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Age determinations on the Tertiary Masino-Bregaglia (Bergell) intrusives (Italy, Switzerland): a review

by *Werner Hansmann*[1]

Abstract

Among the Periadriatic intrusions, the Masino-Bregaglia (MB hereafter) igneous body, located N of the Insubric Line at the Swiss-Italian border, is crucial for the understanding of the tectonics of the Central Alps. This fact and features, such as the unique 10 km exposed range of intrusion levels, and the occurrence of exhumed MB igneous rocks in Alpine sedimentary deposits (Gonfolite Lombarda), has attracted numerous geochronological studies. Since 1960 a variety of age dating techniques has been applied to refine the geochronology of the mainly tonalitic to granodioritic MB intrusives for which an Oligocene to Miocene age had been postulated early in this century. The data resulting from these geochronological studies including those for the boulders from the Gonfolite Lombarda sedimentary succession, are compiled and discussed in this article.

For the MB granodiorite four different mineral chronometers (U/Pb on allanite, thorite and titanite and Th/Pb on allanite) yielded identical ages within error limits with a weighted mean age of 30.15 ± 0.21 Ma. Interpretation of age data for the older tonalite remains more difficult. For the westernmost margin of the tonalite a magmatic crystallization history from 32.9 Ma to approximately 28 Ma is documented by interpreted zircon U/Pb and allanite Th/Pb crystallization ages. For the eastern part of the tonalite a Th/Pb age of 31.5 ± 0.35 Ma on allanite and a zircon U/Pb age of 31.88 ± 0.09 Ma have been determined. The Novate Granite, though genetically not associated with the other MB intrusives has been dated at 25 Ma by U/Pb on monazites.

A considerable number of mineral ages of samples from the MB intrusive body reflect its cooling and exhumation history, which is complex due to its deep emplacement in the crust, at levels corresponding to upper amphibolite facies at its western boundary and to upper greenschist facies at its eastern margin. Cooling and exhumation of the MB igneous body and surrounding rocks took place earlier in the east than in the west. Emplacement of the eastern part of the MB intrusive body postdated the thermal peak of the Lepontine metamorphism, whereas at the deeper intrusion level exposed in the west high grade metamorphic conditions still prevailed during and after emplacement.

Minerals from boulders from the Gonfolite Lombarda give consistently older cooling ages than corresponding ages from in situ MB intrusives, indicating that the boulders were derived from levels of the intrusion substantially above the MB igneous rocks currently exposed at the surface. From the exhumation history of the western margin of the tonalite near Bellinzona, erosion of a vertical column of up to 26 km of intrusives since the earliest deposition of MB boulders at about 29 Ma can be inferred.

Keywords: intrusion, cooling, exhumation, geochronology, conglomerate, Bergell (Bregaglia) intrusion, Central Alps.

1. Introduction

The calc-alkaline Masino-Bregaglia igneous body, one of the so-called Periadriatic intrusions in the Alps, is among the intrusions with the highest concentration of radiometric age data worldwide. The MB igneous body has attracted numerous geochronological investigations for several reasons: (i) it is located in a key position in the nappe edifice of the Central Alps, (ii) MB igneous rocks and MB-derived boulders in sedimentary deposits (the Gonfolite Lombarda) represent an originally vertical column of an intrusion of more than 20 km, allowing the study of systematics of the cooling and exhumation histories of a deep-seated intrusion, (iii) age constraints since about

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1920 and an increasing number of age data made the MB intrusion a well known geological unit suited for testing new or improved dating techniques, and (iv) the composite nature of the MB igneous body prompted attempts to resolve the age difference between distinct igneous phases by geochronological methods.

It is the aim of this article to review the geochronological data on the MB igneous body and neighbouring units. The ages determined by a variety of radiometric dating techniques are compiled (Appendix: Tab. 1 and 2), discussed and summarized. Other aspects of the MB intrusion are treated in companion papers in this volume (e.g. BERGER et al., 1996; SCHMID et al., 1996; TROMMSDORFF and CONOLLY, 1996).

In the first part of this review results of studies relevant to the geochronology of the MB intrusives are presented and the most important results will be commented on and partly revised where appropriate. This part is in three sections, comprising (i) a historic overview of the age estimates of MB rocks from the time before isotope dating methods were available; (ii) a presentation of the radiogenic isotope geochronological data; (iii) an outline of studies on the Gonfolite Lombarda relevant to the geochronology of the MB intrusives. The Gonfolite Lombarda is a coarse-clastic sedimentary unit containing a large number of MB boulders and mineral grains derived from the intrusions and is exposed in the region of Como (Northern Italy, see Fig. 1).

In the second part of the review the age data will be discussed in light of their significance to the geochronology of the MB intrusive rocks. The following topics will be addressed: (i) the relations between the MB intrusives and the metamorphic conditions in their environment of emplacement, (ii) the intrusive sequence and absolute ages of the different MB igneous rocks and, (iii) the cooling and exhumation history of the MB intrusives and their country rocks.

2. Geological framework

The MB igneous body is located north of the Insubric Line in the border region of Switzerland and Italy in the Central Alps (Fig. 1). The major part of the body is situated near the boundary between the Penninic and Austroalpine nappes at the eastern margin of the Lepontine (WENK, 1956) structural dome. The body is a composite pluton of mainly granodiorite and tonalite. The latter is located at the margins and forms the southern part. A narrow zone of tonalite extends from the main part of the intrusive body towards the west, to the Iorio Pass near Bellinzona. This zone was recently interpreted as the feeder of the whole MB intrusive body (ROSENBERG et al., 1995). The tonalite shows a marked parallel fabric along its southern margin. Minor igneous rocks are gabbros (REUSSER, 1987; DIETHELM, 1985; 1989), mafic dikes (DIETHELM, 1989) and several generations of aplites and pegmatites. A leucogranitic intrusion in the area of Novate and numerous associated pegmatites and aplites have traditionally been considered as a part of the MB igneous complex too. A genetic relationship between the Novate intrusion and the MB intrusives, however, was ruled out on the basis of geochemical evidence (REUSSER, 1987; OSCHIDARI and ZIEGLER, 1992; VON BLANCKENBURG et al., 1992). Because of the close spatial association of the Novate intrusion and the MB igneous rocks sensu stricto, however, the age determinations on Novate rocks will be included here.

Due to the nappe-like geometry of the MB igneous body (WENK, 1973) there existed a controversy about the genesis and timing of the intrusion with respect to nappe emplacement and Alpine deformation. TROMMSDORFF and NIEVERGELT (1983) concluded from their review of field relations between the MB intrusive body and its country rocks that the MB intrusion crosscuts Margna and Penninic nappes at the eastern margin, and thus postdates nappe formation in this area. Furthermore they stated that the strongly contrasting relationships between the MB intrusives and country rocks at the NE and SW borders of the igneous body reflect a difference of intrusion depth amounting to about 10 km. In a recent study, BERGER et al. (1996) showed that at the southeastern MB border, the tonalite intrusion postdated the formation of the Austroalpine Steep Belt. Subsequent to their emplacement and prior to their complete crystallization the MB igneous rocks were synintrusively deformed during Alpine N–S shortening and E–W stretching (DAVIDSON et al., 1996). A detailed description of relations of the different deformational events to the intrusive history of three distinct areas along the E–W extension of the MB igneous body is given by BERGER et al. (1996).

Field evidence defines the following magmatic sequence in the MB area:

(i) Andesitic-basaltic dikes that crosscut the Alpine foliation in the neighbouring units (NIEVERGELT and DIETRICH, 1977) show a contact metamorphic overprint in the MB aureole (GAUTSCHI and MONTRASIO, 1978). These were interpreted as precursors of the main intrusions on geochemical grounds (DIETHELM, 1989; VON BLANCKENBURG et al., 1992).

(ii) Gabbros and hornblendites occur as variously-sized inclusions only in the tonalite and are interpreted as early magmatic differentiates (DIETHELM, 1985, 1989).

(iii) The two main intrusions, the tonalite ("Serizzo") and the granodiorite ("Serizzo Ghiandone" in the older Italian literature). These are in contact along a complex transition zone (MOTICSKA, 1970; REUSSER, 1987) but age relationships of the two are ambiguous in the western part of the main igneous body. The tonalite is considered to be older (e.g. CORNELIUS, 1928; BUCHER-NURMINEN, 1977; BERGER and GIERÉ, 1995). Field evidence in support of this hypothesis is given by a small granodioritic stock intruding the tonalite in the Val Sissone (MONTRASIO and TROMMSDORFF, 1983; BERGER and GIERÉ, 1995).

(iv) Lamprophyric dikes of calc-alkaline and shoshonitic compositions are present in the granodiorite with variable degrees of disintegration from undisturbed dikes through disrupted dikes and swarms of inclusions to isolated inclusions. These dikes intruded the granodioritic magma prior to its complete solidification (DIETHELM, 1989).

(v) The youngest major intrusion in the area is represented by a garnet-bearing two-mica-leucogranite, the Novate Granite. Pegmatites, leucocratic micro-granites and aplites are widespread in the whole MB region. Some of these dikes radiate from the Novate intrusion. Among the several generations of leucocratic dikes (e.g. MOTICSKA, 1970), REUSSER (1987) distinguished pre- and post granodioritic types, therefore only some of the dikes can actually be associated with the Novate intrusion.

3. Age estimates from the time before isotopic age dating

Before isotopic methods were available in geochronology the age of the MB intrusion was

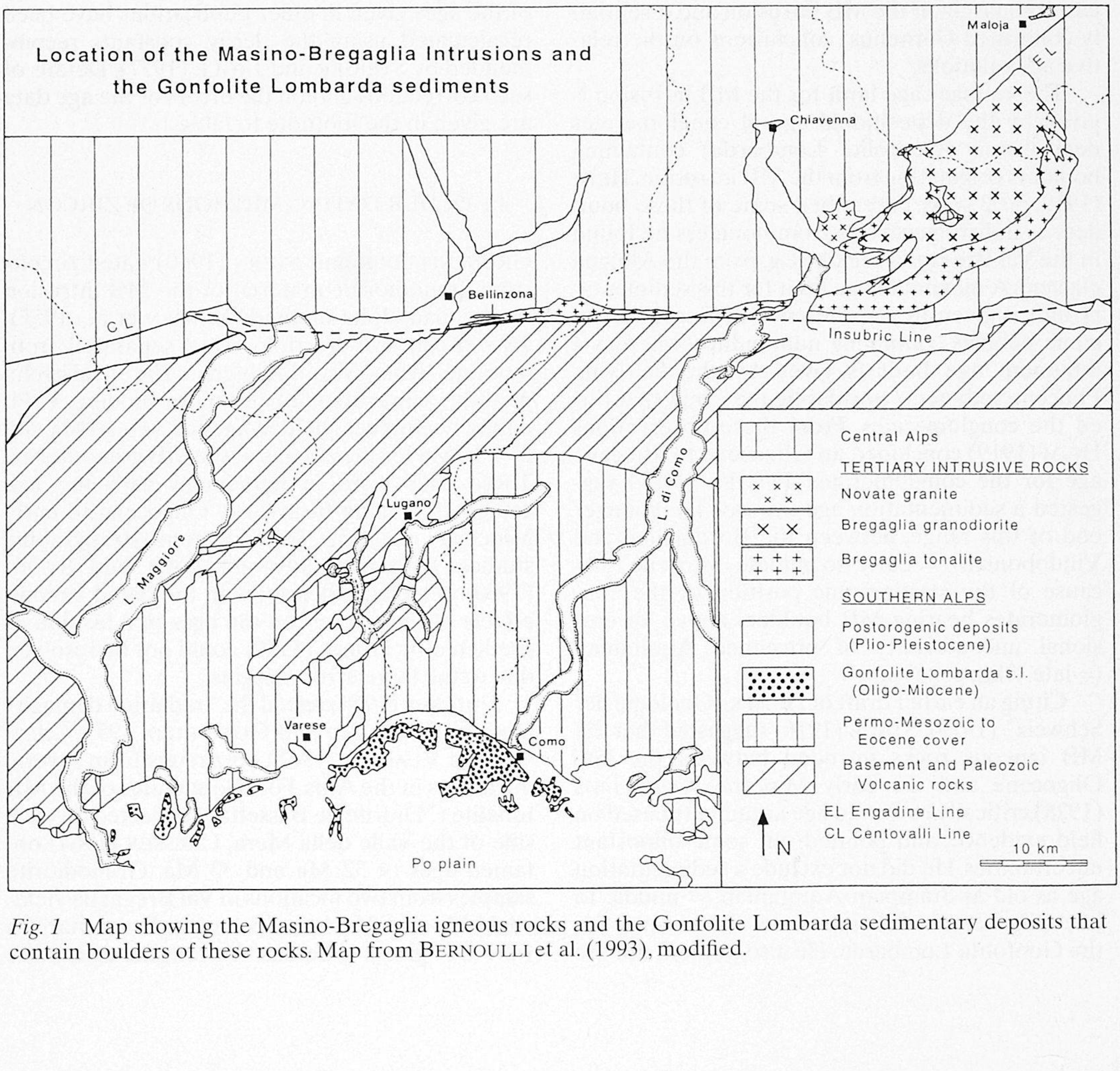

Fig. 1 Map showing the Masino-Bregaglia igneous rocks and the Gonfolite Lombarda sedimentary deposits that contain boulders of these rocks. Map from BERNOULLI et al. (1993), modified.

bracketed using relative geological age relations. STEINMANN (1913) was the first to postulate a [late] Tertiary age for the MB intrusion. In his view, the MB granodiorite was distinct from the older granites of the Julier and Bernina areas because of an absence of green alteration minerals usually observed in the latter group and because of different geologic relationships with Alpine structures. Though STEINMANN (1913) argued that the MB granodiorite cuts across the steeply south-dipping Alpine nappes and that its country rocks partly display a contact metamorphic overprint he did not report detailed observations supporting his arguments. CORNELIUS (1913) reported field evidence confirming Steinmann's postulates; he observed that Alpine nappe-boundaries were cut by the MB granodiorite and that a contact-metamorphic aureole was present in the units at the NE border of the intrusion. As the intrusion post-dated the Penninic nappe structure, he was led to propose an age younger than Oligocene. STAUB (1918) carefully reinvestigated the contacts at the eastern margin of the MB intrusion and essentially confirmed Cornelius' conclusions on the relative age relations.

The younger age limit for the MB intrusion is given by the depositional age of conglomerates near Como (Gonfolite Lombarda) containing boulders originating from the MB intrusion. HEIM (1919, p. 93 seqq.) described some of these boulders as indistinguishable from boulders he found in the Val Bregaglia region (e.g. from the Albigna glacier). A maximum age limit for this sedimentary unit is given by the presence of Eocene limestone pebbles containing nummulites, whereas a minimum age limit is given by the flat-lying Pliocene sediments postdating the event that tilted the conglomerates. From these observations HEIM (1919) concluded an Oligocene to Miocene age for the conglomerates. PFISTER (1921) suggested a sedimentation age towards the younger end of this range, between the Burdigalian and Vindobonian (= early to middle Miocene) because of the stratigraphic position of the conglomerates bearing MB boulders above an erosional unconformity of presumed Aquitanian (= late Oligocene) age.

Citing an earlier draft of HEIM's "Geologie der Schweiz" (1919), STAUB (1916) suggested that the MB igneous rocks intruded between the late Oligocene and the early Miocene. CORNELIUS (1928) critically reviewed age arguments based on field evidence, and pointed out some important uncertainties. He did not exclude a sedimentation age as old as Stampian-Aquitanian (= middle to late Oligocene in the time scale of that time) for the Gonfolite Lombarda. He also pointed out the composite nature of the MB intrusive body which comprises an older, tonalitic and two younger granitic intrusions (porphyritic MB granite and the younger leucocratic Novate Granite) and further argued that between these igneous phases an age difference equivalent to a stratigraphic stage (corresponding to a few million years) could not be ruled out.

4. Absolute age determinations of rocks from the Masino-Bregaglia igneous body and its country rocks

Age determinations on the MB rocks are divided into the following groups: (i) older dating methods on zircons, (ii) Rb/Sr and K/Ar dating of micas, (iii) fission track dating on apatite, (iv) U–Th–Pb dating on zircons and other accessory minerals, and (v) other methods. The age results are listed in table 1 (Appendix) and the localities of the dated samples are shown on figure 2. Some of the ages given in older publications have been recalculated using the decay constants recommended by STEIGER and JÄGER (1977). Details of such corrections and on the errors of the age data are given in the footnote to table 1.

4.1. OLDER DATING METHODS OF ZIRCON

GRÜNENFELDER and STERN (1960) dated zircons from granodioritic material of the MB intrusion by the lead-alpha method (LARSEN et al., 1952). Two zircon size fractions were separated from moraine from Val d'Albigna. The lead-alpha method, a precursor of the more modern U/Pb dating techniques, yielded ages of 30 ± 10 Ma and 25 ± 10 Ma for the zircons of the MB granodiorite. These ages were in agreement with the age estimates ranging from early Oligocene to early Miocene resulting from tectonic-stratigraphic studies. Although GRÜNENFELDER and STERN (1960) detected older cores in the dated zircons, effects of these cores on the ages in a fashion as predicted by HOPPE (1959) could not be resolved due to the large error margins.

CHESSEX (1964) tested the "radiation damage" method (HOLLAND and GOTTFRIED, 1955; CHESSEX and VUAGNAT, 1961) on zircons from several intrusions in the Alps. For two samples of the MB tonalite ("Diorite de Bassetta") collected on each side of the Valle della Mera, CHESSEX (1964) obtained ages of 32 Ma and 33 Ma. Granodiorite samples from two locations in Val Bregaglia yielded 24 Ma and 21 Ma, respectively. Error margins were not given. Whereas the tonalite ages were

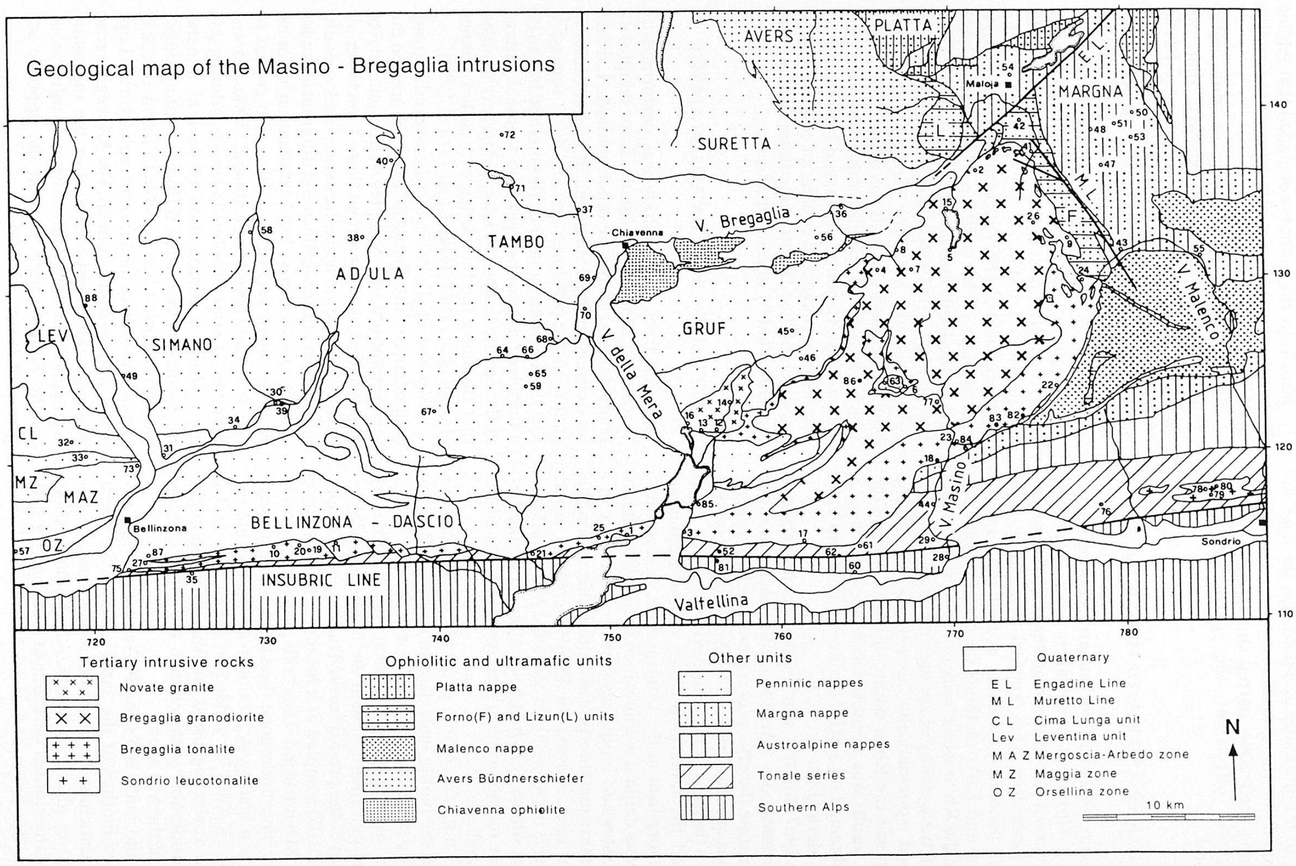

Fig. 2 Geological map of the Masino-Bregaglia igneous body and surrounding units, modified after TROMMSDORFF and NIEVERGELT (1983), BERGER and GIERÉ (1995) and HERMANN and MÜNTENER (1996). Numbers are sampling locations of dated samples and refer to table 1 (Appendix).

close to the presently accepted age, the ages determined for the granodiorite were too young, probably reflecting partial annealing or other systematic effects of this particular dating method.

4.2. Rb/Sr AND K/Ar DATING OF MICAS

Between 1960 and 1990 numerous dating studies in the Alps were undertaken by E. Jäger and members of her research group at the Berne isotope laboratory. They applied new dating techniques becoming available at that time, i.e. the Rb/Sr- and K/Ar methods on micas and amphiboles, the Rb/Sr whole rock isochron method, and fission track dating of apatite and zircon. The first method systematically applied by the Berne group was the Rb/Sr dating of micas. Among the early results was a biotite Rb/Sr age of 22.6 ± 2.3 Ma obtained on a MB tonalite sample from Valle della Mera (Jäger, 1962).

In 1967 Jäger et al. presented a compilation of Rb/Sr mica ages from the Central Alps. In order to illustrate the effects of regional metamorphism on mica ages they plotted Rb/Sr mica ages on two maps (biotites and muscovites) which also showed the mineral isograds of the Lepontine metamorphism in the Central Alps. A closed region was defined within which the Rb/Sr systems of biotites and biotite ages were affected by the Lepontine metamorphism. Within this region the biotite ages showed an E–W decreasing trend with ages between 20–25 Ma in the MB area. Muscovites whose ages had been affected by the Lepontine metamorphism were generally restricted to a smaller area.

Jäger et al. (1967) explicitly interpreted the two Rb/Sr biotite ages determined on MB granodiorite samples (B17: 23.2 ± 1.3 Ma; Z6: 25.8 ± 1.5 Ma) as cooling ages. These ages were within error margins identical with the biotite age (25.3 ± 1.0 Ma) of the pre-Mesozoic Truzzo granite gneiss (KAW 105) sampled at a locality relatively close to the MB intrusion. Thus both units were considered to have undergone the same cooling and exhumation history. A biotite from the Novate intrusion (KAW 133) yielded an age of only 18.3 ± 1.0 Ma. It was suggested that this intrusion might be considerably younger than the other igneous rocks of the MB area.

In the mid-1960's the K/Ar method was applied to biotites of the same samples on which Rb/Sr data have been obtained previously (Armstrong et al., 1966). The K/Ar ages and Rb/Sr ages of the biotites were almost identical (e.g. MB sample Z6: K/Ar 24.6 ± 2.5 Ma; Rb/Sr 25.8 ± 1.5 Ma). Thus the authors concluded that Alpine K/Ar ages on the biotites also represented cooling ages.

Application of K/Ar dating to white micas (Purdy and Jäger, 1976) showed that this method yielded cooling ages between the Rb/Sr-muscovite ages and the K/Ar-biotite ages of the same rock. The differences between K/Ar ages of muscovite/biotite pairs were relatively small for samples of the MB and Ticino regions, pointing to rapid cooling of these areas (e.g. sample KAW 552 from the MB area: muscovite 26.3 ± 1.0 Ma, biotite 24.7 ± 1.3 Ma).

Wagner et al. (1977) determined biotite K/Ar ages of 28.4 ± 1.3 Ma to 29.3 ± 1.4 Ma on MB boulders in the Gonfolite Lombarda for which Gulson and Krogh (1973) had obtained a U–Pb zircon age of 30.1 Ma. They concluded that these boulders cooled at a rate of about 150 °C/Ma, which was considerably faster than observed elsewhere in the Lepontine area, and interpreted the rate as post magmatic cooling of relatively shallow levels of the MB intrusion rather than as cooling controlled by uplift and erosion.

4.3. FISSION TRACK DATING OF APATITE

A fission track dating study was performed by Wagner et al. (1977) on apatite from samples already dated at Berne by other methods. Laboratory observation of annealing of fission tracks in apatite at temperatures above 120 °C suggested that the ages determined by this method had to be interpreted as cooling ages. The regional pattern of the apatite fission track ages closely resembled that obtained for biotite ages in earlier studies (Jäger et al., 1967; Purdy and Jäger, 1976).

Wagner et al. (1977) also discovered a strong dependence of the apatite fission track ages on the topographic altitude. Samples from higher elevations yielded older ages than those from lower altitudes. In some areas apatite fission track ages obtained from samples collected at different altitudes could be used to derive local exhumation histories. Thus the main part of the MB region cooled to 120 °C already between 11 Ma and 15 Ma and was exhumed at a rate of only 0.18 mm/year during this time. Using a combination of several mineral chronometers that dated different cooling stages for a given rock it was possible to reconstruct exhumation histories for different regions in the Lepontine metamorphic domain. The MB region rose at a high rate immediately after the magmatic events and later slowed down, whereas other areas e.g. the Simplon area, showed the opposite sequence of exhumation rates.

WAGNER et al. (1979) presented a cooling and exhumation history for the MB intrusive body. Their apatite fission track ages between 9.7 ± 0.5 Ma and 16.8 ± 0.8 Ma were in part well correlated with topographic altitude, allowing them to derive an uplift rate of 0.41 mm/year for the period between 17 and 13 Ma and a slower rate of 0.26 mm/year for the period between 14 and 12 Ma.

Apatite fission track ages of 24.1 Ma to 25.9 Ma on MB boulders from the Gonfolite Lombarda (WAGNER et al., 1979) were at least 6 million years older than those from in situ samples of the MB region and confirmed the previous interpretations based on K/Ar ages (WAGNER et al., 1977), that these boulders must have originated from intrusion levels considerably higher than the rocks currently exposed on the surface. Using an exhumation rate of 0.7 mm/Ma, a value to take into account the faster exhumation during the early part of the exhumation history determined on other MB samples, the authors extrapolated their elevation versus apatite fission track age diagram to derive an original elevation for the MB boulders from the Gonfolite Lombarda of 4–6 km higher than the present day highest altitude in the MB intrusives (Mte. Pioda 3431 m).

4.4. U–Th–Pb DATING OF ZIRCONS AND OTHER ACCESSORY MINERALS

GULSON and KROGH (1973) dated mg-sized zircon samples of different igneous rocks from the MB area as well as from boulders of the Gonfolite Lombarda using improved U–Pb techniques (KROGH, 1973). They also dated titanite, apatite, allanite and a phase taken for monazite. Their most surprising result was, that old lead components were present in these young igneous zircons. Zircons from the Novate Granite were significantly more discordant and the authors indeed observed rounded cores in this zircon population. The strongly scattering zircon data did not define a smooth discordia line. The scatter could have resulted from heterogeneous inherited components, minor differences between the intrusion ages of the different igneous rock types, or combinations of Pb loss and inheritance. The zircon data neither yielded a well-defined intercept age nor allowed the resolution of an age difference between the tonalite and the granodiorite. The interpretation of the data from the accessory phases remained difficult due to their relatively unradiogenic lead isotope compositions, and consequently substantial common lead corrections. By far the best analytical result was obtained on the "monazite" sample, which yielded a concordant data point at 30.1 Ma (^{206}Pb/^{238}U-age recalculated using the constants recommended by STEIGER and JÄGER, 1977). However, based on the data given by GULSON and KROGH (1973, Table 1: 10 wt% U and 44 wt% Th [calculated from the ^{208}Pb/^{206}Pb ratio]), this sample cannot be regarded as monazite, but more likely as a Th–U phase such as uranothorite or a mixture of uranothorite and monazite. Thus the age of the MB intrusion of 30.1 Ma was essentially based on one analysis of a mineral separate not correctly identified.

KÖPPEL and GRÜNENFELDER (1975) dated monazites from the Lepontine metamorphic region by the U/Pb method. They interpreted the ages as being concordant due to the close agreement of the ^{206}Pb/^{238}U- and the ^{207}Pb/^{235}U-ages which did not differ by more than 0.5 Ma. They concluded that these ages reflect the age of monazite formation under high-grade metamorphic conditions rather than cooling through the blocking temperature of the U/Pb system. The regional monazite age distribution pattern showed similarities with that of the Rb/Sr ages on biotites (JÄGER et al., 1967), but one marked difference: the youngest monazite ages were found in Val Leventina, in contrast to the youngest biotite ages in the Simplon area. The oldest Alpine U/Pb monazite ages of about 31 Ma, however, were found in the MB area (Fig. 4a). The age of 26 Ma obtained for the Novate granite confirmed the earlier hypothesis that this granite was younger than the other MB intrusives. The monazite ages of a quartzitic inclusion (30.5 Ma) in the Novate granite and of a regional metamorphic rock (31.9 Ma) neighbouring the MB intrusion were very similar but distinctly older than the Novate intrusion. From these age relationships KÖPPEL and GRÜNENFELDER (1975) concluded that young monazites do not loose significant amounts of radiogenic lead even at temperatures in excess of 600 °C, such as those prevailing during the incorporation of the quartzitic inclusion in the granitic magma.

Continuing progress in U–Th–Pb analytical techniques allowed VON BLANCKENBURG (1992) to date single zircons and several other accessory phases by the U–Th–Pb method from a granodiorite and a tonalite from the easternmost part of the MB intrusive body. Although cores were present in the zircon populations of both rock types, he was able to analyze inheritance-free single grains and small groups of crystals. Three concordant zircon analyses of the tonalite gave identical results within analytical uncertainties and yielded a weighted mean ^{206}Pb/^{238}U age of 31.88 ± 0.09 Ma. Titanite and apatite yielded identical ages within error margins of 28.9 and 28.6 Ma, respectively. These young ages were interpreted as the result of lead loss or recrystallization. In contrast, allanite yielded a U/Pb age of 34.1 Ma corrected for initial excess ^{230}Th (SCHÄRER, 1984). This age is clearly older than the zircon age of the tonalite, and most probably reflects systematic uncertainties in the parameters used for the correction. However, Th/Pb dating of allanite, which previously was successfully applied to the Alpine Rensen pluton (BARTH et al., 1989) yielded an age of 31.5 ± 0.35 Ma for the tonalite, which was identical within error limits with the zircon U–Pb age.

The zircons from the granodiorite showed apparent ages between 30.5 and 26 Ma. These ages were obtained on U-rich zircons (0.2–0.35% U) and might reflect various degrees of Pb loss, and due to presence of inherited components also a combination of Pb-loss and inheritance.

In the case of the granodiorite the U/Pb age of titanite (30.16 Ma), the U/Pb age of allanite corrected for excess ^{230}Th (30.5 Ma) and the Th/Pb age of allanite (30.10 ± 0.25 Ma) were all identical within error, and a mean age of 30.13 ± 0.13 Ma was calculated for the intrusion of the granodiorite. Apatite yielded a slightly younger age of 29.4 ± 1.2 Ma, statistically not resolved from the age of the accessory minerals discussed above. Thorite from the granodiorite yielded differing U/Pb and Th/Pb ages of 28.3 ± 0.1 Ma and 27.56 ± 0.3 Ma respectively, most likely reflecting lead loss from this Th,U-rich phase (40%Th, 20% U). Lead loss from Tertiary thorites had been previously reported for zoned thorites characterized by extremely U-rich rims (up to 28% UO_2) from the Adamello batholith (HANSMANN, 1986).

VON BLANCKENBURG (1990) dated three single zircons from a cumulitic gabbro enclosed in the tonalite at a location in the east of the MB intrusive body. The U/Pb ages of the three zircons partly overlapped at approximately 31.5 Ma. Because a calculated weighted mean yielded a relatively large MSWD value, the author preferred to give a range limiting the age of the gabbro between 31.3 Ma and 31.7 Ma. This age range however conflicted with the zircon U/Pb age of 31.88 ± 0.09 Ma of the tonalite hosting the gabbroic inclusion.

OBERLI et al. (1996) presented a U–Th–Pb study on zircons and allanites from a sample of tonalite from the western end of the pluton near Bellinzona. The abraded single zircon crystals yielded U/Pb ages between 32.9 and 32.0 Ma and the Th/Pb ages obtained on fragments of density fractions of the allanites were between 32 and 28 Ma. Decreasing Th/Pb ages of allanite fragments correlated with their decreasing Th contents and were interpreted to reflect Th control in the tonalitic magma by allanite precipitation. In contrast, the increase of U and common Pb contents in allanite as well as the increase of the U concentration in zircon correlated with both decreasing U/Pb ages in zircons and Th/Pb ages in allanites, and mirrored the incompatible behaviour of these trace elements during crystallization of the tonalite.

The presence of large quantities of excess ^{230}Th- derived ^{206}Pb in allanite was taken as an argument against simple Pb-loss during magmatic and regional cooling, and the authors concluded that closure temperatures for the U–Th–Pb systems in allanite and zircons exceed the solidus temperature of tonalite (> 700 °C). The significant age differences of zircon and allanite crystallization suggests an extended magmatic history of several million years for the tonalite emplacement at the present sampling level.

In a study on Alpine and pre-Alpine magmatism along the root zone of the Central Alps ROMER et al. (1996) included a sample of the Melirolo augengneiss from a location near Bellinzona. Some authors had considered this augengneiss to be genetically related to the MB tonalite (WEBER, 1957; FUMASOLI, 1974). U/Pb dating of the zircons (ROMER et al., 1996), however, yielded strongly discordant and scattered data, suggesting that this zircon population was composed of Variscan and even older components rejuvenated by Alpine metamorphism. The mean age of 32.8 ± 0.7 Ma resulting from 4 concordant titanite fractions was interpreted as an age of metamorphic growth rather than magmatic precipitation in the protolith of the augengneiss. Further evidence arguing against a simple magmagenetic relationship between the Melirolo augengneiss and the MB tonalite has been given by the relatively high initial ^{87}Sr/^{86}Sr-value of 0.7159 calculated for the augengneiss for the time at 30 Ma, which clearly exceeds the value of 0.710 obtained for the MB tonalite (VON BLANCKENBURG et al., 1992; OSCHIDARI and ZIEGLER, 1992).

4.5. OTHER AGE DETERMINATIONS

In an attempt to date the MB intrusives and their country rocks by the Rb/Sr whole rock isochron technique, GULSON (1973) was successful only in the case of the Tambo unit, for which he produced an isochron corresponding to an age of 303 ± 14 Ma. The low inital ^{87}Sr/^{86}Sr-value of 0.704 stated for the isochron, is probably a misprint in the text, and does not match the intercept of 0.714 shown in the isochron diagram. Data of samples collected from other rock units such as the Gruf migmatitic complex, the MB granodiorite, and the Novate intrusion and associated dikes, showed large scatters preventing the definition of isochrons for these units.

DEUTSCH and STEIGER (1985) determined K/Ar-ages on a series of amphiboles from rocks from the Central Alps, including two tschermakitic hornblendes from Bagni del Masino in the MB area. The age of 32.0 ± 1.2 Ma obtained from the tonalite sample was interpreted as the age of the tonalite intrusion, whereas the hornblende age of 30.5 ± 1.0 Ma of an amphibolite from the tectonic window at Bagni was ascribed to growth or recrystallization of hornblende due to contact metamorphism.

WIEDENBECK and BAUR (1986) examined an E–W age profile through the MB tonalite by K/Ar dating of amphiboles. The higher ages between 36.0 ± 0.9 Ma and 32.1 ± 1.0 Ma obtained on samples from the east were tentatively interpreted as reflecting an earlier event, possibly magmatic emplacement, whereas the ages of 29–30 Ma obtained on samples from Val Masino further to the west were interpreted as closure ages of the K/Ar system following the regional metamorphic peak.

WIEDENBECK (1986) reported K/Ar and Rb/Sr mineral ages along a N–S profile in Valtellina passing from the MB tonalite (biotite K/Ar and Rb/Sr approximately 23.5) to the Southern Alps, crossing the Insubric zone (Rb/Sr on muscovite up to 220 Ma). The mineral ages obtained on the MB sample confirmed results from earlier studies (JÄGER et al., 1967).

Results of a second E–W profile through the MB tonalite were presented by VILLA and VON BLANCKENBURG (1991). Biotite K/Ar ages on 6 samples decreased from E to W from 26.4 ± 0.6 Ma to 21.0 ± 0.6 Ma. These ages were identical within error margins to K/Ar biotite and Rb/Sr biotite ages of previous studies (ARMSTRONG et al., 1966; JÄGER et al., 1967; WIEDENBECK, 1986) obtained from the same regions of the intrusion. Ar/Ar results on the same samples, however, reflected the presence of excess ^{40}Ar in all dated samples. The authors concluded that the K/Ar ages on amphiboles of earlier studies were biased towards too old ages due to the presence of excess ^{40}Ar and could no longer be interpreted as intrusion ages. The presence of excess ^{40}Ar in amphibole in 4 out of the 6 samples resulted in an age pattern that did not follow the regularly E to W decreasing biotite K/Ar ages. Nevertheless amphibole ages east of Valle della Mera were between 28 and 29 Ma, whereas the westernmost samples were between 25 and 26 Ma. VILLA and VON BLANCKENBURG (1991) concluded that all amphibole ages reflect cooling ages and that the metamorphic peak temperatures along the E–W extension of the MB intrusives were reached at different times. In the east, where the shallower part of the igneous body is exposed, the peak of the Lepontine metamorphism occurred between approximately 35 and 38 Ma, before the MB magmas intruded; in the west the metamorphic peak outlasted the intrusion of the deeper levels of the pluton at 23–29 Ma.

5. The Gonfolite Lombarda

A succession of clastic sedimentary rocks is exposed along the southern boundary of the Alps. This succession comprises the Chiasso Formation and the Gonfolite Lombarda, is up to 3 km thick, and extends as a narrow E–W trending zone from the Como area to Lago Maggiore (Fig. 1). These Oligocene-Miocene sediments were deposited during exhumation and erosion of the Central Alps. Because these coarse clastic deposits superficially resemble the molasse N of the Alps, the term south-Alpine molasse was used until the second half of this century.

These Oligocene-Miocene deposits (Fig. 3) are divided into two major units separated by an unconformity (e.g. GELATI et al., 1988). The lower unit consists of the marly silty to sandy Chiasso Formation, which has occasional turbidites. It is overlain by the mainly coarse clastic Gonfolite Group sensu stricto. The Gonfolite Group sensu stricto (Fig. 3) was divided into three spatially and chronologically distinct depositional sequences which correspond, from bottom to top to: Como Conglomerate, Lucino Conglomerate and Gurone Sandstone.

Most of the older studies on the Gonfolite Lombarda were summarized by LONGO (1968). The present summary is restricted to studies containing information relevant to geochronological aspects of the MB intrusion, e.g. the stratigraphic distribution of MB rock types, the petrographic and geochemical characteristics of these rocks, and age determinations of the sedimentary succession and the MB boulders (Tab. 2, Appendix).

It was CHELUSSI (1903) who first recognized the similarities between the conspicuous MB boulders in the Gonfolite Lombarda and samples of the "Serizzo Ghiandone della Valtellina" (= MB granodiorite) from the Val Masino collected by MELZI (1893). Among the MB boulders CHELUSSI (1903) recognized both major MB rock types and reported microscopic features typical for the MB igneous rocks such as myrmekites and allanite rimmed by epidote. He revised earlier opinions on the provenance of these coarse clastic components in the "south-Alpine Molasse" which had proposed a source in Val Sesia and the Biella area.

In a detailed petrographic study of the boulders contained in the Gonfolite Lombarda PFISTER (1921) distinguished several MB igneous rock types: porphyritic and equigranular granodiorite, three varieties of tonalite, diorite and a porphyritic quartz diorite unknown in the currently exposed MB region. A leucocratic two-mica-granite was interpreted to be derived from the Novate intrusion.

In their investigations of the lithological content of vertical profiles through the Gonfolite Lombarda FIORENTINI-POTENZA (1957) and LONGO (1968) found that typical MB granodiorite was lacking at the base of the profile, whereas a Novate-type granite and MB tonalite varieties were present throughout the whole profile. According to LONGO (1968) typical MB tonalite and granodiorite first occur only at 500 m above the base of the profile. He also pointed out the difficulty of unambiguously identifying leucocratic boulders with gneissic texture as Novate granite due to presence of similar gneisses from other Alpine units. LONGO (1968) cites a K–Ar age of 35 ± 4 Ma (pers. comm. of G.N. Hansen to Longo) on a hornblende from one of the tonalite boulders he collected in the Gonfolite Lombarda.

The age of the main part of fossil-free Como Formation was biostratigraphically bracketed by CITA (1958) between early Oligocene and late Oligocene. JÄGER (1973) reported a K/Ar result of 28 Ma (late Oligocene) for biotite from one of Longo's boulder samples. This age conflicted with the stratigraphically determined age constraints for the Como Formation (CITA, 1958). Furthermore, a cooling age of 28 Ma would mark the passage of the sample across a temperature threshold of 300 °C, i.e., the rock was still part of an exhuming metamorphic terrain at that time. The dated sample still had to reach the surface, become eroded, transported and finally deposited in the Como Conglomerate.

These conflicting ages prompted RÖGL et al. (1975) to revise the biostratigraphy of the sediments immediately below and above the Como Conglomerate. For the underlying Chiasso Formation an age between 28 Ma and 26 Ma (NP 24, P21, early Chattian) was determined, and for the overlying "Cavallasca Formation" (= Prestino Mudstones in Fig. 3) an age between 24 and 22 Ma (late Chattian to Aquitanian) was obtained. These new age constraints for the deposition of the conglomerates of the Como Formation were consistent with fission track data on apatite obtained on boulders derived from the MB intrusion (WAGNER et al., 1979). The fission track data range from 25.9 Ma to 23.4 Ma and reflect cooling of the source region of these boulders to 120 °C during uplift. The authors estimated that the source region had reached the surface by 23 Ma.

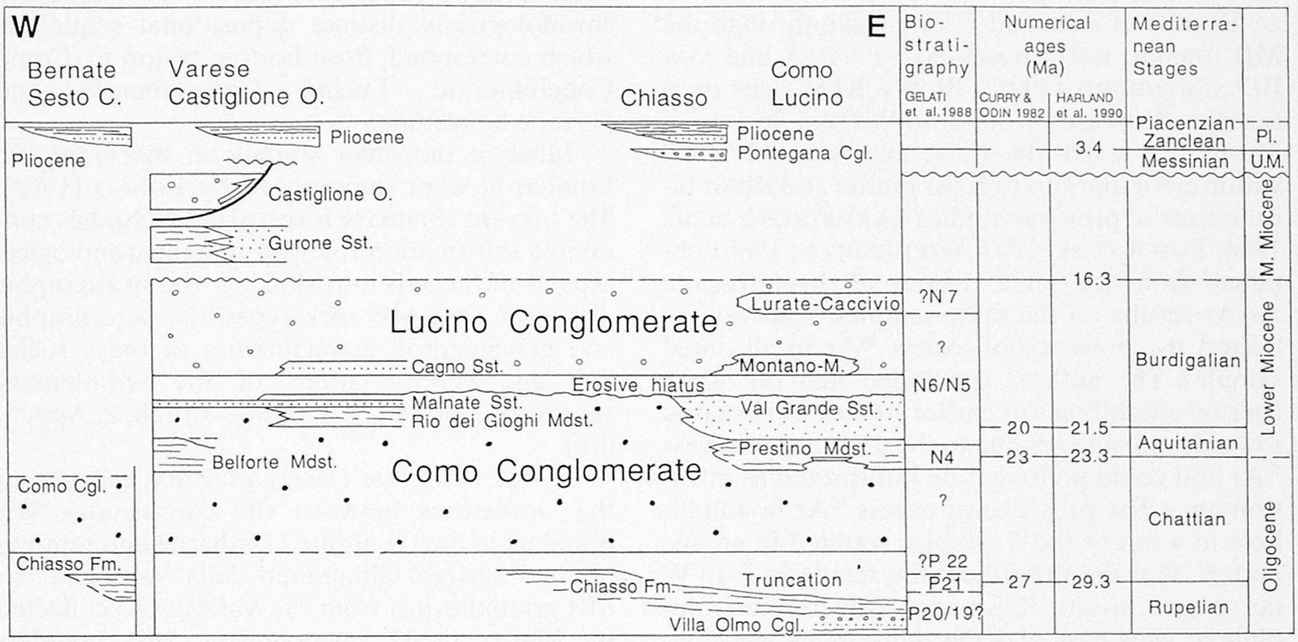

Fig. 3 Stratigraphic chart of the Chiasso Formation and the Gonfolite Lombarda Group from BERNOULLI et al. (1993).

GELATI et al. (1988) determined biostratigraphically a Rupelian age (P19/P20; 30–36 Ma, HAQ et al., 1987) for the base of the Chiasso Formation. In contrast to earlier studies (FIORENTINI-POTENZA, 1957; LONGO, 1968) these authors detected boulders of porphyritic MB granodiorite even within the lowest 50 m of the Como Conglomerate.

GIGER and HURFORD (1989) determined mineral cooling ages on dioritic, tonalitic and granodioritic boulders from the Chiasso Formation and the different formations of the Gonfolite Lombarda Group, applying the K/Ar method on biotites and amphiboles, and fission track dating on apatite and zircon. On a tonalite boulder from a conglomeratic intercalation in the Chiasso Formation (Villa Olmo Conglomerate) they obtained a biotite age of 31.7 ± 0.5 Ma. This is slightly older than the age of sedimentation and is indicative of high cooling and erosion rates. Tonalite boulders showing magmatic textures and altered amphiboles from lower horizons of the Como Formation were interpreted to be derived from shallower levels of the MB intrusive body. For these boulders cooling rates of 25–35 °C/Ma were derived. Tonalite boulders from higher parts of the sedimentary sequence showing oriented fabric and recrystallization features were ascribed to deeper levels of the intrusion. From the relatively small difference between the biotite K/Ar ages and the fission track ages of apatite and zircon determined on a deformed sample, GIGER and HURFORD (1989) inferred an extremely high cooling rate exceeding 100 °C /Ma.

In their Nd and Sr isotope study OSCHIDARI and ZIEGLER (1992) showed that the boulders plot on the same calc-alkaline curve defined by samples from currently exposed parts of the MB intrusion on an ε_{Nd} versus ε_{Sr} diagram. The data for the Novate granite clearly deviated from the MB trend, and thus rule out a genetic relationship. Oschidari's and Ziegler's ε_{Nd} versus ε_{Sr} curve parallels the trend observed by VON BLANCKENBURG et al. (1992), showing a slight displacement towards lower ε_{Nd} values.

GIGER (1991) and OSCHIDARI (1991) revised interpretations of earlier studies in which leucocratic granitic rocks distributed over the whole conglomerate section had been assigned to a Novate type granite source (PFISTER, 1921; LONGO, 1968). GIGER (1991) found Novate type garnet-bearing leucogranites of Tertiary age only in the stratigraphically higher Miocene Lucino formation.

BERNOULLI et al. (1993) attempted to date the sediments of the Chiasso Formation and the Gonfolite Lombarda sensu stricto by application of Sr-isotope stratigraphy on mollusc shells present in these sediments. They obtained 26–28 Ma for the underlying Chiasso Formation, 23 Ma for the Valgrande Sandstone above the Como Conglomerate and 17–19 Ma for the Lucino Formation. The cooling history of boulders from well-documented horizons within the sedimentary succession was derived from K/Ar ages on mica and fission track dating of apatite and zircon. Radiometric dating yielded constraints for the maximum depositional age of 29.2 Ma ± 3.5 Ma (1 σ) for the Como Conglomerate and 21.0 ± 2.4 Ma for the Lucino conglomerate. The interpretation of the biotite cooling ages of 31.7 ± 0.5 and 31.9 ± 0.4 Ma from a boulder in the Villa Olmo Conglomerate remained difficult. The Villa Olmo Conglomerate is embedded in the Chiasso Formation below the biostratigraphic Rupelian-Chattian boundary, to which an age of between 30 Ma and 27.0 Ma has been assigned (e.g. HAQ et al., 1985; CURRY and ODIN, 1982). Most time scales would imply high mean cooling rates (100–150 °C/Ma) for this tonalite boulder. Magmatic textures and observed hornblende alteration in this tonalite boulder led GIGER and HURFORD (1989) to postulate a shallow intrusion level for this sample. Thus its high mean cooling rate could reflect post-magmatic cooling of an upper level of the intrusion subsequent to emplacement into a cool environment rather than regional cooling by rapid exhumation and erosion.

6. Discussion

6.1. RELATIONS BETWEEN REGIONAL METAMORPHISM AND EMPLACEMENT LEVEL OF THE MB INTRUSIVES

Age relations between the emplacement of the MB intrusives and the peak of regional metamorphism are important for the interpretation of the ages obtained on the dated minerals. Most of the MB intrusive body is located in the Lepontine (WENK, 1956) metamorphic dome. The "peak" of metamorphism in this dome was between 38 and 35 Ma according to JÄGER (1973), whereas DEUTSCH and STEIGER (1985) postulated an age between 23 and 29 Ma. For the upper Penninic and lower Austroalpine nappes along the eastern border of the MB igneous body the age of regional metamorphism was determined as late Cretaceous to early Tertiary (e.g. JÄGER, 1973; DEUTSCH, 1983; HANDY et al., 1996). These two metamorphic domains appear to overlap in the MB region but the area of overlap is not clearly defined.

Relative age relations between the regional metamorphic peak and the emplacement of the MB intrusives are well established for its eastern and northeastern part, where the MB intrusion postdates the peak of regional metamorphism as evidenced by a contact aureole (e.g. TROMMSDORFF and EVANS, 1972; WENK et al., 1974; TROMMSDORFF and NIEVERGELT, 1983). A contact metamorphic overprint has not been observed, however, in the western part of the MB intrusive body nor along the tail between the Mera and Ticino valleys (REUSSER, 1987). Monazite ages of migmatites from Valle Bodengo (HÄNNY et al., 1975) and from gneisses of the Ticino Valley (KÖPPEL and GRÜNENFELDER, 1975) document that high metamorphic conditions prevailed to 23 Ma around the western extension of the MB tonalite.

A rough estimate for the original emplacement level of the currently exposed rocks of the MB igneous body can be derived from the metamorphic grade of the country rocks. On the eastern margin the MB magmas intruded into rocks showing characteristics of the Alpine regional metamorphic upper greenschist to lower amphibolite facies. Here the pre-intrusion mineral assemblage of the Malenco ultramafic rocks is olivine + antigorite + diopside (TROMMSDORFF and EVANS, 1972) corresponding to a regional metamorphic peak temperature of approximately 450 °C at 65 Ma (TROMMSDORFF and CONOLLY, 1996). For the time of intrusion itself TROMMSDORFF and CONOLLY (1996) calculated an ambient temperature of 350 ± 20 °C. The central part (Bagni del Masino), the western part of the main intrusive body (Valle della Mera) and its western extension towards Bellinzona were emplaced into amphibolite to upper amphibolite grade country rocks, where partial melting locally is evident (FUMASOLI, 1974; HÄNNY et al., 1975; SCHMID et al., 1996). The formation of partial melts indicates that ambient temperatures in the order of 650 °C (JOHANNES, 1984) prevailed.

Geobarometry along an E–W profile through the tonalite (REUSSER, 1987; DAVIDSON et al., 1996) yielded pressures increasing from 4.5–6 kbar in the east to 7.5–8 kbar in the west corresponding to depths of 18 km and 27 km, respectively (REUSSER, 1987). The geobarometric results for the eastern part of the MB igneous body contrast pressure estimates between 3.5 and 4 kbar for the contact metamorphic rocks in the neighbouring MB contact aureole (TROMMSDORFF and CONOLLY, 1990, 1996). BERGER et al. (1996) interpreted this pressure difference to be the result of a strong differential uplift of the solidified tonalite with respect to its country rocks along the so-called [Val] Preda Rossa shear zone (BERGER and GIERÉ, 1995) along the contact.

Due to the medium to high ambient temperatures at the emplacement levels of the MB magmas slow post-intrusive cooling is expected. Most of the dated minerals, however, only behave as stable geochronometers considerably below igneous solidification temperatures. Some U- and Th-enriched accessory minerals have closure temperatures near or above the solidus temperature of granitoid rocks and are suited for the age determination of slowly cooling igneous rocks. Estimates for the blocking temperatures of some important accessory minerals present in MB igneous rocks are: zircon U/Pb and Th/Pb: > 800 °C (HEAMAN and PARRISH, 1992), > 700 °C (OBERLI et al., 1996); monazite U/Pb: 725 ± 25 °C (PARRISH, 1990); allanite U/Pb and Th/Pb: > 700 °C (OBERLI et al., 1996). The U/Pb blocking temperature for titanite was found to be size-dependent between 600 °C and 650 °C (MEZGER et al., 1993), whereas ZHANG and SCHÄRER (1996) proposed a value of 712 °C for its lower limit.

6.2. EMPLACEMENT AGES OF THE MB IGNEOUS PHASES

An age range of 31.3 Ma to 31.7 Ma was determined by VON BLANCKENBURG (1990) for three zircons from a sample of a gabbro xenolith in the tonalite in Val Sissone. This is slightly younger than the 31.88 ± 0.09 Ma obtained from zircons of the enclosing tonalite (VON BLANCKENBURG, 1992).

In order to resolve this apparently contradictory age relationship between xenolith and host rock, VON BLANCKENBURG (1990) discussed three possible scenarios:

(i) The zircons from the gabbro had experienced Pb loss. This was ruled out by negative results of leaching tests of the gabbroic zircons.

(ii) The age difference is real and reflects the attainment of zircon saturation at different times in magma batches which separated from the same original mafic magma and then underwent different evolutionary paths. In the magma that evolved to tonalite (e.g. by assimilation-fractional crystallization-processes) zircon saturation was reached earlier than in the gabbroic magma, in which zircon saturation was attained only in the late interstitial liquid. Large blocks of such gabbro then were incorporated in partly solidified tonalite.

(iii) Zircon in the cumulitic gabbro represents a metamorphic reaction product of primary baddeleyite and formed during thermal pulses that followed the tonalite intrusion. This last hypothesis was favoured by von Blanckenburg, however, baddeleyite has not yet been observed in the gabbro.

The possibility of inheritance in the zircons from the tonalite has not been discussed, because the three zircons yielded overlapping apparently concordant ages. For these three zircon samples the weighted mean of the ^{206}Pb/^{238}U system yielded an average age of 31.88 ± 0.09 Ma. The application of the same calculation procedure to the ^{207}Pb/^{235}U system yields an average age of 32.18 ± 0.24 Ma. The data point of these average ages does not fall on the concordia curve, hence suggesting the presence of inherited components, as is also indicated by the zircon total fraction from the sample, and the real age of the tonalite may be younger than 31.88 Ma. However, because ^{207}Pb/^{235}U is very sensitive to analytical parameters the discrepancy between the ^{207}Pb/^{235}U age and the ^{206}Pb/^{238}U age might solely be due to analytical bias. In allanite inheritance appears to be rather rare (BARTH et al., 1993). The Th/Pb allanite age of 31.5 ± 0.35 of the same tonalite sample (VON BLANCKENBURG, 1992) matches the gabbro zircon ages and may better approximate the intrusion age. This allanite Th/Pb age, however, is not yet confirmed by other age data of similar precision in the area.

The sample from the western extension of the tonalitic intrusion near Bellinzona yielded zircon U/Pb ages between 32.9 and 32.0 Ma, and allanite Th/Pb ages from 32.0 to about 28 Ma (OBERLI et al., 1996). These ages were interpreted to approximate crystallization ages of the respective phases in an evolving magma, an interpretation that is supported by chemical data of these phases. The spread of the individual mineral ages documents a protracted crystallization interval of several million years for the tonalitic intrusion at this site. The prolonged cooling history of the tonalitic magma to its solidus (650–700 °C) supports the previous interpretation of the high grade metamorphic conditions at the level of emplacement.

Comparison of the zircon ages from the eastern and western samples of the tonalite shows that zircons from the west are older (32.9–32.0 Ma) than those from the east (≤ 31.88 Ma). However the zircons from the west have been abraded and hence represent only early stages of magmatic zircon formation, whereas the zircons from the east were complete crystals and document the whole interval of zircon growth. In many magmatic rocks (e.g. from the Adamello batholith, HANSMANN, 1986) zircons show enrichment of U and radiogenic Pb in their rims, indicating that their bulk radiogenic clocks formed relatively late with respect to crystal growth.

Although the mineral ages document several million years of the magmatic history of the tonalite for the western sampling site, the question of the exact time of its intrusion remains difficult to resolve. This difficulty stems from the fact that the exact setting of crystallization of the dated minerals during ascent and evolution of the magma are not well constrained. Based on Th/U systematics of the whole rock sample and of the dated accessories separated from it, OBERLI et al. (1996) concluded that substantial amounts of allanite and zircon had precipitated and had been removed before and during ascent to its final emplacement level. The authors gave an age estimate for the final emplacement of ≤ 31.5 Ma.

For the granodiorite from Val Bona, a northeastern sampling location, VON BLANCKENBURG (1992) determined on 3 mineral chronometers ages overlapping within errors limits. These ages overlap also with the 30.1 ± 0.3 Ma determined by GULSON and KROGH (1973) for thorite from granodiorite from the Albigna area. A weighted mean of the results obtained by 4 different chronometers resulted in an age of 30.15 ± 0.21 Ma (2 σ) for the intrusion of the granodiorite.

For the Novate Granite a U/Pb age on monazite of 26 Ma was determined (KÖPPEL and GRÜNENFELDER, 1975). At the time of publication of these data, closure temperatures were proposed for monazites as low as 530 °C (PURDY and JÄGER, 1976; WAGNER et al., 1977). Recalculation of the age of the monazite from the Novate granite using modified values for data correction and applying the decay constants recommended by STEIGER and JÄGER (1977) yielded a ^{207}Pb/^{235}U age of 25.0 Ma and a ^{206}Pb/^{238}U age of 25.4 Ma (KÖPPEL pers. comm., 1996). The fact, that ^{206}Pb/^{238}U age of this monazite sample is older by 0.4 Ma than the corresponding ^{207}Pb/^{235}U age suggests the presence of ^{206}Pb from initial excess of ^{230}Th in these monazites. Conservation of such signature of excess ^{206}Pb therefore indicates, that the monazites did not loose significant amounts of radiogenic lead even at temperatures above the granite solidus (620–650 °C) . The age of 25 Ma thus can be considered to closely approximate the intrusion age of the Novate granite. The same age has been obtained for a leucocratic dike NE of Bellinzona (GEBAUER, 1996), whereas ROMER et al. (1996) determined an age range from 20 to 29 Ma for similar dikes in the central and western Lepontinic area.

6.3. COOLING AND EXHUMATION HISTORY

Cooling after the peak of the Alpine metamorphism is reflected by older ages of minerals with

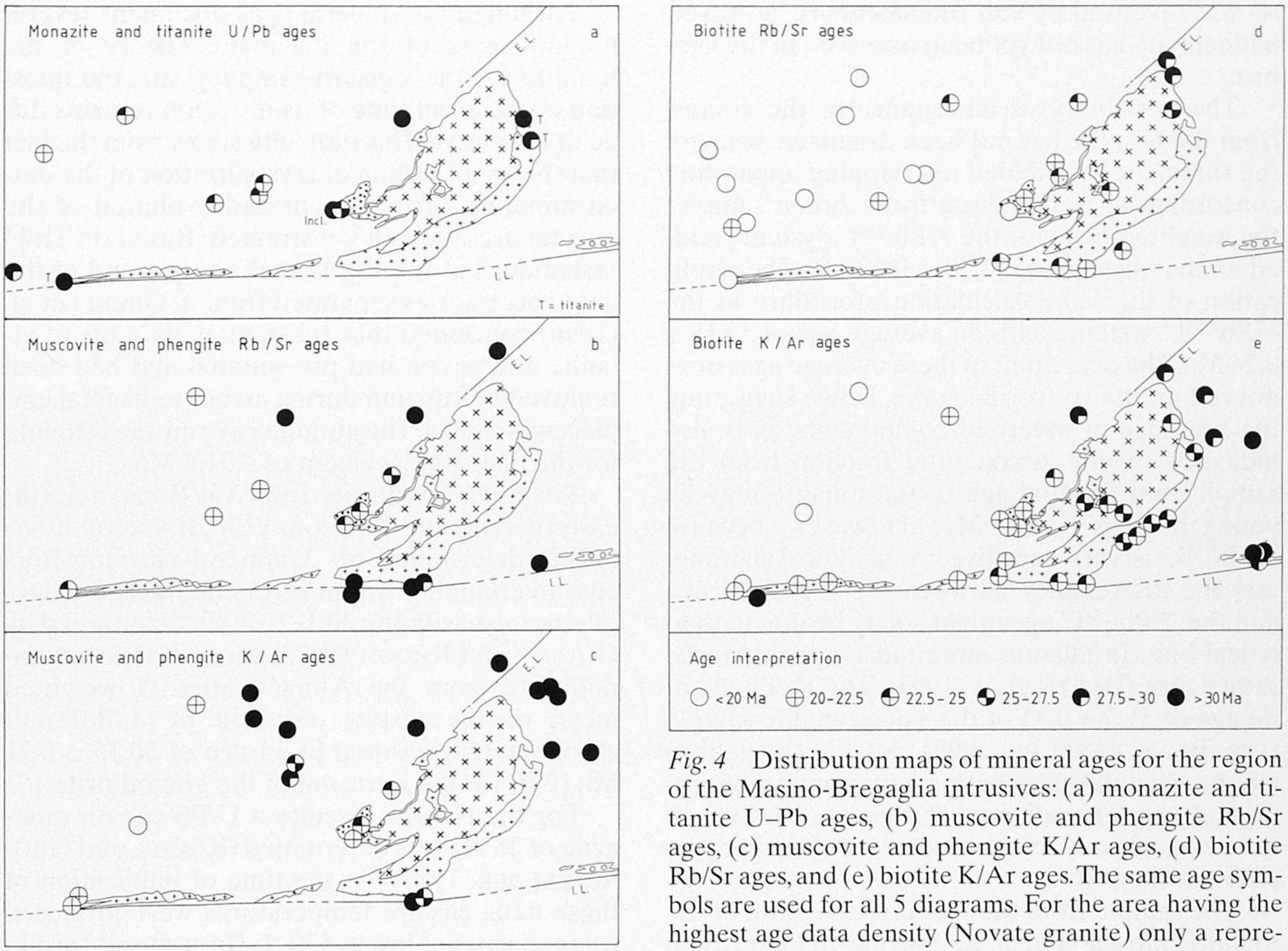

Fig. 4 Distribution maps of mineral ages for the region of the Masino-Bregaglia intrusives: (a) monazite and titanite U–Pb ages, (b) muscovite and phengite Rb/Sr ages, (c) muscovite and phengite K/Ar ages, (d) biotite Rb/Sr ages, and (e) biotite K/Ar ages. The same age symbols are used for all 5 diagrams. For the area having the highest age data density (Novate granite) only a representative part of the data are shown. The age symbol for the country rock inclusion in the Novate granite, labeled "Incl." in figure 4a is drawn overlapped by the age symbol of the corresponding host rock.

the highest blocking temperatures and progressively younger ages for those with the lowest closure temperatures. The large number of mica ages has allowed to map the regional distribution of cooling ages corresponding to the closure temperatures of the Rb/Sr systems of white mica and biotite (JÄGER et al., 1967), the K/Ar systems of white mica and biotite (PURDY and JÄGER, 1976) as well as the annealing temperature of apatite fission tracks (WAGNER et al., 1977).

Mineral ages from the MB intrusion and its frame are compiled in figures 4a (monazite and titanite U/Pb ages), 4b,c (white mica Rb/Sr and K/Ar ages) and 4d,e (biotite Rb/Sr and K/Ar ages). The mica ages show a general decrease towards the west.

Only a few ages for the peak of the Lepontine metamorphism or for the high-T stages of cooling in the MB region have been obtained by appropriate mineral chronometers. Two monazite U/Pb ages from country rocks W and NW of the main part the MB igneous body (Fig. 4a) of about 31 Ma (KÖPPEL and GRÜNENFELDER, 1975) indicate that in the eastern part of the Lepontine metamorphic dome, high-T metamorphism prevailed until about 30 Ma, whereas monazite ages from the Bellinzona area are about 27 Ma and for the north central Ticino about 21 Ma, respectively. The few U/Pb titanite ages (Fig. 4a), for which the closure temperatures of ≥ 600 °C are given (MEZGER et al., 1993; ZHANG and SCHÄRER, 1996), have been interpreted differently. In the area of Bellinzona, a U/Pb age of 32.8 Ma is considered as the age of metamorphic titanite formation (ROMER et al., 1996), a titanite age of 28.9 Ma from the Val Sissone tonalite reflects recrystallization or Pb loss (VON BLANCKENBURG, 1991) and a titanite age of 30.16 Ma from the MB granodiorite from Val Bona, which is identical with 3 other mineral chronometers, is interpreted as the age of intrusion (VON BLANCKENBURG, 1991).

Regional cooling is also not well documented for the medium temperature range (350–500 °C) in the MB intrusion, due to the lack of white mica in the MB igneous rocks. Furthermore only a few muscovite cooling ages are available for the Novate granite and the country rocks of the MB intrusion (Figs 4b, 4c).

Considerably more age data (K/Ar and Rb/Sr) exist for biotites (Figs 4d, 4e). In the eastern part of the MB region no significant differences are distinguished between biotite ages from the MB intrusion and from country rocks, indicating that below 300 °C these rocks shared a common exhumation history. This also probably holds for the western part, though is not directly supported by data.

The trend of decreasing ages to the west (Fig. 4d,e) is well documented by the K/Ar biotite profile of Villa and von Blanckenburg (1991) with ages from 26.4 Ma in the east to 21.0 Ma in the west. This trend is partly paralleled by Ar/Ar hornblende data (Villa and von Blanckenburg, 1991) and hornblende K/Ar ages (Wiedenbeck and Baur, 1986) but due to the presence of excess ^{40}Ar most of these ages cannot strictly be interpreted as cooling ages.

Age data obtained by different radiogenic clocks on the same sample allow the construction of a temperature-time path of the rock. If assumed that the vertical temperature gradient was constant, the exhumation history of the source region of the sample can also be derived. Despite the large number of age determinations there is only a limited number of samples available on which two or more age determinations have been performed.

Villa and von Blanckenburg (1991) reported a detailed cooling history for the easternmost part of the MB intrusive body (Fig. 5), assuming that the tonalite and the granodiorite shared the same cooling history after the intrusion of the latter. Cooling of the granodiorite started at an estimated solidus temperature of 680 °C at 30.1 Ma. The igneous rocks then cooled below the Ar/Ar blocking temperature of amphibole of 550 °C at 28.6 Ma and reached the 330 °C closure temperature of biotite 26.4 Ma ago. This initially high cooling rate of 90–100 °C/Ma was interpreted as the result of superposition of post-magmatic cooling (> 200 °C/Ma) upon slow regional metamorphic cooling (30–50 °C/Ma). However, if the data from the tonalite are examined separately a problem is revealed: For the time interval following intrusion at 31.88 Ma until passage through the blocking temperature of amphibole at about 550 °C at 28.6 Ma, a relatively slow cooling rate of approximately 50 °C/Ma would result. This is inconsistent with the expectation that post-magmatic cooling would proceed with the highest rate immediately after the intrusion when the thermal gradient between the intrusive body and its frame was at a maximum. A higher initial cooling rate would result if the amphibole age were interpreted as reset by the thermal pulse caused by the intrusion of the granodiorite (see Fig. 5), as has been hold responsible for the rejuvenation of the apatite and titanite U–Pb ages in the same tonalite sample (von Blanckenburg, 1992).

At its western end, the tonalite (Fig. 6) reached its solidus (650–700 °C) probably at about 28 Ma Oberli et al., 1996). It then cooled to 520 °C (a value within the range given by Harrison, 1981, for the closure temperature of igneous hornblende) by 24.8 Ma and reached 320 °C at 21.0 Ma (hornblende Ar/Ar and biotite K/Ar age by Villa and von Blanckenburg, 1991). Sm–Nd data of garnet that formed at about 600 °C from Castione in Val Leventina yield an isochron age of 26.7 ± 1.7 Ma (Vance and O'Nions, 1992), and fit well into this cooling scenario. The overall cooling

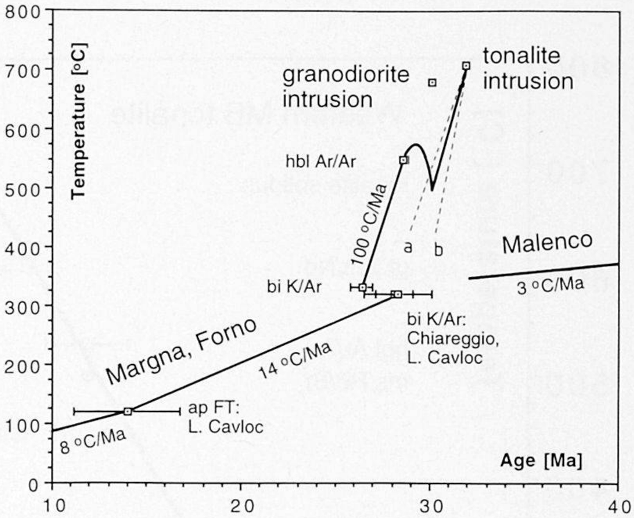

Fig. 5 Cooling of the eastern part of the MB igneous body and adjoining country rocks (Malenco, Margna and Forno units). The cooling history of the country rocks is compiled from data of Trommsdorff and Conolly (1996: Malenco) and age data of samples, which were not or only weakly affected by the MB contact metamorphism, from Wagner et al. (1977: L. Cavloc apatite FT), Hunziker et al. (1992: Chiareggio biotite K/Ar) and Giger (1991: L. Cavloc biotite K/Ar). A hypothetical cooling path is shown for the tonalite (sample Siss3 of von Blanckenburg, 1991 and Villa and von Blanckenburg, 1992). Paths for rapid post magmatic cooling (dashed lines a and b) are drawn for rates of (a) 100 °C/Ma and (b) 200 °C/Ma, respectively. After initial rapid cooling the tonalite was reheated by the thermal pulse from the granodiorite intrusion to a temperature sufficiently hot to prevent Ar retention in hornblende. After cooling below the closure temperature of biotite, the tonalite shared the cooling history with the country rocks.

rate from the tonalite solidus to the closure temperature of biotite in the region of the western part of the tonalite amounts to approximately 50 °C/Ma. Hurford (1986) inferred a mean cooling rate of 65 °C/Ma for the Maggia-Locarno area north of the Insubric Line (Southern Steep Belt or "root zone" of the Penninic nappes) for the time between 23 and 19 Ma. For the period from 19 Ma until the present a mean cooling rate of 14 °C/Ma was calculated. Hurford (1986) also noted that cooling in the Southern Steep Belt started earlier than in the nappes further to the north.

The most complete data set was obtained on the Novate Granite sample KAW553 (Fig. 7; Jäger and Hunziker, 1969; Purdy and Jäger, 1976; Wagner et al., 1977, see table 1). This peraluminous granite intruded 25 Ma ago (Köppel, 1996, pers. comm.) when the MB intrusive body and surrounding rocks had already cooled to the closure temperature of biotite of approximately 300 °C (Wagner et al., 1979). The Novate granite initially cooled at a high mean rate of > 100 °C/Ma to 300 °C at 22 Ma. According to Wagner et al. (1979) cooling then slowed to a rate of 20 °C/Ma until 14 Ma and finally reached 6 °C /Ma during the last 14 Ma.

The exhumation histories (exhumation in the sense of England and Molnar, 1990) of different parts of the MB intrusive body can approximately be assembled from the intrusion ages, the regional cooling histories and assumed average values for the geothermal gradient needed for the calculation of exhumation rates. According to Wagner et al. (1977) exhumation rates are calculated by the formula: uplift [= exhumation] rate = cooling rate/geothermal gradient. Exhumation rates effective during the time the samples cooled through the fission track blocking temperature of apatite have also been derived from the linear relationship between the apatite fission track age and sampling elevation (Wagner et al., 1977, 1979).

Despite the lack of clear age relations between the local metamorphic peak and intrusion

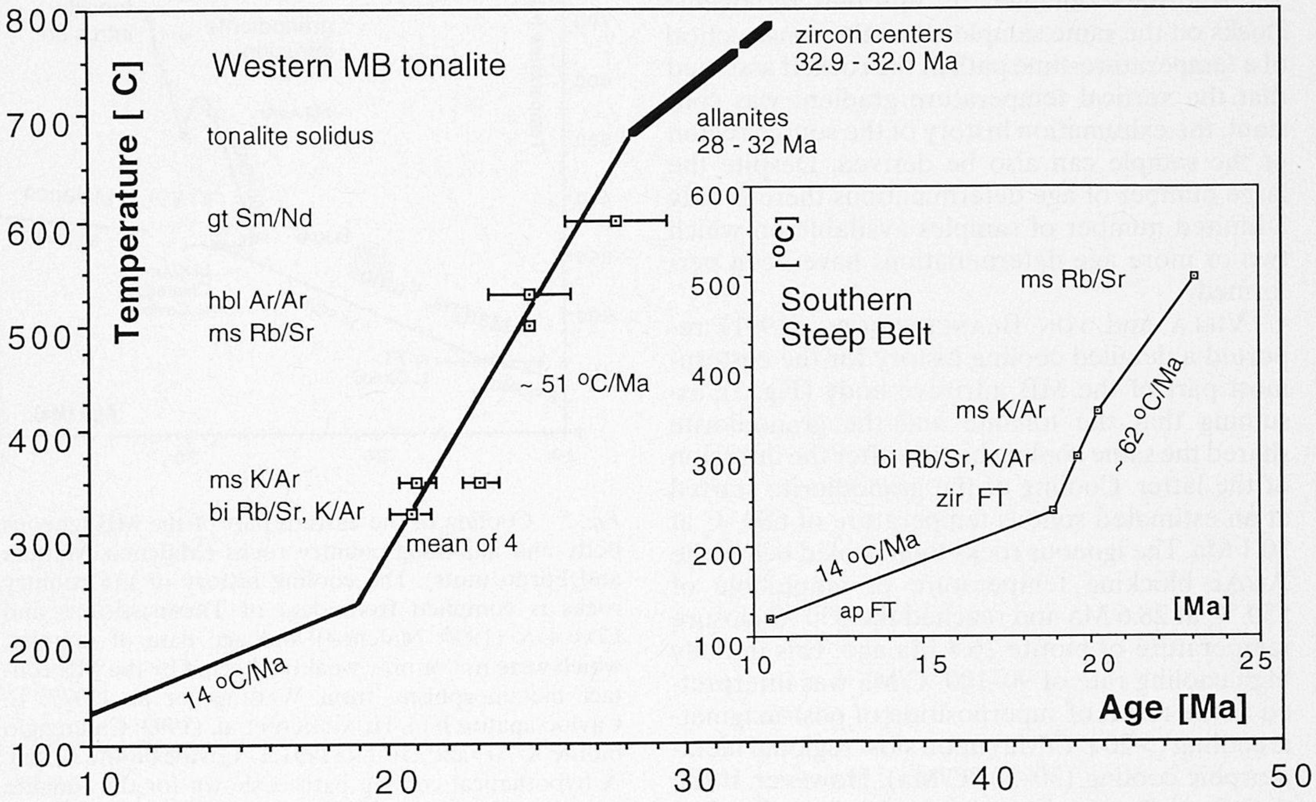

Fig. 6 Cooling history of the western part of the MB tonalite S of Bellinzona. The cooling path is drawn using age data of samples from the MB tonalite or nearby country rocks from Oberli et al. (1996), Villa and von Blanckenburg (1991), Giger (1991) and Romer et al. (1996). The garnet Sm/Nd age of the Castione sample (Vance and O'Nions, 1992) is shown for comparison. Mineral cooling ages were adjusted to an altitude of 1900 m for an exhumation rate of 1.7 mm/year. The starting point of the cooling curve above the tonalite solidus of ~ 680 °C (Lambert and Wyllie, 1974) is given by the older age of the abraded zircon centers (approximating zircon nucleation) and an estimated temperature of 750–800 °C for zircon saturation in a tonalitic magma (Hansmann and Oberli, 1991). The lower part of the cooling curve is approximated by the cooling history of the Southern Steep Belt near Locarno (see inset) given by Hurford (1986).

of the western extension of the tonalite near Bellinzona, it is tentatively postulated that the MB intruded during the extended period when peak metamorphic conditions prevailed. Assuming an average geothermal gradient of 30 °C/km the tonalite in the Southern Steep Belt near Bellinzona may have been exhumed between 28 and 19 Ma at a mean rate of 1.66 mm/a followed by a mean rate of 0.47 mm/a from 19 Ma until present. Integration of this exhumation history would yield an original depth for the tonalite in that region of approximately 24 km, a value only little less than the 27 km derived from geobarometry (REUSSER, 1987).

For the eastern part of the MB intrusive body only partial exhumation paths can be constructed. This is due to the fact that the cooling history above 350 °C reflects magmatic cooling superimposed on regional cooling and that there is a lack of samples for which all stages of the cooling history have been dated. For the Novate area an exhumation rate of 0.7 mm/year for the time between 22 and 13.5 Ma and a value of about 0.2 mm/year for the most recent 13 Ma were estimated by WAGNER et al. (1979; Fig. 8).

These authors also concluded from their fission track data that the MB igneous rocks were uplifted earlier through the 120 °C isotherm than the surrounding units from which they are separated by the Insubric, Engadine and Muretto faults. However, their conclusion appears to be supported only in the case of the Insubric Line. In the case of the Engadine Line one of the samples used for construction of their hypothesis is shown as having been collected north of it (in Fig. 1 by WAGNER et al., 1979) contradicting the reported sampling location south of the Engadine Line. Samples from opposite sides of the Engadine Line in the Maloja area (KAW 90 and KAW 328) show within error limits identical ages (14–15 Ma) suggesting that the vertical movements along this line were older than 15 Ma. BERGER et al. (1996) argue, that major movements along this post-intrusive brittle fault (LINIGER, 1992) were likely to have taken place between 30 and 25 Ma. An alternative regression through the samples 1, 2 and 3 of WAGNER et al. (1979) from the regionally very restricted Val Bondasca–Val Bregaglia area would yield an exhumation rate of about 0.2 mm/year (Fig. 8) which is similar to the one obtained for the southern part of the MB intrusion. Furthermore such a regression would also indicate that exhumation of the the MB intrusive body through the 120 °C isotherm took place later in its northern part than in its southern part. A similar exhumation scenario was observed further to the west in the Maggia area (HURFORD, 1986).

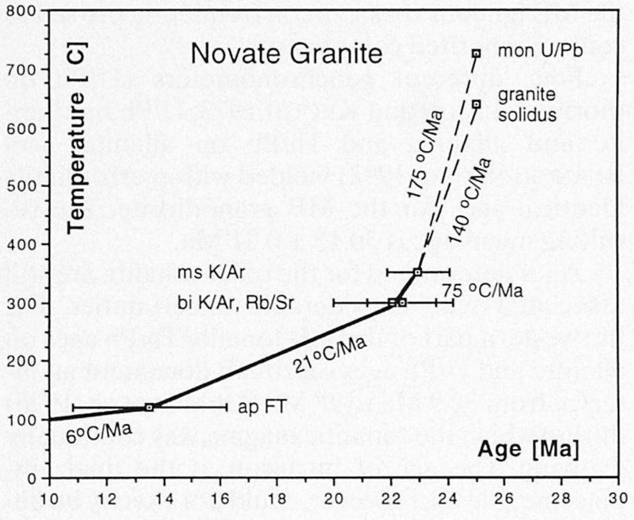

Fig. 7 Cooling history of the Novate granite sample KAW 553 from WAGNER et al. (1979). Diagram modified. The monazite U/Pb age of 25 Ma (KÖPPEL, 1996, pers. comm.) is shown for an estimated granite solidus temperature of 640 °C on the basis of phase diagrams from NANEY (1983) and for its U/Pb closure temperature of 725 °C according to PARRISH (1990). The interpretation of the monazite U/Pb age with respect to the thermal history of the granitic magma remains uncertain. If the monazite formed above the closure temperature of its U/Pb system, then the age reflects cooling through the 725 °C isograd otherwise it reflects monazite formation between 725 °C and a minimum temperature given by the granite solidus of 640 °C.

The biotite K/Ar and apatite fission track ages of MB boulders from the Gonfolite Lombarda

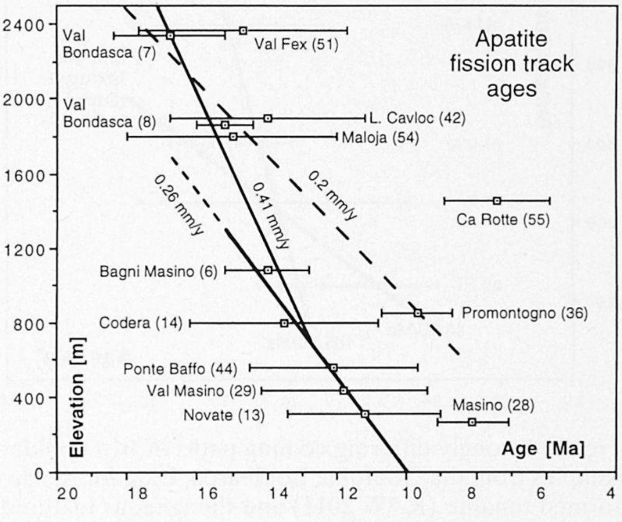

Fig. 8 Elevation versus age diagram of apatite fission track data from WAGNER et al. (1979). Error bars represent 2 σ errors. The samples are labeled by the sampling locality and a location number referring to figure 2. An alternative hypothesis for the northern MB area (dashed line) yields an exhumation rate of 0.2 mm/year which is very similiar to the exhumation rate of 0.26 mm/year obtained for the Val Masino and Novate areas.

(Wagner et al., 1977 and 1979; Giger and Hurford, 1989; Bernoulli et al., 1993) are generally several million years older than those obtained on the igneous rocks currently exposed (Eberhard et al., 1966; Wiedenbeck, 1985; Wagner et al, 1979; Villa and von Blanckenburg, 1991). Thus the source region of the boulders had cooled to 300 °C, and 120 °C respectively, significantly earlier than the rocks outcropping currently, indicating a considerable original vertical distance between these two different levels of the same intrusion. Furthermore cooling rates derived for the temperature range between 300 °C to 120 °C also yielded generally higher values for the MB boulders (50–90 °C/Ma) than for the in situ intrusives (20 °C/Ma; Wagner et al., 1979). Among the boulders a sample of deformed tonalite yielded a value in excess of 150 °C/Ma (Fig. 9). For this sample Giger and Hurford (1989) determined an amphibole K/Ar age which was only about 2 Ma older than the apatite fission track age. Their interpretation was that this tonalite sample had been uplifted from about 15 km (corresponding to an ambient temperature between 400 °C and 500 °C, for the estimated closure temperature for the K/Ar system of hornblende) to about 2 km (estimated depth limit for the preservation of fission tracks in apatite) within 2 million years which would indicate an exhumation rate of 5–6 mm/year. Because other boulders that showed the same biotite K/Ar age yielded much slower cooling and exhumation rates, one has to conclude that either rapid exhumation was restricted to narrow zones (e.g. the Preda Rossa shear zone), or that the high cooling rate of this sample rather reflects post-magmatic cooling at a shallow crustal level.

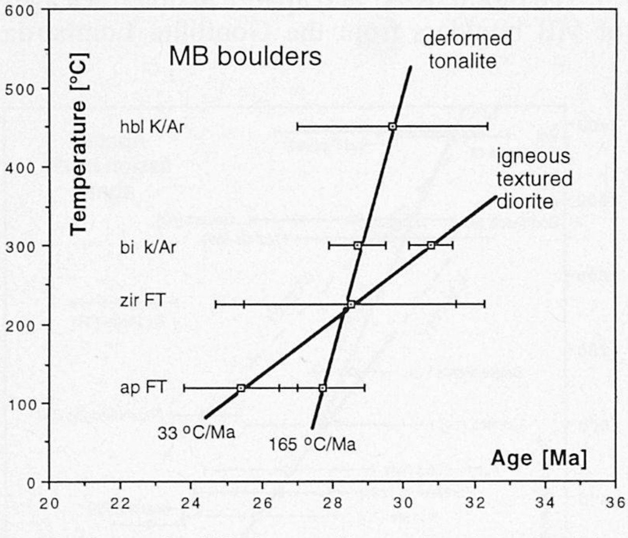

Fig. 9 Strongly differing cooling paths of two boulder samples from the Gonfolite Lombarda. Data for the deformed tonalite (KAW 2011) and the igneous textured diorite (KAW 2025) are from Giger and Hurford (1989). Errors are shown for the 2 σ level. The igneous textured diorite showing slow cooling (33 °C/Ma) is interpreted to originate from a shallow level of the MB intrusion, whereas the deformed tonalite with a high cooling rate of ~ 165 °C/Ma must have been uplifted from a depth of about 15 km within few million years according to Giger and Hurford (1989).

7. Summary and outlook

The MB intrusive body had been estimated to be of Oligocene to Miocene age early in this century (Cornelius, 1913; Staub, 1916). Absolute dating of MB igneous rocks by application of radiometric methods developed since the 1960's, however, have yielded substantial refinements to this previously postulated age of the MB intrusions, albeit only recently. It was the particular geologic situation of the MB igneous body – its deep emplacement level in an ambient high pT-regime – which is the cause of why most of the dating methods available were a priori not suited to determine accurately the intrusion age of the MB igneous rocks. Among the few accessory minerals with radiogenic clocks (U/Pb and Th/Pb) stable up to magmatic temperatures and thus suited for dating the MB igneous rocks, zircon frequently proved to contain inherited components.

Four different geochronometers (U/Pb on thorite: Gulson and Krogh, 1973; U/Pb on titanite and allanite, and Th/Pb on allanite: von Blanckenburg, 1992) yielded within error limits identical ages for the MB granodiorite. The resulting mean age is 30.15 ± 0.21 Ma.

Ages determined for the older tonalite are still associated with considerable uncertainties. For the western part of the MB tonalite Th/Pb ages on allanite and U/Pb ages on zircon document an interval from 32.9 Ma to 28 Ma (Oberli et al., 1996) during which the tonalitic magma was continually evolving. The age of intrusion at the final emplacement level, however, could not exactly be determined. At a sampling location in the east, a zircon U/Pb age of 31.88 ± 0.09 Ma determined for the tonalite (von Blanckenburg, 1992) conflicted with that of an enclosed gabbro (von Blanckenburg, 1990) dated at 31.3–31.7 Ma.

For the Novate granite a monazite U/Pb age of 25 Ma (Köppel and Grünenfelder, 1975; Köppel, 1996) was determined.

Cooling and exhumation of the MB igneous body and the surrounding units is well documented by many mineral cooling ages. Due to its deep emplacement level the MB intrusive body mainly shared its cooling and exhumation history with the ambient Lepontine metamorphic dome. Only at its eastern, shallower end did the MB igneous body initially cool with a high rate and converge with regional cooling at about the closure temperature of biotite. Regional cooling is markedly earlier in the east. Exhumation rates of the MB intrusive body have been derived from its cooling history. For the western part near Bellinzona an initially high exhumation rate of approximately 1.7 mm/year was inferred. Rates then slowed down to reach an average of 0.47 mm/year during the past 19 Ma. For the Novate area the inferred exhumation rates were 0.7 mm/year between 22 Ma and 13.5 Ma and 0.2 mm/year from 13 Ma to the present (WAGNER et al., 1979).

Cooling ages obtained on MB boulders from the Gonfolite Lombarda sediments are consistently older than corresponding ages from in situ MB samples, reflecting a source level of the boulders in the original intrusion substantially above the levels currently exposed at the surface. A maximum depositional age of the Como Conglomerate containing MB boulders was determined as 29.2 ± 3.2 Ma (BERNOULLI et al., 1993), indicating that by this time parts of the MB intrusion already had reached the surface and had became eroded, whereas deeper parts of the intrusion currently exposed S of Bellinzona were still above the solidus temperature and at a depth of about 27 ± 4 km (REUSSER, 1987).

With respect to the geochronology of the MB igneous body there are still many uncertainties. No age data are available for the intrusion of several generations of dikes: the basaltic-andesitic precursors, the calc-alkaline and shoshonitic partly disintegrated dikes in the granodiorite, and the various generations of leucocratic dikes pertaining to the MB and the Novate intrusions.

Crystallization of a magma over several million years, as interpreted by OBERLI et al. (1996) for the westernmost part of the MB intrusion, introduce new problems for the interpretation of age results as the chronometers of some accessory minerals date the time of their closure and this may be any time between magma emplacement and cooling through the liquidus. In addition, OBERLI et al. (1996) found evidence that a fraction of the dated zircons and allanites formed in the magma prior to ascent to the final emplacement site. Thus U/Pb mineral age relations may be in conflict with field relations if the dated U/Pb phases of neighbouring intrusives had undergone different crystallization histories. Furthermore zircon U/Pb ages of deep-seated granitoid intrusions in high-grade metamorphic terrains might by too old by several million years. In such cases the textural relations of the dated accessories are of key importance for the interpretation of the determined U/Pb ages.

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Appendix

Tab. 1 Age results for the Masino-Bregaglia intrusives and the surrounding units. Mineral abbreviations and the explanations given for the different columns apply to table 1 and table 2.

Mineral abbreviations:
all = allanite; ap = apatite; bi = biotite; chl = chlorite; gt = garnet; hb = hornblende; ks = alkali feldspar; ky = kyanite; mon = monazite; ms = muscovite; phe = phengite; plg = plagioclase; qz = quartz; sap = sapphirine; sil = sillimanite; tho = thorite; tit = titanite; WR = whole rock; zir = zircon.

Explantions to table columns:
Sample: Original sample labels are used. If such were lacking the samples were labelled with the initals of the first author of the cited source followed by numbers in increasing order.
Location: *1: Two different sampling locations are given: Albigna dam and Capanna del Forno. *2: The sample location and petrographic description of this amphibolite suggest, that it could be a MB tonalite from the westernmost part of the tonalite tail near Bellinzona.
Loc.: Number refers to location number shown on figure 2. Samples from sites very close to each other are shown under one location number only.
Method.: FT = fission track, RD = radiation damage; Pb/α = Lead-Alpha.
Age: The ages are given in million years. Ages calculated with decay constants different from those recommended by Steiger and Jäger (1977) have been adjusted and are annoteded by *A under remarks. U/Pb ages: ^{206}Pb/^{238}U and the ^{207}Pb/^{235}U age are given in this order for concordant cases; for little discordant cases only the ^{206}Pb/^{238}U age is given, strongly discordant zircons are either represented by: disc = discordant or the cause for discordance: inh. = inheritance, loss = Pb loss. Age ranges given are explained in the text.
±: Age error in million years. Errors are given for the 2 σ-level; various exceptions are annotated under remarks. n.i. = not indicated.
Remarks: *A: Age has been adjusted to decay constants recommended by Steiger and Jäger (1977). Factors applied fur such age correction are the following: f(K/Ar) = 1.0265; f(Rb/Sr) = 1.0352; f(^{207}Pb/^{235}U) = 0.987; f(^{206}Pb/^{238}U) = 0.993. *D: ^{206}Pb/^{238}U age has been corrected for radioactive disequilibrium (Schärer, 1984). *M followed by number n: If n age determinations for an identical sample were given, the mean was calculated and the error was calculated by Gaussian error propagation. *S followed by a number n: Age calculated from SHRIMP analyses at n spots. *Sr: Ages were calculated by the referenced authors using a value for "common" Sr shown in parantheses.
Remarks relevant for errors: *a and *b mark errors which have been calculated by the authors using formulas given in ref. 4 p. 6 and ref. 3 p. 27 resp.; *c: general error estimates were given for the ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages of 1% and 1.5% respectively. *d Error estimate based on reproducibility tests from other labs. *e: The errors given in ref. 6 resemble 1 σ errors if compared with errors of refs. 5,18 and 27. *n: A statement for the meaning of the given errors is lacking in the referenced source of data.
Ref.: The numbers refer to the following sources of data: **1** Armstrong et al., 1966; **2** Jäger and Hunziker, 1969; **3** Jäger et al., 1967; **4** Purdy and Jäger, 1976; **5** Wagner et al., 1977; **6** Wagner et al., 1979; **7** Hanson et al., 1966; **8** Weber, 1966; **9** Gulson, 1973; **10** Grünenfelder and Stern, 1960; **11** Chessex, 1964; **12** Gulson and Krogh, 1973; **13** Köppel and Grünenfelder, 1975; **14** Hänny et al., 1975; **15** Deutsch and Steiger, 1985; **16** Wiedenbeck and Baur, 1986; **17** Wiedenbeck, 1986; **18** Giger and Hurford, 1989; **19** Villa and von Blanckenburg, 1991; **20** von Blanckenburg, 1992; **21** Bernoulli et al., 1993; **22** Lardelli, 1981; **23** Vance and O'Nions, 1992; **24** von Blankkenburg, 1990; **25** Hunziker et al., 1992; **26** McDowell, 1970; **27** Oschidari and Ziegler, 1992; **28** Gebauer, 1996; **29** Trommsdorff, 1996, pers. comm.; **30** Wenk et al., 1974; **31** Köppel, 1996, pers. comm.; **32** Oberli et al., 1996; **33** Romer et al., 1996; **34** Giger, 1991; **35** Fuhrmann et al., 1987; **36** Munardi, 1989.

Tab. 1

Sample	Rock type	Tectonic unit	Loc.	Location	Coordinates	Alt.	Method	Age	±	Remarks	Ref.
29 Bs 2	qz diorite	MB intrusion	1	1 km E Sorico	751.0/115.3	200	Zir RD	32.0	n.i.		11
31 Bl 3	qz monzonite	MB intrusion	2	Vallun dal Largh			Zir RD	24.0	n.i.		11
44 Bs 2	qz diorite	MB intrusion	3	N Nouva Olonia	754.4/115.6	200	Zir RD	33.0	n.i.		11
KAW 2399	tonalite	MB intrusion	3	S Lago di Mezzola	754.55/115.81	204	Bi K/Ar	25.4	1.8		36
KAW 48	tonalite	MB intrusion	3	S Lago di Mezzola	754.65/116.03	560	Bi Rb/Sr	22.6	2.3	*A,*Sr (0.7091),*b	3
KAW 48B	tonalite	MB intrusion	3	S Lago di Mezzola	754.65/116.03	210	Bi K/Ar	22.8	0.6		34
Mer 1	tonalite	MB intrusion	3	N Nouva Olonia	754.3/115.7	200	Hb Ar/Ar	28.80	0.33		19,24
Mer 1	tonalite	MB intrusion	3	N Nouva Olonia	754.3/115.7	200	Bi K/Ar	23.7	0.6		19,24
57 Bl 5	qz monzonite	MB intrusion	4	Val Bondasca			Zir RD	21.0	n.i.		11
Alb 1	granodiorite	MB intrusion	5	Lago d'Albigna	770.0/132.0	2200	Zir Pb/α	30.0	10.0	fine fraction	10
Alb 1	granodiorite	MB intrusion	5	Lago d'Albigna	770.0/132.0	2200	Zir Pb/α	25.0	10.0	coarse fraction	10
B 17	granodiorite	MB intrusion	6	Bagni del Masino	766.82/123.4		Bi Rb/Sr	23.2	1.3	*A, *Sr (0.7091), debris	3
B 17	granodiorite	MB intrusion	6	Bagni del Masino	766.82/123.4		Bi K/Ar	23.9	0.3	debris	34
BM 7	BM igneous rock	MB intrusion	6	Bagni del Masino		1080	Ap FT	14.0	0.6	*n, *e	6
KAW 918	tonalite	MB intrusion	6	Bagni del Masino	767.1/123.4	1100	Zir U/Pb	inh.		2 discordant fractions	12
KAW 918	tonalite	MB intrusion	6	Bagni del Masino	767.1/123.4	1100	Tit U/Pb	32.6		*A	12
KAW 918	tonalite	MB intrusion	6	Bagni del Masino	767.1/123.4	1100	Ap U/Pb	19.5		*A	12
KAW 919	granodiorite porph.	MB intrusion	6	Bagni del Masino	766.9/123.4	1100	Zir U/Pb	inh.		3 discordant fractions	12
Mas 19	tonalite	MB intrusion	6	Bagni del Masino	767.15/123.44		Hb K/Ar	32.0	1.2		15
MW 6	tonalite	MB intrusion	6	Bagni del Masino	767.2/123.5		Hb K/Ar	32.1	1.0		16
BM 2	BM igneous rock	MB intrusion	7	Val Bondasca		2340	Ap FT	16.8	0.8	*n, *e	6
BM 3	BM igneous rock	MB intrusion	8	Val Bondasca		1860	Ap FT	15.3	0.7	*n, *e	6
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	Tho Th/Pb	27.56	0.30	Pb loss	20
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	Ap U/Pb	29.4	1.2	*D	20
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	All Th/Pb	30.1	0.25		20
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	Zir U/Pb	inh.,loss			20
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	Tho U/Pb	28.33	0.07	Pb loss	20
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	All U/Pb	30.5	0.59	*D	20
Bona 1	granodiorite porph.	MB intrusion	9	Val Bona	776.8/132.4	2550	Tit U/Pb	30.16	0.24	*D	20
Ge 20	tonalite	MB intrusion	10	Alpe Gesero	730.5/115.7	1890	Hb Ar/Ar	24.6	1.4	pseudo isochron	19,24
Ge 20	tonalite	MB intrusion	10	Alpe Gesero	730.5/115.7	1890	Bi K/Ar	21.0	0.6		19,24
Iorio 2	tonalite	MB intrusion	11	Alpe la Boga	734.12/115.4	1850	Hb Ar/Ar	26.01	0.77	pseudo isochron	19,24
Iorio 2	tonalite	MB intrusion	11	Alpe la Boga	734.12/115.4	1850	Bi K/Ar	21.0	0.6		19,24
KAW 1040	granite	Novate intrusion	12	Novate / Codera	756.3/121.3	650	Zir U/Pb	inh.		1 fraction	12

Tab. 1 (cont.)

Sample	Rock type	Tectonic unit	Loc.	Location	Coordinates	Alt.	Method	Age	±	Remarks	Ref.
KAW 2620	leucogranite	Novate intrusion	12	E Novate	756.05/121.25	625	Ms K/Ar	21.8	0.4	*M 3	36
KAW 2620	leucogranite	Novate intrusion	12	E Novate	756.05/121.25	625	Bi K/Ar	21.5	0.6	*M 3	36
KAW 2620	leucogranite	Novate intrusion	12	E Novate	756.05/121.25	625	Zir FT	18.1	3.2		34, 36
KAW 2620	leucogranite	Novate intrusion	12	E Novate	756.05/121.25	625	Ap FT	15.1	2.2		36
KAW 132	pegmatite	Novate intrusion	13	Novate-Mezzola	755.52/121.28	310	Ms Rb/Sr	22.5	1.6	*A,WR corr., *b	3
KAW 132	pegmatite	Novate intrusion	13	Novate-Mezzola	755.52/121.28	310	Ap FT	11.2	2.4	*e	5
KAW 133	granitic gneiss	Novate intrusion	13	Novate-Mezzola	755.52/121.28	310	Bi Rb/Sr	18.3	1.0	*A, WR corr., *b	3
KAW 2401	tonalite	MB intrusion	13	Novate-Mezzola	755.05/121.30	204	Bi K/Ar	21.0	0.6	enclave in Novate Granite	36, 34
KAW 2621	leucogranite	Novate intrusion	14	Monticello	757.35/122.3	1025	Zir FT	19.9	3.6		34, 36
KAW 2621	leucogranite	Novate intrusion	14	Monticello	757.35/122.3	1025	Bi K/Ar	21.9	1.6	*M 2, bi-chl	36
KAW 2621	leucogranite	Novate intrusion	14	Monticello	757.35/122.3	1025	Ap FT	16.7	2.6		36
KAW 553	granite	Novate intrusion	14	Codera	757.15/123.05	800	Ms K/Ar	22.9	1.1	*A, *a	4
KAW 553	granite	Novate intrusion.	14	Codera	757.15/123.05	800	Ms Rb/Sr	24.5	9.4	*A, WR corr., *n	2,4
KAW 553	granite	Novate intrusion.	14	Codera	757.15/123.05	800	Bi Rb/Sr	22.1	2.1	*A, WR corr., *n	2,4
KAW 553	granite	Novate intrusion	14	Codera	757.15/123.05	800	Ap FT	13.5	2.7	*e	5
KAW 553	granite	Novate intrusion	14	Codera	757.15/123.05	800	Bi K/Ar	22.4	1.2	*A, *a	4
KAW 935	granodiorite porph.	MB intrusion	15	Albigna dam	769.8/134.2	2110	Ap U/Pb	28.0		*A	12
KAW 935	granodiorite porph.	MB intrusion	15	Albigna dam	769.8/134.2	2110	All U/Pb	34.2		*A	12
KAW 935	granodiorite porph.	MB intrusion	15	Albigna dam	769.8/134.2	2110	Tho U/Pb	30.1/29.9	~ 0.3	*A, "monazite"	12
KAW 935	granodiorite porph.	MB intrusion	15	Albigna dam	769.8/134.2	2110	Zir U/Pb	inh.		4 discordant fractions	12
KAW 935	granodiorite porph.	MB intrusion	15	Albigna dam	769.8/134.2	2110	Tit U/Pb	28.8		*A	12
KAW 2622	leucogranite	Novate intrusion	16	Riva (Novate)	754.67/121.67	207	Zir FT	18.1	3.0		34, 36
KAW 2622	leucogranite	Novate intrusion	16	Riva (Novate)	754.67/121.67	207	Bi K/Ar	21.4	1.6	*M 2	36
KAW 2622	leucogranite	Novate intrusion	16	Riva (Novate)	754.67/121.67	207	Ap FT	13.1	4.0		36
KG 13	granite	Novate intrusion	16	Riva (Novate)	754.45/121.85	210	Mon U/Pb	26.0	n.i.		13
KG 13 a	granite	Novate intrusion	16	Riva (Novate)	754.45/121.85	210	Mon U/Pb	25.4/25.0	n.i.	same sample as KG 13	31
KG 14	inclusion in granite	Novate intrusion	16	Riva (Novate)	754.45/121.85	210	Mon U/Pb	30.5	n.i.		13
LC-DS01	tonalite	MB intrusion	17	2 km N Traona	761.24/114.78		Hb K/Ar	28.8	2.2		17
LC-DS01	tonalite	MB intrusion	17	2 km N Traona	761.24/114.78		Bi K/Ar	23.6	0.5	*M 2	17
LC-DS01	tonalite	MB intrusion	17	2 km N Traona	761.24/114.78		Bi Rb/Sr	23.5	0.5	bi-WR-isochron	17
MW 4	tonalite	MB intrusion	17	2 km NW Mello	761.2/114.8		Hb K/Ar	29.8	1.0		16
Ma 1	tonalite	MB intrusion	18	SW Cataeggio	769.05/119.6	900	Hb Ar/Ar	28.3	2.4	pseudo isochron	19, 24
Ma 1	tonalite	MB intrusion	18	SW Cataeggio	769.05/119.6	900	Bi K/Ar	25.9	0.6		19, 24
MW 1	augengneiss	MB intrusion	19	Jorio Pass	732.5/114.6		Hb K/Ar	28.6	1.0		16

Tab. 1 (cont.)

Sample	Rock type	Tectonic unit	Loc.	Location	Coordinates	Alt.	Method	Age	±	Remarks	Ref.
MW 2	tonalite	MB intrusion	20	Jorio Pass	732.1/114.9		Hb K/Ar	29.6	0.9		16
MW 3	tonalite	MB intrusion	21	Livo	745.5/114.7		Hb K/Ar	29.6	1.0		16
MW 7	tonalite	MB intrusion	22	Val Preda Rossa	776.0/123.8		Hb K/Ar	36.0	0.9		16
MW 5	tonalite	MB intrusion	23	Val Masino	770.2/120.5		Hb K/Ar	29.5	0.8		16
Siss 1	gabbro	MB intrusion	24	Alpe Sissone	777.3/130.2	2460	Zir U/Pb	31.3–31.7			24
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	All U/Pb	34.1	0.51	*D	20
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	Bi K/Ar	26.4	0.6		19, 24
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	Ap U/Pb	28.6	0.76	*D	20
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	All Th/Pb	31.5	0.35		20
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	Hb Ar/Ar	28.59	0.16		19, 24
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	Zir U/Pb	31.88	0.09	3 concordant; 2 discordant	20
Siss 3	tonalite	MB intrusion	24	Val Sissone	777.1/129.9	2450	Tit U/Pb	28.9	0.32	*D	20
Sor 1	tonalite	MB intrusion	25	Sorico	749.3/115.39	210	Bi K/Ar	22.5	0.6		19, 24
Sor 1	tonalite	MB intrusion	25	Sorico	749.3/115.39	210	Hb Ar/Ar	31.3	1.5	pseudo isochron	19, 24
Z6	granodiorite porph.	MB intrusion	26	Cap. d. Forno (*2)	774.8/133.7	2570	Bi K/Ar	24.6	2.5	*A, *d,	1
Z6	granodiorite porph.	MB intrusion	26	Cap. d. Forno (*2)	774.8/133.7	2570	Bi Rb/Sr	25.8	1.5	*A, *M 2, *Sr (0.7091), *b	3
FM 2	amphibolite	MB intrusion ??	27	V. Morobbia (*1)	723.15/114.49	600	Hb K/Ar	26.3	0.8	N of Insubric Line	26
FO-96	tonalite	MB intrusion	27	Val Morrobbia			Zir U/Pb	32.9–32.0	n.i.		32
FO-96	tonalite	MB intrusion	27	Val Morobbia			All U/Pb	28–32.0	n.i.		32
KAW 3287	pegmatite	Bellinzona zone	27	E Pianezzo	723.25/114.5	620	Ms K/Ar	22.3	0.6		34
KAW 3287	pegmatite	Bellinzona zone	27	E Pianezzo	723.25/114.5	620	Ms Rb/Sr	24.0	0.2	K-feldspar corr.	34
KAW 3289	tonalite	MB intrusion ??	27	S Paudo	723.20/114.46	590	Bi K/Ar	20.4	0.8		34
BM 10	pre-intrusive rock	Southern Alps	28	V. Adda / V. Masino		265	Ap FT	8.1	0.5	*n, *e	6
BM 6	pre-intrusive rock	Tonale series	29	Val Masino		430	Ap FT	11.8	1.2	*n, *e	6
Cal 30	amphibolite	Cima Lunga	30	Val Calanca	730.7/123.67		Hb K/Ar	24.9	0.5	3 fractions-isochron	15
CH88-3	calcsilicate	Castione zone	31	Castione	~ 723.8/121.2		Gt Sm/Nd	26.7	1.7	5-pt.-isochron	23
KAW 76	bi-ms-gneiss	Castione zone	31	Castione	723.85/121.0	260	Ap FT	6.9	1.4	*e	5
KAW 76	bi-ms-gneiss	Castione zone	31	Castione	723.85/121.0	260	Bi Rb/Sr	19.0	1.3	*A, *n	5, 2
DG1	gt-peridotite 2	Cima Lunga	32	Alpe Arami	~ 718.8/121.2		Zir U/Pb	35.4	0.7	*S 7, rims: 33.4 ± 0.5 Ma	28
DG2	gt pyroxenite 1	Cima Lunga	32	Alpe Arami	~ 718.8/121.2		Zir U/Pb	35.1	1.5	*S 4, older cores	28
DG3	gt-pyroxenite 2	Cima Lunga	32	Alpe Arami	~ 718.8/121.2		Zir U/Pb	35.4	0.8	*S 7, rims: 33.4 ± 0.5 Ma, cores	28
DG4	migm. orthogneiss	Cima Lunga	33	ESE Alpe Arami	~ 719.6/120.4		Zir U/Pb	32.4	1.1	*S 7, rims: 25.0 ± 0.8 Ma	28
DG5	pegmatite	Cima Lunga	34	N San Vittore			Zir U/Pb	25.1	0.6	*S 4	28

Tab. 1 (cont.)

Sample	Rock type	Tectonic unit	Loc.	Location	Coordinates	Alt.	Method	Age	±	Remarks	Ref.
FM 1	bi-plg-orthogneiss	Ceneri zone	35	Val Morobbia	725.75/114.11		Bi K/Ar	272.0	6.0	*A, S of Insubric Line	26
BM 1	pre-intrusive rock	Tambo nappe	36	Promontogno		850	Ap FT	9.7	0.5	*n, *e	6
KAW 281	gneiss	Tambo nappe	36	Promontogno	763.7/134.3		Bi K/Ar	29.7	1.6	*A, *a	4,9
KAW 281	gneiss	Tambo nappe	36	Promontogno	763.7/134.3		Ms Rb/Sr	36.5	2.7	*A, WR corr., *n	2,9
KAW 281	gneiss	Tambo nappe	36	Promontogno	763.7/134.3		Ms K/Ar	44.3	2.0	*A, *a	4,9
KAW 281	gneiss	Tambo nappe	36	Promontogno	763.7/134.3		Bi Rb/Sr	24.8	1.0	*A, WR corr., *n	2,9
KAW 105	granitic gneiss	Tambo nappe	37	N San Guglielmo	748.7/134.4	590	Bi K/Ar	22.8	1.0	*A, *a	4
KAW 105	granitic gneiss	Tambo nappe	37	N San Guglielmo	748.7/134.4	590	Zir U/Pb	disc.		1 discordant fraction	8
KAW 105	granitic gneiss	Tambo nappe	37	N San Guglielmo	748.7/134.4	590	Ap FT	10.2	2.0	*e	5
KAW 105	granitic gneiss	Tambo nappe	37	N San Guglielmo	748.7/134.4	590	Ms Rb/Sr	246	10	*Sr (0.7091), *b	3
KAW 105	granitic gneiss	Tambo nappe	37	N San Guglielmo	748.7/134.4	590	Ms K/Ar	60.4	2.4	*A, *a	4
KAW 105	granitic gneiss	Tambo nappe	37	N San Guglielmo	748.7/134.4	590	Bi Rb/Sr	25.3	1.0	*A, WR corr. , *b	3
KAW 145	bi-gneiss	Adula nappe	38	Soazza	735.85/133.02	580	Ap FT	6.4	1.3	*e	5
KAW 145	bi-gneiss	Adula nappe	38	Soazza	735.85/133.02	580	Bi Rb/Sr	19.2	2.1	mean of 2, *A, *Sr (0.7091), *b	3
KAW 146	bi-ms-gneiss	?	39	Val Calanca			Bi K/Ar	19.2	0.9	*A, *a	4
KAW 146	bi-ms-gneiss	?	39	Val Calanca			Ms K/Ar	19.4	0.8	*A, *a	4
KAW 146	bi-ms-gneiss	?	39	Val Calanca			Bi Rb/Sr	18.3	3.2	*A,WR corr., *n	2,4
KAW 189	gneiss	Adula nappe	40	Soazza	737.63/137.47	620	Bi K/Ar	19.7	1.1	*A, *a	4
KAW 189	gneiss	Adula nappe	40	Soazza	737.63/137.47	620	Ap FT	7.1	1.4	*e	5
KAW 189	gneiss	Adula nappe	40	Soazza	737.63/137.47	620	Bi Rb/Sr	19.0	2.7	*A, WR corr., *n	4
KAW 189	gneiss	Adula nappe	40	Soazza	737.63/137.47	620	Ms K/Ar	21.9	1.1	*A, *a	4
KAW 189	gneiss	Adula nappe	40	Soazza	737.63/137.47	620	Ms Rb/Sr	26.9	11.0	phe, *A, WR corr., *n	4
KAW 327	gneiss	Forno-Lizun	41	Plan Canin	~ 774.8/137.5		Bi Rb/Sr	28.2	3.6	*A, WR corr., *n	2
KAW 328	bi-gneiss	Forno-Lizun	42	Lago di Cavloc	774.08/139.45	1900	Bi K/Ar	28.1	1.0		34
KAW 328	gneiss	Forno-Lizun	42	Lago di Cavloc	774.08/139.45	1900	Bi Rb/Sr	28.0	3.9	*A, WR corr., *n	2,34
KAW 328	gneiss	Forno-Lizun	42	Lago di Cavloc	774.08/139.45	1900	Ap FT	14.0	2.8	*e	5,34
KAW 330	bi-orthogneiss	Margna nappe	43	Chiareggio	779.88/131.81	1620	Ms K/Ar	39.2	2.2	phe, *n	25,29
KAW 330	bi-orthogneiss	Margna nappe	43	Chiareggio	779.88/131.81	1620	Bi K/Ar	28.3	1.8	*n	25,29
KAW 550	gneiss	Tonale series	44	Ponte Baffo	768.8/117.0	560	Ap FT	12.1	2.4	*e	5
KAW 550	gneiss	Tonales eries	44	Ponte Baffo	768.8/117.0	560	Bi Rb/Sr	24.2	1.6	*A, WR corr., *n	2
KAW 552	pegmatite	Gruf unit	45	Val Piana	760.7/127.3		Ms Rb/Sr	26.3	1.0	*A, WR corr., *n	2,4
KAW 552	pegmatite	Gruf unit	45	Val Piana	760.7/127.3		Ms K/Ar	24.7	1.3	*A, *a	4
KAW 552	pegmatite	Gruf unit	45	Val Piana	760.7/127.3		Bi Rb/Sr	21.0	1.4	*A, WR corr., *n	2

Tab. 1 (cont.)

Sample	Rock type	Tectonic unit	Loc.	Location	Coordinates	Alt.	Method	Age	±	Remarks	Ref.
KAW 552	pegmatite	Gruf unit	45	Val Piana	760.7/127.3		Bi K/Ar	23.9	1.4	*A, *a	4
KAW 554	sap-granulite	Gruf unit	46	SW Rif. Brasca	~ 761.2/125.4		Bi Rb/Sr	26.8	1.5	*A, WR corr, *n	2
KAW 644	bi-sil-gneiss	Margna nappe	47	Val Fedoz	778.8/136.8	2340	Bi K/Ar	29.8	2.0	*n	25,29
KAW 645	phe-gneiss	Margna nappe	48	Val Fedoz	778.2/138.8	2110	Ms K/Ar	67.4	2.8	phe, *n	25,29
KAW 75	gneiss	Leventina	49	Claro	721.93/125.18	310	Ap FT	6.4	1.3	*e	5
KAW 75	gneiss	Leventina	49	Claro	721.93/125.18	310	Bi Rb/Sr	17.4	1.1	*A, *Sr (0.7091), *M 2; *b	3
KAW 774	phe-gneiss	Margna nappe	50	Val Fex	780.75/139.75		Hb K/Ar	103.0	6.0	*n	25,29
KAW 775	phe-augengneiss	Margna nappe	51	Val Fex	779.7/139.0	2370	Ms K/Ar	63.4	2.6	*n	25,29
KAW 775	phe-augengneiss	Margna nappe	51	Val Fex	779.7/139.0	2370	Ap FT	14.7	2.9	*e	5,29
KAW 776	phe-augengneiss	Margna nappe	51	Val Fex	779.7/139.0	2370	Ms K/Ar	63.5	2.7	phe, *n	25,29
L 75/15	pegmatite	Tonale series	52	N Dubino	756.32/114.45		Ms Rb/Sr	226.1	n.i.	*Sr (0.710)	22
KAW 777	phe-orthogneiss	Margna nappe	53	P. Vadret, Val Fex	780.6/138.4		Ms K/Ar	61.2	2.6	*n	25
KAW 90	phe-gneiss	Margna nappe	54	Maloja Palace	773.6/141.95	1800	Ms Rb/Sr	75.6	19.0	*n, WR corrected	2,29
KAW 90	phe-gneiss	Margna nappe	54	Maloja Palace	773.6/141.95	1800	Ap FT	15.0	3.0	*e	5,29
KAW 958	augengneiss	Margna nappe	54	Maloja Kulm	773.44/141.98		Ms K/Ar	240.0	10.0	*n	25,29
KAW 958	augengneiss	Margna nappe	54	Maloja Kulm	773.44/141.98		Ms K/Ar	105.0	5.0	phe, *n	25,29
KAW 959	phe-gneiss	Margna nappe	54	Maloja Palace	773.6/141.95	1800	Ms K/Ar	270.0	10.0	*n	25,29
KAW 959	phe-gneiss	Margna nappe	54	Maloja Palace	773.6/141.95	1800	Ms K/Ar	77.8	3.2	*n	25,29
KAW 959	phe-gneiss	Margna nappe	54	Maloja Palace	773.6/141.95	1800	Ms K/Ar	119.0	5.0	phe + ms, *n	25,29
KAW 956	gneiss	Margna nappe	55	Ca Rotte (Malenco)	784.3/131.3	1450	Bi K/Ar	43.0	1.9	bi + hb, *n	25
KAW 956	gneiss	Margna nappe	55	Ca Rotte (Malenco)	784.3/131.3	1450	Bi K/Ar	39.7	6.3	chl+bi, *n	25
KAW 956	gneiss	Margna nappe	55	Ca Rotte (Malenco)	784.3/131.3	1450	Ms K/Ar	75.0	3.2	*n	25
KAW 956	gneiss	Margna nappe	55	Ca Rotte (Malenco)	784.3/131.3	1450	Ap FT	7.4	1.5	*e	5
KAW 957	pegmatite	Margna nappe	55	Ca Rotte (Malenco)	784.3/131.3	1450	Ms K/Ar	76.5	3.9	*n	25,29
KG 10	bi-ms-gneiss	Adula nappe	55	Alpe del Notaro	739.88/122.79		Mon U/Pb	22.8	n.i.	same sample as RH816	13
KG 12	metapelite	Tambo nappe	56	Vöga (Bregaglia)	762.2/132.6		Mon U/Pb	31.9	n.i.		13,30,31
KG 7	ky-sil-bi-ms-gneiss	Orselina zone	57	Cugnasca	715.35/114.8		Mon U/Pb	27.7	n.i.	xenotime ?	13,31
KG 8	ky-sil-bi-ms-gneiss	Simano nappe	58	Cauco	729.35/133.4		Mon U-Pb	23.7	n.i.		13,31
KG 9	bi-ms-gneiss	Adula nappe	59	Val Garzelli	745.27/124.24		Mon U/Pb	22.8	n.i.	same sample as RH 812	13
LC-DS02	amphibolite	Southern Alps	60	S Civo	764.30/112.77		Hb K/Ar	365.5	7.8	*M 2	17
LC-DS03	amphibolite	Tonale series	61	Roncaglia	764.47/114.69		Hb K/Ar	40.2	0.6	*M 2	17
LC-DS04	ms-bi-chl-gneiss	Tonale series	61	Roncaglia	764.35/114.54		Bi Rb/Sr	21.3	0.4	bi-WR- isochron	17
LC-DS04	ms-bi-chl-gneiss	Tonale series	61	Roncaglia	764.35/114.54		Bi K/Ar	24.0	0.4	*M 2	17
LC-DS04	ms-bi-chl-gneiss	Tonale series	61	Roncaglia	764.35/114.54		Ms Rb/Sr	29.0	10.0	ms-WR-isochron	17

Tab. 1 (cont.)

Sample	Rock type	Tectonic unit	Loc.	Location	Coordinates	Alt.	Method	Age	±	Remarks	Ref.
LC-DS04	ms-bi-chl-gneiss	Tonale series	61	Roncaglia	764.35/114.54		Ms K/Ar	25.4	0.4	*M 2	17
LC-DS06	ms-bi-gt-mylonite	Insubric zone	62	ENE Mello	763.64/114.07		Ms Rb/Sr	220.0	22.0	ms-WR-isochron	17
LC-DS06	ms-bi-gt-mylonite	Insubric zone	62	ENE Mello	763.64/114.07		Ms K/Ar	105.4	2.1		17
LC-DS07	ms-bi-gt-mylonite	Insubric zone	62	ENE Mello	763.64/114.01		Ms Rb/Sr	174.0	26.0	ms-WR-isochron	17
LC-DS07	ms-bi-gt-mylonite	Insubric zone	62	ENE Mello	763.64/114.01		Ms K/Ar	61.8	1.3		17
Mas 9z	amphibolite	Bellinzona zone	63	Bagni del Masino	766.1/124.2		Hb K/Ar	30.5	1.0		15
RH 808	pegmatite undef.	Adula nappe	64	Boggia (Bodengo)	743.91/126.07		Bi Rb/Sr	19.9	0.6	*A, WR corr.	14
RH 813	granitoid gneiss	Adula nappe	65	NE Alpe Garzelli	745.49/124.92		Zir U/Pb	inh., loss		1 discordant fraction	14
RH 813	granitoid gneiss	Adula nappe	65	NE Alpe Garzelli	745.49/124.92		Mon U/Pb	23.5/23.5	~ 0.3	*c	14
RH 814	migmatite	Adula nappe	66	Val Bodengo	745.34/126.0		Bi Rb/Sr	19.0	0.6	*A, bi-ks-WR-plg-isochron	14
RH 814	migmatite	Adula nappe	66	Val Bodengo	745.34/126.0		Ms Rb/Sr	21.2	0.6	*A, ms-ks-WR-plg-isochron	14
RH 814	migmatite	Adula nappe	66	Val Bodengo	745.34/126.0		Zir U/Pb	inh., loss		1 discordant fraction	14
RH 816	migmatite	Adula nappe	67	Alpe del Notaro	739.88/122.79		Mon U/Pb	23.7/23.7	~ 0.3	*c	14
RH 816	migmatite	Adula nappe	67	Alpe del Notaro	739.88/122.79		Bi Rb/Sr	20.1	0.6	*A, min-isochron	14
RH 816	migmatite	Adula nappe	67	Alpe del Notaro	739.88/122.79		Zir U/Pb	inh., loss		2 discordant fractions	14
RH816	migmatite	Adula nappe	67	Alpe del Notaro	739.88/122.79		Ms Rb/Sr	20.1	0.6	*A, min-isochron	14
RH 824	granitoid gneiss	Adula nappe	68	Barzena	746.64/127.05		Zir U/Pb	inh., loss		4 discordant fractions	14
W 192	pegmatite	Tambo nappe	69	Mese (V. Mera)	749.5/130.5	310	Ms K/Ar	25.7	2.0	*A	7
W 251	pegmatite	Tambo nappe	69	Mese (V. Mera)	749.5/130.5	310	Ms K/Ar	27.7	2.0	*A	7
W 312	pegmatite	Gruf unit	70	S. Caterina (Mera)	749.3/128.7	260	Ms K/Ar	27.7	2.0	*A	7
W 61	pegmatite	Tambo nappe	71	Baccino Truzzo	744.6/136.0	2080	Ms K/Ar	177.6	9.0	*A	7
W 792	pegmatite	Tambo nappe	72	E Motto Alto	743.9/139.0		Ms K/Ar	304.9	15.0	*A	7
B 18	gneiss	Mergoscia zone	73	Gorduno	722.7/119.8		Bi Rb/Sr	20.1	2.3	*A, *Sr (0.7091)	3
Riv 17	amphibolite	Mergoscia zone	73	Gorduno	722.7/119.9		Hb K/Ar	23.4	0.8		15
Tambo	crystalline rocks	Tambo nappe	74	several localities			WR Rb/Sr	303	14	*A, *n	9
US 92-A11	augengneiss	Bellinzona zone	75	Val Morobbia	n. a.		Zir U/Pb	disc.		5 scattering fractions	33
US 92-A11	augengneiss	Bellinzona zone	75	Val Morobbia	n. a.		Tit U/Pb	32.8	0.7	4 ± concordant fractions	33
US 92-A11	augengneiss	Bellinzona zone	75	Val Morobbia	n. a.		Bi Rb/Sr	19.5	0.9	3xbi-ks-WR-isochron	33
L 75/17	pegmatite	Tonale series	76	NW Polaggia	778.35/116.57		Ms Rb/Sr	159.9	n.i.	*Sr (0.710)	22
HD-B1	granodiorite porph.	MB intrusion	77	S San Martino			Bi K/Ar	24.7	n.i.	debris	35
HD-B1	granodiorite porph.	MB intrusion	77	S San Martino			Bi Ar/Ar	25.3	1.6	debris	35
KAW 3290	leucotonalite	Sondrio intrusion	78	E Ruvarti	784.50/117.03	940	Zr FT	23.3	3.8		34
KAW 3290	leucotonalite	Sondrio intrusion	78	E Ruvarti	784.50/117.03	940	Bi K/Ar	32.3	0.6	*M 2	34
KAW 3291	tonalite	Sondrio intrusion	79	Triangia	784.90/116.55	820	Bi K/Ar	29.6	0.6	*M 2	34

Tab. 1 (*cont.*)

Sample	**Rock type**	**Tectonic unit**	**Loc.**	**Location**	**Coordinates**	**Alt.**	**Method**	**Age**	**±**	**Remarks**	**Ref.**
GD 317	bi-gneiss	Tonale series	80	Prati Vesolo	785.18/117.14	1030	Bi K/Ar	33.1	0.8	enclave in Sondrio pluton	34
KAW 2398	gneiss	southern Alps	81	N Dubino	756.17/113.80	380	Ms Rb/Sr	292.3	5.6		36,34
KAW 2623	tonalite	MB intrusion	82	V. Preda Rossa	747.18/122.0	1955	Bi K/Ar	26.4	0.8		36,34
KAW 2624	tonalite	MB intrusion	83	V. Sasso Bisolo	772.95/121.55	1500	Bi K/Ar	26.0	0.6		36,34
KAW 2625	tonalite	MB intrusion	84	V. Sasso Bisolo	770.75/120.40	1025	Bi K/Ar	24.7	0.6		36,34
KAW 2400	granite dike	Novate intrusion	85	S. Fedele	755.25/117.51	202	Bi K/Ar	21.7	3.6		36
KAW 2626	granodiorite	MB intrusion	86	E Rif. Omio	764.75/124.45	1950	Bi K/Ar	27.4	1.0		34.36
KAW 3288	bi-ms-gneiss	Bellinzona zone	87	N Paudo	723.43/114.38	745	Ms K/Ar	20.3	0.6		34
KAW 3288	bi-ms-gneiss	Bellinzona zone	87	N Paudo	723.43/114.38	745	Bi K/Ar	19.9	0.6		34
KAW 137	gneiss	Leventina unit	88	Osogna	719.69/129.41	300	Ap FT	6.0	1.2	*e	5
KAW 137	gneiss	Leventina unit	88	Osogna	719.69/129.41	300	Bi Rb/Sr	18.2	1.9	*A, *n	5,2
KG 2	bi-ms-gneiss	Leventina unit	88	Osogna	719.7/129.3		Mon U/Pb	21.2	n.i.		13,31

Tab. 2 Age results for the Masino-Bregaglia boulders from the Gonfolite Lombarda. Mineral abbreviations and the explanations for the different columns are given in the captions to table 1.

Sample	**Rock type**	**Stratigraphic unit**	**Location**	**Coordinates**	**Method**	**Age**	**±**	**Remarks**	**Ref.**
GD 243	granodiorite	Lucino Formation	Malnate	710.900/72.650	Bi K/Ar	23.8	0.4		21
KAW 1002	granodiorite	Como Formation	Pedrinate	n.a.	Zir U/Pb	inh.		2 discordant fractions	12
KAW 1003	granodiorite porph.	Como Formation	Pedrinate	n.a.	Ap FT	23.4	1.0		6
KAW 1003	granodiorite porph.	Como Formation	Pedrinate	n.a.	Bi K/Ar	29.3	1.4	*A,*n	5,6
KAW 1003	granodiorite porph.	Como Formation	Pedrinate	n.a.	Zir U/Pb	19.9		1 fract. , analyt. problems	12
KAW 1004	granodiorite porph.	Como Formation	Pedrinate	n.a.	Ap FT	24.1	0.9		6
KAW 1004	granodiorite porph.	Como Formation	Pedrinate	n.a.	Bi K/Ar	29.1	2.6	*A, *n	5,6
KAW 1005	granodiorite porph.	Como Formation	Pedrinate	n.a.	Ap FT	25.9	0.8		6
KAW 1005	granodiorite porph.	Como Formation	Pedrinate	n.a.	Bi K/Ar	28.5	1.3	*A, *n	5,6
KAW 1005	granodiorite porph.	Como Formation	Pedrinate	n.a.	Bi K/Ar	28.4	1.3	*A, *n	5,6
KAW 2011	diorite	Como Formation	Pedrinate	721.45/76.45	Ap FT	25.4	1.6	*M 3	18
KAW 2011	diorite	Como Formation	Pedrinate	721.45/76.45	Bi K/Ar	30.8	0.6		18
KAW 2011	diorite	Como Formation	Pedrinate	721.45/76.45	Hb K/Ar	37.1	7.0		18
KAW 2011	diorite	Como Formation	Pedrinate	721.45/76.45	Zir FT	28.5	3.0		18
KAW 2019	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Bi K/Ar	26.9	0.8	*M 2	18

Tab. 2 (cont.)

Sample	**Rock type**	**Stratigraphic unit**	**Location**	**Coordinates**	**Method**	**Age**	**±**	**Remarks**	**Ref.**
KAW 2020	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Ap FT	25.7	1.2	*M 3	18
KAW 2020	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Bi K/Ar	28.6	0.6		18
KAW 2020	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Hb K/Ar	34.2	6.8		18
KAW 2020	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Zir FT	27.8	2.8		18
KAW 2025	tonalite	Como Formation	Pedrinate	721.45/76.45	Ap FT	27.7	1.2		18
KAW 2025	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Bi K/Ar	28.7	0.8		18
KAW 2025	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Hb K/Ar	29.7	2.7	*M 2	18
KAW 2025	tonalite deformed	Como Formation	Pedrinate	721.45/76.45	Zir FT	28.5	3.8		18
KAW 2035	diorite	Como Formation	Pedrinate	721.45/76.45	Bi K/Ar	28.2	1.2		18
KAW 2035	diorite	Como Formation	Pedrinate	721.45/76.45	Hb K/Ar	32.4	5.8		18
KAW 2481	tonalite	Como Formation	Comabbio	695.9/70.2	Ap FT	29.2	7.0		21,27
KAW 2481	tonalite	Como Formation	Comabbio	695.9/70.2	Bi K/Ar	32.3	0.4	*n	21,27
KAW 2481	tonalite	Como Formation	Comabbio	695.9/70.2	Bi Rb/Sr	32.8	1.8	WR corr., *n	21,27
KAW 2481	tonalite	Como Formation	Comabbio	695.9/70.2	Zir FT	30.9	5.4		21,27
KAW 2485	tonalite	Como Formation	SW Taino	690.6/67.62	Bi K/Ar	29.8	0.4	*n	21,27
KAW 2485	tonalite	Como Formation	SW Taino	690.6/67.62	Bi Rb/Sr	28.5	2.3	*n	21,27
KAW 2486	tonalite	Como Formation	Sesto-Calende	692.8/65.72	Bi K/Ar	31.9	0.4	*M 2, *n	21,27
KAW 2486	tonalite	Como Formation	Sesto-Calende	692.8/65.72	Bi Rb/Sr	31.4	1.4	*M 2,*n	21,27
KAW 2720	tonalite	Como Formation	Chiasso/Pedrinate	723.20/76.40	Bi K/Ar	31.3	1.0		18
KAW 2949	tonalite	Como Formation	Chiasso	723.95/76.50	Bi K/Ar	32.1	0.8		18
KAW 3126	granodiorite	Lucino Formation	Lucino	724.20/71.03	Bi K/Ar	27.7	1.0	*M 2	18
KAW 3148	tonalite	Villa Olmo Congl.	Como	726.25/75.15	Bi K/Ar	31.8	0.9	*M 2	18
KAW 3244	gt-leucogranite	Lucino Formation	Castiglione-Olona	710.85/68.275	Ap FT	20.4	4.0		21
KAW 3244	leucogranite	Lucino Formation	Castiglione-Olona	710.85/68.275	Ms K/Ar	22.9	0.6	*M 2	21
KAW 3244	gt leucogranite	Lucino Formation	Castiglione-Olona	710.85/68.275	Ms Rb/Sr	24.1	0.3	*n	21