordance between ionprobe and Sm–Nd data exists for the eclogites at Alpe Arami. BECKER (1993) reported a whole-rock (WR), cpx, grt-isochron, yielding 37.5 ± 2.2 Ma, that is analytically indistinguishable from the SHRIMP-age of c. 35.8 ± 2.8 Ma for the magmatic zircons in this primary magmatic eclogite and the more precise ages of 35.4 ± 0.7 and 35.4 ± 0.8 for the garnet-peridotite and garnet-pyroxenite zircons. In contrast, the Sm–Nd data (WR, cpx, grt) from a garnet-pyroxenite are significantly older, 44 ± 5.7 Ma. The Sm–Nd data of two garnet-peridotites are also very slightly older than the zircon ionprobe data that gave 35.4 ± 0.7 Ma. In one case BECKER (1993) obtained 40 ± 3.6 Ma and in the second sample an errorchron resulted. The corresponding grt-cpx tie line, excluding the whole-rock data point, gave 40.6 ± 3.7 Ma. Thus, the Sm–Nd data by themselves indicate the presence of disequilibrium. For a more detailed discussion of the Sm–Nd data see GEBAUER (1996).

3. The Internal Massifs

3.1. THE COESITE-BEARING UNIT OF THE DORA-MAIRA MASSIF (DMM)

Ion-microprobe (SHRIMP) data for zircons were recently published by GEBAUER et al. (1997) for various rock types of the coesite-bearing unit of the Dora-Maira Massif: 1) a whiteschist-type pyrope-quartzite; 2) a jadeite-rich layer as well as 3) a phengite-schist inclusion within pyrope quartzite; 4) a 15 cm pyrope megablast within a pyrope quartzite and; 5) a biotite-phengite gneiss, the metagranitic country-rock of the whiteschists. All the above rock types can be shown to have undergone HP- or UHP-metamorphism with maximum P-T conditions reaching 37 kbar at about 800 °C (SCHERTL et al., 1991).

Except for the biotite-phengite gneiss, zircons from all other rocks analyzed contain metamorphic domains or domains (or whole crystals) of magmatic aspect that formed at 35.4 ± 1.0 Ma (Late Eocene). The Alpine oscillatory zoned crystals or crystal domains probably precipitated from an interstitial UHP-melt (or a supercritical fluid approaching a partial melt composition).

Small, 35 Ma old metamorphic domains also occur at or around apparent coesite and high-Si phengite inclusions in zircon that probably formed magmatically at c. 275 Ma. Thus, these "UHP-inclusions" must have entered the zircons along cracks during or close to the UHP-peak causing partial or complete recrystallization of the magmatic zircon domains. They were then armoured by the surrounding zircon and thus survived retrogression during exhumation. About 275 Ma is the most probable age of the magmatic protoliths of all analyzed rock types. The data suggest that the protoliths of the whiteschists are the Permian granitoid country-rocks that were locally metasomatized during rift-related fluid circulation and shearing to form "leucophyllites" (chlorite-muscovite-quartz schists) around 210–260 Ma ago.

The data do not supply any evidence for a geological event around 100 Ma, the "age" of UHP-metamorphism as inferred from conventional, multigrain zircon dating (PAQUETTE et al., 1989) or various Ar-dating techniques (e.g. MONIÉ, 1984; SCAILLET et al., 1990, 1992; MONIÉ and CHOPIN, 1991). The existence of oscillatory zoned 35 Ma old zircons as well as resorbed zircons confirms the conjecture of SCHERTL et al. (1991) that partial melting occurred during subduction zone metamorphism. It further argues strongly against the assumption that greenschist facies conditions were not exceeded in the Tertiary.

Existing mica and fission track ages of the dated rocks (TILTON et al., 1991; GEBAUER et al., 1997), yielding ages at c. 29 Ma for the greenschist facies overprint, together with the SHRIMP- and thermo-barometric data, allow estimates of exhumation and cooling rates. Calculated for cooling to c. 300 °C at c. 10 km depth, the resulting values are 20 km/Ma (= 2 cm/a) at an average cooling rate of c. 80 °C/Ma. As mentioned before, these figures are similar to those for the Adula nappe in the Central Alps (GEBAUER, 1996) or for HP-rocks of the Himalaya (SPENCER and GEBAUER, 1996). The exhumation-related geothermal gradient between c. 800 °C and 300 °C yields c. 4 °C/km for the dated UHP-rocks, in perfect agreement with the petrologically derived data of SCHERTL et al. (1991).

The 35 Ma year old UHP metamorphism in the DMM conforms well with SHRIMP data for another Internal Massif of the Western Alps, the Monte Rosa Massif. It also agrees well with the previously discussed UHP-HP metamorphism at Alpe Arami and Cima di Gagnone in the Adula-Cima Lunga nappe system. Cooling below c. 300 °C was coeval in both the Dora-Maira and the Gran Paradiso Internal Massifs at c. 29–30 Ma (HURFORD et al., 1991; GEBAUER et al., 1997). Thus, these four different units are likely to be of similar paleogeographic origin (southernmost European margin) and therefore suffered a similar Alpine subduction episode. However, due to the 25 Ma old reheating in at least the southern steep belt of the Lepontine, undisturbed or less disturbed cooling can only be detected outside the Lepontine. Here, it apparently took about 5–6 Ma after the T-peak to reach cooling below c. 300 °C. Thus, assuming similar post-peak cooling rates in the Adula nappe of the southern steep belt, the DMM, the Gran Paradiso and the Monte Rosa Massifs, the southern steep belt cooled to c. 300 °C somewhere between c. 25 and 29 Ma, taking the extreme error margins of the SHRIMP-data. This is in agreement with inferences made from the P-T-t paths derived for the Alpe Arami and Cima di Gagnone areas of the Adula-Cima Lunga nappe (GEBAUER, 1994 and 1996). It additionally argues against assumptions of a c. 28 Ma old T-peak in the southern Lepontine. The petrologically deduced reheating after the subduction-related Eocene P-T peak in the Internal Massifs took place at considerably lower temperatures (< 500–550 °C; BORGHI et al., 1996) than in the southern steep belt and the areas immediately to the N of it. The few Rb–Sr and Ar–Ar data in the Monte Rosa nappe for example, giving biotite ages between c. 22–26 Ma (HUNZIKER and BEARTH, 1969; MONIÉ, 1985), may be a consequence of this reheating event. At present, the most plausible cause for this reheating episode may be hot asthenospheric counterflow after delamination of subducted lithosphere (e.g. VON BLANCKENBURG and DAVIES, 1995). However, in contrast to VON BLANCKENBURG and DAVIES (1995) slab delamination is thought to have occured at c. 40 Ma, the beginning of rapid exhumation from mantle depths (Fig. 1). Re-equilibration of middle to upper crustal isotherms after reheating must have therefore been completed after 25 Ma (Fig. 1).

3.2. THE MONTE ROSA MASSIF

Like the other Penninic domains of the Western and Central Alps, the Monte Rosa Massif was also believed to have undergone HP-metamorphism in the Early Cretaceous. This was based on Rb–Sr whole-rock data of HUNZIKER (1970) on strongly sheared orthogneisses that gave 120 ± 20 Ma. An Ar–Ar phengite-date of 110 ±3 Ma was obtained by CHOPIN and MONIÉ (1984). Together with further Ar–Ar data on a second generation of phengite and phlogopite giving 65 Ma, MONIÉ (1985) argued for a 110 Ma subduction event followed by a 65 Ma old blueschist facies overprint in the Monte Rosa Massif.

Rb–Sr data on a high-pressure "metapelite" gave an apatite-whole-rock "age" of 102 ± 2 Ma, while the apatite-phengite pair gave 91 ± 2 Ma (PAQUETTE et al., 1989). The latter "age" was thought to be partially reset during the 65 Ma blueschist facies overprint proposed by CHOPIN and MONIÉ (1984). The data were nevertheless interpreted to "confirm the existence of a mid-Cretaceous high-pressure metamorphic event in the Monte Rosa massif". U–Pb multi-grain zircon data on the same "metapelites" by the same authors were correctly discarded. Both upper intercept "age" (891 +73/–67 Ma) and lower intercept "age" (192 ± 5 Ma) are clearly an artefact due to the presence of at least 3 different zircon domains and/or populations.

Based on the arguments given in the introduction, these contradictory data cannot – apart from the unlikely geodynamic consequences – be considered reliable and so it was necessary to apply better geochronological techniques to constrain the Alpine evolution of the Monte Rosa Massif. A phengite-bearing quartzite of the Gornergrat series, commonly interpreted to belong to the post-Variscan sedimentary cover of the Monte Rosa basement, yielded zircon rim SHRIMP-ages at 34.9 ± 1.4 Ma (RUBATTO, 1998; RUBATTO and GEBAUER, in preparation) interpreted to reflect peak metamorphic conditions. Such trace element-poor zircon rims have been observed in numerous other gneissic rocks of the Alps and elsewhere and probably formed as a result of reorientation of the crystal lattice close to the metamorphic peak. The c. 35 Ma age agrees with previous CL-based SHRIMP data for the UHP-unit of the Dora-Maira Massif (GEBAUER et al., 1997) and the Cima Lunga-Adula nappe (GEBAUER, 1996). These data may be taken to argue that the Gornergrat series was correctly interpreted to belong to the cover of the Monte Rosa Massif (e.g. BEARTH, 1952; BEARTH and SCHWANDER, 1981) and that it cannot be related to the thinned continental margin of the Piemont-Ligurian ocean (Zermatt-Saas Zone) that was metamorphosed earlier, i.e. 44.1 ± 0.7 Ma ago (see below). Thus, the Monte Rosa Massif and its sedimentary cover may well be part of the European continental margin, a hypothesis recently put forward also by FROITZHEIM (1997). A more detailed discussion on these problems is given in the next section.

Recent Rb–Sr data of 36 Ma (BUTLER et al., 1996) for a white mica from the Gran Paradiso Massif were interpreted to reflect HP-metamorphism. Although this interpretation fits well with the described scenario, independent confirmation by further data is necessary.

4. Briançonnais

For the middle-Penninic Tambo, Suretta and Schams nappes scattering K–Ar data on micas and hornblende are available (see e.g. compilation by SCHREURS, 1993). Taking concordant Rb–Sr and K–Ar ages (HURFORD et al., 1989; STEINITZ and JÄGER, 1981), the time interval of 35 Ma – 40 Ma may best approach deformation close to peak metamorphic conditions (greenschist facies).

Very recently, Ar/Ar data were reported for synkinematic white micas from the Siviez-Mischabel nappe, the largest nappe of the Gd. St. Bernard nappe system (MARKLEY et al., 1998). Most ages, although significantly different from each other, fall into an age range of c. 36 to 41 Ma. This period of c. 5 Ma was interpreted to reflect the time of nappe emplacement and deformation under greenschist-grade P-T conditions. No correlation of ages with the location of the samples within the nappe can be detected. Younger ages down to c. 20 Ma were interpreted to reflect postkinematic thermal events, i.e. Oligocene magmatism in the lower Penninic nappes or Miocene reheating in the hanging wall of the Simplon fault during extensional faulting. It is suggested here that regional high-grade metamorphism at 32–33 Ma in the Lepontine may be more likely to have affected the mineral ages than Oligocene magmatism. In any case, a Miocene effect seems to be present locally.

Rb–Sr white mica ages are also available for high-strain rocks from the Entrelor/Nomenon backthrust within the Gr. St. Bernard/Briançonnais basement and cover (FREEMAN et al., 1997). Whereas backthrusting under greenschist facies conditions (c. 450 °C) is well constrained at 34 ± 1 Ma, an older event at c. 38 Ma, possibly related to regional metamorphism, was inferred. Similarly uncertain Rb–Sr and Ar–Ar mineral data exist for the Mischabel backfold of the Gr. St. Bernard that range from 35–40 Ma (BARNICOAT et al., 1995). Due to the similarity of the most reliable data of this middle Penninic domain, 35–40 Ma was taken as the most likely age of metamorphism for the geodynamic model shown in figure 2.

It is interesting to note that this age range (35–40 Ma) coincides with the age range derived by various authors for the peak of Alpine metamorphism in the Lepontine Alps (e.g. JÄGER, 1973; JÄGER and HANTKE, 1983; HUNZIKER et al., 1989). The so-called "Lepontine event" at 38 ± 2 Ma has been inferred from a few mica ages outside the staurolite isograd to the West (e.g. HUNZIKER, 1969) and to the East (STEINITZ and JÄGER, 1981) of the Lepontine dome. Inside the staurolite isograd reliable and reproducible ages at 38 Ma do not exist. Due to the lack of such ages in the high-grade metamorphic part of the Lepontine Alps, the term "Lepontine event" was proposed

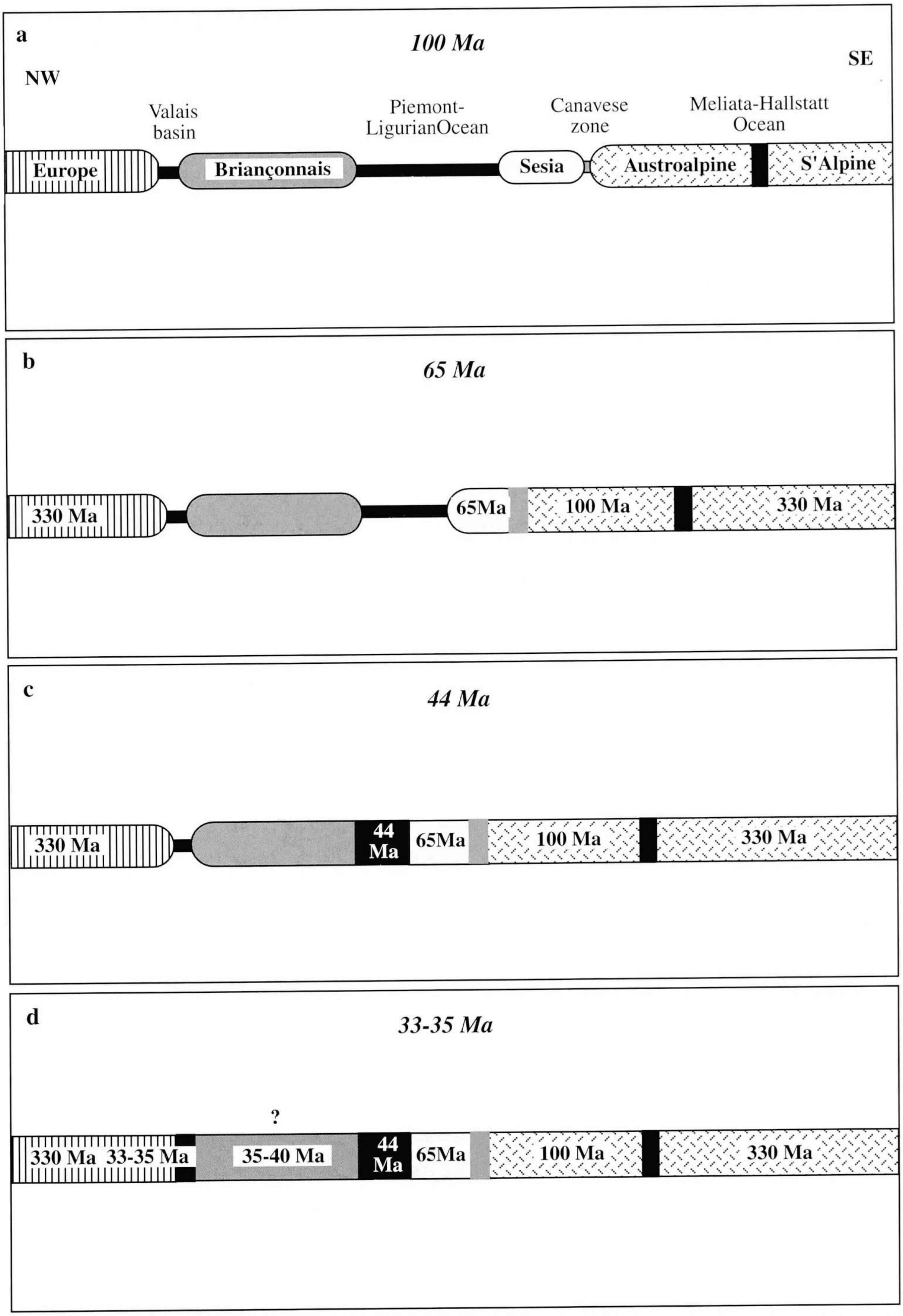

Fig. 2 Schematic cartoons demonstrating a model for the geodynamic evolution of the Western and Central Alps. The Meliata-Hallstatt suture is projected westwards into this profile. Ages refer to subduction induced metamorphism.

to be abandoned and replaced by the term "Meso-Alpine" event (e.g. HUNZIKER and MARTINOTTI, 1984). In any case, the inference of a 38 Ma event for the whole of the Lepontine turned out to be wrong as the temperature peak for the rocks of the subducted European crust was found to be at about 33 Ma (see above). The scattering 35–40 Ma mica ages obtained from the greenschist facies metamorphic rocks, west (see e.g. Fig. 6 of BARNICOAT et al., 1995) and east of the high-grade metamorphic Lepontine dome, are interpreted here as approaching Eocene metamorphic overprinting of the Briançonnais continental crust. Assuming northward movement of the Apulian against the European plate since the Late Cretaceous, the intervening terranes were successively docked starting from the South (Fig. 2). Thus, subduction of the Middle Penninic Briançonnais is expected to be younger than subduction of the South Penninic Piemont-Ligurian-oceanic crust (44 Ma; see next chapter) and older than subduction and subduction-induced metamorphism of the European continental margin (33–35 Ma). The c. 35–40 Ma mica ages found in the low-grade metamorphic Briançonnais of the Suretta and Bernard nappe systems would thus fit well into such a scenario. Uncertainty remains as to the distinction of tectonic units (e.g. Monte Rosa or Dora-Maira) that may be derived from the Briançonnais or the southern European continental margin. Geochronologically, it would fit better if the Middle Penninic (Briançonnais) Bernard nappe was rooted south of the Monte Rosa nappe, which may then have formed the southernmost margin of the European plate. The Antrona ophiolites and the Furgg mélange would then represent remnants of the Valais ocean (FROITZHEIM, 1997). Obviously, geochronological data for both protolith ages and peak metamorphic conditions of subducted Valais trough rocks, especially of the ophiolites, are highly desirable. This should allow the distinction between Piemont-Ligurian oceanic crust and Valais basin and should also constrain distinct Tertiary subduction episodes in this extremely complex and crucial part of the Alpine orogen.

5. The oceanic rocks of the Piemont-Ligurian ocean

As for most other geological units of the Central and Western Alps, subduction of oceanic crust to HP- or even UHP conditions had been thought to be also Early Cretaceous (see e.g. review by HUNZIKER et al., 1992). Again, CL-based SHRIMP dating has led to a drastic revision of previous views on the subduction history of the oceanic crust exposed in the Pennine realm (RUBATTO and GEBAUER, 1996; RUBATTO et al., 1997). The specific geological unit studied was the Zermatt-Saas Zone (ZSZ), a key area for the understanding of the geodynamic evolution of Mesozoic oceanic relics in the Western and Central Alps. Although Alpine metamorphic temperatures of the ZSZ only reached c. 600 °C, it was still possible to find metamorphic zircon domains within an eclogite and a metasediment at the UHP-locality of Lago di Cignana that yielded 44.1 ± 0.7 Ma. As both pressure (28–30 kbar) and temperature peak (580–630 °C; REINECKE, 1991 and 1995) approximately coincide, this age most probably dates peak metamorphic conditions prevailing during deepest subduction. Similarly, zircons from the Mellichen gabbro in the Täsch valley gave Middle Eocene metamorphic ages, while the comagmatic zircons of this HP-metagabbro yielded 163.5 ± 1.8 Ma. In addition, comagmatic zircons of the possibly UHP-Allalin metagabbro yielded 164.0 ± 2.7 Ma. These Middle Jurassic ages are, together with recent ages for ophiolitic gabbros of the French Prealps (BILL et al., 1997) the first precise, geochronological data on ophiolite formation within the Penninic realm. Inherited zircons in metabasalts and metagabbros may indicate contamination by continental crust. This would argue against typical MORB-scenarios, i.e. the ophiolites were formed in a small oceanic basin, possibly floored or rimmed by thinned continental crust. Such a scenario appears to be in line with the absence of typical sheeted dike complexes all over the ophiolites of the Piemont-Ligurian ocean preserved in the Alps. Alternatively, the zircons detected in the metabasalts and metagabbros may be inherited from mantle sources. In this case, they may have formed in trapped liquids during partial mantle melting events and/or mixed into the mantle during Variscan and/or pre-Variscan subduction of continental or continent-derived rocks. The absence of sheeted dike complexes may then be explained with slow spreading, as e.g. presently observed for the Mid Atlantic ridge (LAGABRIELLE and CANNAT, 1990).

Similar ages (160 ± 8 Ma) on primary phlogopites from two pyroxenites within the Totalp peridotite were obtained in the Eastern Swiss Alps, using the $^{39}Ar/^{40}Ar$ technique (PETERS and STETTLER, 1987). The Penninic Totalp peridotite, metamorphosed under low-grade Alpine conditions, is considered to be of subcontinental origin, exhumed by rifting along a narrow Piemont-Ligurian ocean in the Middle Jurassic (PETERS and STETTLER, 1987). Mantle upwelling is thought to have caused the formation of the pyroxenites 160 Ma ago. The interpretation of a small

Piemont-Ligurian ocean is thus in good agreement with the interpretation made for the ZSZ.

Recently, similar ages, c. 166 Ma (BILL et al., 1997), were obtained also for ophiolitic gabbros of the Gets nappe in the French Prealps arguing that this nappe is also rooted in the Piemont-Ligurian ocean.

The 44.1 ± 0.7 Ma age for UHP (HP) metamorphism in the ZSZ is obviously incompatible with the long believed Lower Cretaceous subduction metamorphism. Moreover, the further subdivision of the Eo-Alpine orogeny into an early, eclogitic phase (140–85 Ma) and a late, glaucophane-bearing phase (85–60 Ma; HUNZIKER et al., 1992) is incompatible with the new data.

The SHRIMP-data are much more precise than a first Sm–Nd mineral isochron (52 ± 18 Ma) obtained by BOWTELL et al. (1994). Recent improvements in this technique, mainly in terms of garnet purification, resulted in ages of 44 ± 3 Ma (AMATO et al., 1997), respectively 40 ± 4 Ma (AMATO, pers. comm.). These data now agree much better with the SHRIMP-data (44.1 ± 0.7 Ma). Rb–Sr phengite ages from retrogressed eclogites (BARNICOAT et al., 1995) gave 44.6 ± 1 Ma and 42.3 ± 1.4 Ma, respectively and agree with the corresponding $^{39}Ar/^{40}Ar$ ages. These ages were interpreted to date either phengite growth or very rapid cooling after growth.

The Monviso ophiolites, to the W of the internal Dora-Maira Massif, have been studied recently by both the Sm–Nd and Rb–Sr techniques (CLIFF et al., 1998). Two grt-cpx ages of two eclogites (400–500 °C/20 kbar) gave 60 ± 12 Ma and 62 ± 9 Ma, respectively. Two phe-cpx Rb–Sr ages from two different samples gave slightly discordant ages of 41.6 ± 0.4 Ma and 39.2 ± 0.8 Ma, respectively. The authors imply "that high pressures may have persisted in these rocks for up to 20 Ma". Obviously, the c. 61 Ma Sm–Nd ages are in conflict with the data discussed before as the Monviso ophiolites are accepted, as the Zermatt-Saas-Fee ophiolites, to be also part of the Piemont-Ligurian ocean. Similarly, $^{39}Ar/^{40}Ar$ ages on phengites of Monviso gabbros, yielding c. 50 Ma (MONIÉ and PHILIPPOT, 1989), were problematic when compared to the SHRIMP and especially the Sm–Nd data. Accepting the fact that due to the possible presence of excess Ar, $^{39}Ar/^{40}Ar$ mineral ages are maximum ages, the c. 61 Ma Sm–Nd "ages" of CLIFF et al. (1998) must be erroneous. This would also agree with the conclusion from P-T-t (absolute) data from various Alpine orogenic belts (e.g. GEBAUER and LIATI, 1997) that it is unlikely that eclogite facies conditions around 400–500 °C and 20 kbar persisted for c. 20 Ma. For example, half the time (c. 10 Ma) was sufficient for the Rhodope complex of northern Greece to complete a whole P-T-t loop above c. 300 °C, reaching even 800 °C at similar depth as the Monviso ophiolites. In case the Sm–Nd data are geologically meaningful, the whole P-T-t loop of the Monviso ophiolites must then be expected to have lasted much longer than 20 Ma. This, but already the apparently c. 20 Ma lasting P-T peak under eclogite facies conditions, encounters serious problems with the ages of metamorphism in the adjacent Sesia Zone (c. 65 Ma) and the Briançonnais (c. 35–40 Ma; see Fig. 2). Unfortunately, Lu-Hf garnet – whole rock data from a Monviso eclogite (DUCHÊNE et al., 1997), giving 49.1 ± 1.2 Ma, do not help much. They only coincide with the probably biased Ar data of MONIÉ and PHILIPPOT (1989). Although this new technique yielded concordant age results with the SHRIMP data for the UHP-rocks of Dora-Maira, this was not the case for a felsic eclogite of the Sesia Zone arguing that there is still considerable uncertainty regarding the problem of mineral purification and isotopic equilibrium. Thus, in case of the Monviso ophiolites, future geochronological work will hopefully constrain the age of the Tertiary HP-metamorphism more precisely than it was possible so far.

Comparing the c. 10 Ma younger subduction ages of the continental crust of the Adula nappe with those of the HP-UHP oceanic crust of the ZSZ (see Fig. 2), it is plausible that low- to medium grade Alpine metamorphism in the Briançonnais, e.g. in the Tambo, Suretta or Gran St. Bernard nappes, should be younger than subduction metamorphism in the ZSZ. On the other hand, it should be older than subduction metamorphism of the southernmost edge of the European plate, i.e. in the Central Alps the Adula-Cima Lunga nappe. This is in agreement with the relatively imprecise mineral data of various parts of the Briançonnais yielding c. 35–40 Ma. Cessation of flysch sedimentation in the Valais trough did not occur before Middle Eocene (e.g. ZIEGLER, 1956). Thus, subduction of this oceanic basin (SCHMID et al., 1990) followed by the adjacent European margin below the mid-Penninic Briançonnais, and possibly below the Sesia-Lanzo Zone, must have started after collision of the Briançonnais with the Sesia-Lanzo crust, i.e. after 44 Ma. This is in line with the two Late Eocene/Oligocene P-T-t loops of felsic rocks especially from the Alpe Arami and Cima di Gagnone areas within the Adula-Cima Lunga nappe system. Similarly, the c. 38 Ma Rb–Sr phengite ages at the periphery of the Lepontine area (HUNZIKER, 1969; STEINITZ and JÄGER, 1981), e.g. in the low-grade mid-Penninic Suretta nappe (Briançonnais) are in good agreement with such a hypothesis.

6. The Sesia-Lanzo Zone (SLZ)

The SLZ, together with the Margna nappe best explained as an extensional allochthon formed during rifting of the Austroalpine margin (FROITZHEIM et al., 1996), has long been considered as a large piece of continental crust subducted during the Cretaceous (HUNZIKER, 1974; HUNZIKER and MARTINOTTI, 1984; STÖCKHERT et al., 1986). The most frequently cited data are Rb–Sr whole-rock data yielding an Early Cretaceous "age" of 129 ± 15 Ma (OBERHÄNSLI et al., 1985). Since the first CL-based SHRIMP-data became available for a number of HP mafic and felsic rocks of the Monte Mucrone area, the lower Aosta valley and from Cima di Bonze (RUBATTO et al., 1995; RUBATTO et al., 1997; RUBATTO and GEBAUER, 1997), the hypothesis of Early Cretaceous subduction had to be abandoned. U–Pb titanite data (INGER et al., 1996; RAMSBOTHAM et al., 1994) and Ar–Ar laser data (RUFFET et al., 1997) around 65 Ma were also interpreted in favour of a HP-metamorphic transformation of the "eclogitic micaschist complex" at the Cretaceous-Tertiary boundary. Lu-Hf garnet data (DUCHÊNE et al., 1997) gave 74.6 ± 4.1 Ma and 69.2 ± 2.7 Ma, respectively and are slightly, but significantly higher. Thus, the idea that the SLZ was subducted together with and in the same geodynamic context as the other Austroalpine HP-units to the East had to be abandoned. For the latter, both SHRIMP-data (GEBAUER and PAQUETTE, unpubl.) and conventional zircon data (PAQUETTE and GEBAUER, 1991) as well as Sm–Nd data (THÖNI and JAGOUTZ, 1992) from the Austroalpine of the Eastern Alps argued for a subduction-related HP metamorphism around 100 Ma, after closure of the Meliata-Hallstatt ocean. As the oceanic crust of the Piemont-Ligurian ocean was subducted around 44 Ma (see above), the subducted Variscan crust of the SLZ was most probably derived from a rifted Austroalpine fragment at the northern margin of the Adriatic plate. In this context, the Canavese zone probably separated the Sesia continental crust from the Apulian margin of the Adriatic plate. During Late Cretaceous convergence it then acted as a suture zone along which the SLZ was subducted to the S below the Apulian margin (see Fig. 2b).

The subduction of the SLZ probably started about 11 Ma before peak metamorphic conditions (c. 600 °C / 18 kbar; e.g. KOONS, 1982) were reached. This follows from the dating of quartz-veins that most typically formed at c. 300 °C during dehydration of the sedimentary precursor of the eclogitic micaschists. Hydrothermal zircons in such a vein gave SHRIMP-ages at 76.1 ± 1.1 Ma and were not reset during peak metamorphic conditions at 65 Ma (RUBATTO et al., 1997). From this and the petrological data, subduction and heating rates of c. 1 cm/a (10 km/Ma) and 40 °C/Ma can be calculated. Higher rates (c. 2–3 cm/a and 125 °C/Ma) were derived for the only comparable case in the Alpine Rhodope Complex in northern Greece, arguing in both cases for plate tectonic rates during subduction, and, in the case of Rhodope, also during exhumation and cooling. The convergence rates that can be derived from such data agree very well with rates derived from geological reasoning for the Central Alps (e.g. SCHMID et al., 1996a).

As for the determination of the cooling history after peak metamorphic conditions, difficulties arise due to reheating as a result of the later Lepontine greenschist facies overprinting. Thus, the fission track data on zircon and apatite, yielding c. 33 Ma and 25 Ma respectively, probably rather date cooling after the low-grade Lepontine overprinting (HURFORD, 1984). Many mica "ages", apart from the effects of excess Ar or Sr-isotopic disequilibrium, are probably also affected by the Lepontine overprinting and can therefore not be used for reliable estimates of the cooling path(s).

7. Alpine magmatic rocks in the Sesia-Lanzo and the adjacent Southern Alpine Ivrea Zone

The emplacements of the Biella granitoids and the Traversella diorite into the SLZ, giving ages around 30 Ma (HUNZIKER and BEARTH, 1969; ROMER et al., 1996), are probably also related to the Eocene-Oligocene subduction processes and possible lithospheric delamination. Additionally, Oligocene andesites cover the top of the Sesia basement. Similar ages were also obtained within the adjacent Ivrea Zone at Miagliano (31 Ma; CARRARO and FERRARA, 1968) and very close to the Insubric Line (GEBAUER et al., 1992b). Here, U–Pb dating (SHRIMP) of magmatic zircons from a meta-gabbrodiorite dike within the Balmuccia peridotite yields an Oligocene age (31.1 ± 1.5 Ma). Similarly, a meta-gabbrodiorite within the Lower Layered Group, adjacent to the Balmuccia peridotite, yields an age of 26.0 ± 0.8 Ma. Based on petrological data and microstructural observations both rocks must have been emplaced into, and equilibrated within, deep crustal levels implying very rapid exhumation rates along the immediate contact of the Insubric mylonite belt with the Ivrea Zone. The initial ε_{Nd}-values of +7.7 and +11.1, as well as other geochemical data, suggest a heterogeneous depleted mantle source for the two gabbroic rocks, possibly created approximately SE subduction of Mesozoic oceanic crust. Such a model is in line with S-directed, Eo-Oligocene subduction of similar oceanic crust of the Valais trough inferred for the Lepontine Alps (GEBAUER et al., 1992a). Also, the above mentioned Alpine intrusives into the SLZ, the Biella and Traversella plutons, are probably of similar origin.

8. Summary and geodynamic model to explain the multi-episodic character of the geochronological data

The following geodynamic model, illustrated on four schematic cartoons, is largely based on relatively recent geochronological data. It follows closely data and data interpretations given by GEBAUER (1994), RUBATTO et al. (1995); GEBAUER (1996); RUBATTO and GEBAUER (1996); GEBAUER et al. (1997); RUBATTO et al. (1997); GEBAUER and RUBATTO (1998) and RUBATTO (1998). This model is based on geochronological evidence that the Central and Western Alps are entirely built on Gondwana-type crust that was involved in Ordovician and Carboniferous orogenies (e.g. GEBAUER, 1993; SCHALTEGGER and GEBAUER, 1999, this volume). Main characteristics of this continental crust are the presence of inherited zircons formed during the Panafrican orogeny (c. 600 Ma). These ages are missing in the other supercontinent, Laurasia. Ages around 1.0, 2.1 and 2.6 Ga as well as a lack of data around c. 1.5 Ga – often observed in Laurasia – is further support of the Gondwana derivation of the different microcontinents (terranes) in the Western and Central Alps. Of course, at this stage of investigation it is difficult to say whether only one S-directed lithospheric slab, with variably large continental blocks on top, plunged below the Austroalpine margin. In such a case more or less continuous lithospheric subduction started along the Canavese zone c. 76 Ma ago and ended c. 33 Ma ago with the final subduction of the European continental margin. Alternatively, and this is more in line with the terrane models as developed in Northern America, at least two distinct subduction planes developed when the Piemont-Ligurian and the Valais ocean were subducted separately, in time and space, along two different subduction planes. Both continuous, single subduction or discontinuous, multiple subductions are in line with new geochronological data indicating that subduction to at least 60 km and immediate exhumation can be completed in as little time as c. 10 Ma (GEBAUER and LIATI, 1997). Keeping this in mind, it is not surprising that metamorphic peak conditions of a specific tectonic unit may have lasted less than 1 Ma. Naturally, the model below, including stratigraphic, structural, petrological and geophysical data, has to be tentative and modifications will be necessary when more and better data are available.

1) After a series of multi-episodic extensional and rifting events (Late Carboniferous to Triassic) at the end of and following the Variscan orogenic cycle, the Alpine cycle started with Jurassic rifting and/or production of oceanic crust. The best documented example of this stage is the formation of the Piemont-Ligurian ocean (Fig. 2a) for which geochronological data from c. 160 Ma to 166 Ma exist. The presence of inherited zircons of probable crustal origin in the Zermatt-Saas Fee ophiolites (metagabbros, metabasalts and metasediments) can be taken as an argument against a typical MOR-setting. Instead, the nearby presence of continental crust is indicated, rather favouring the former existence of a narrow ocean. No geochronological data exist yet for the Early Cretaceous opening of the Valais basin as indicated by stratigraphic evidence (e.g. FLORINETH and FROITZHEIM, 1994; Fig. 2a). The same is true for the older Canavese zone (Fig. 2a).

2) Omitting the c. 100 Ma old E–W directed subduction of Austroalpine continental crust after closure of the Meliata-Hallstatt ocean in the Eastern Alps (Fig. 2 a, b), a first SE directed subduction episode, detected in the HP continental crust of the Sesia-Lanzo Zone, probably started at c. 76 Ma. It reached maximum burial at c. 65 Ma, i.e. at the Cretaceous-Tertiary boundary (Fig. 2b). The Canavese zone probably acted as an important suture for this orogenic subcycle that is clearly separated from the older Austroalpine orogenic cycle of the Eastern Alps. No traces of this orogenic episode are found in the Central, Western and Southern Alps dealt with in this paper. The indication of the Meliata-Hallstatt suture in figure 2 is simply a westward projection into the simplified profile through the Western, respectively Central Alps. Exhumation of the Sesia-Lanzo continental crust likely occurred immediately after maximum subduction. The Oligocene fission track ages are interpreted here as being the result of cooling after "Lepontine" greenschist-facies overprinting of the Sesia-Lanzo Zone.

3) Further northward movement of the Apulian plate, together with the freshly docked Sesia-Lanzo terrane, resulted in subduction of the oceanic crust of the Piemont-Ligurian ocean.

Peak metamorphic conditions under HP- and UHP conditions were reached at 44.1 ± 0.7 Ma, i.e. in the Middle Eocene (Fig. 2c). Rapid exhumation caused cooling below 350 °C already in the Early Oligocene. Immediate Oligocene overprinting, i.e. at 33–32 Ma and possibly also at 25 Ma, under low-grade metamorphic conditions can, in some areas, be inferred from a number of geochronological data.

4) After the closure of the Piemont-Ligurian ocean, the continental crust of the Briançonnais (e.g. Suretta, Tambo or Bernard nappe) was subducted. Unfortunately, the data base defining its Alpine metamorphic evolution is not yet well constrained. Thus an age range of 35–40 Ma has here been chosen based on the most reliable data (Fig. 2d). Additionally, due to the uncertainties in palaeogeographic reconstructions, it is not clear if, and which parts of the Briançonnais were subducted to HP/UHP conditions.

5) After closure of the last basin, the Valais trough, continental crust, probably of the European margin, was subducted up to UHP conditions (e.g. Dora-Maira). Again, due to the difficulties of palaeogeographic positioning (i.e. Briançonnais or European margin) uncertainties for geodynamic reconstructions remain. The geochronological data by themselves rather argue for a common rooting of the Internal Massifs (at least Dora-Maira and Monte Rosa) and the Adula-Cima Lunga nappe at the European margin. The mafic/ultramafic HP-UHP rocks of the Adula-Cima Lunga nappe (Alpe Arami and Cima di Gagnone) record a relatively complete P-T-t loop between 43 Ma and 33 Ma, respectively 43 Ma and 30 Ma with temperature peaks at c. 33 Ma for the subducted continental slab and c. 35 Ma for mantle rocks that were derived from lower parts of the subduction system. The geochronological data strongly argue for tectonic intermingling of these mantle rocks with rocks of the continental crust at c. 33 Ma.

6) Alpine magmatic activity started at c. 31.5 Ma (Bergell tonalite), with a clear peak at 30 Ma, and finished at around 25 Ma with the Novate granite and many pegmatites and aplites in the southern steep belt. This c. 25 Ma episode caused reheating and fluid activity in the southern steep belt and probably also in other tectonic units, e.g. the Monte Rosa Massif and adjacent units. As a consequence, many mineral ages were partly or fully reset at that time. At present, the most plausible cause for this reheating episode may be hot asthenospheric counterflow after delamination of subducted lithosphere (e.g. VON BLANCKENBURG and DAVIES, 1995).

7) Final cooling to c. 100 °C can be as old as 25 Ma (Sesia-Lanzo Zone; HURFORD et al., 1989) or as young as 1.4 Ma (Mont Blanc Massif; SEWARD and MANCKTELOW, 1994), depending on the individual exhumation histories of the different tectonic units.

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