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Thermochronological constraints on the multiphase exhumation history of the Ivrea-Verbano Zone of the Southern Alps

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ABSTRACT

The Ivrea-Verbano Zone of the western Southern Alps (NW Italy) exposes a well-preserved tilted section across the lower continental crust, making it a key region for studying deep crustal and exhumation processes. This paper refines the cooling and exhumation history of the Ivrea-Verbano Zone using K/Ar dating of mica and illite-rich fault gouges as well as zircon fission track and (U-Th)/He thermochronology. The adjacent Strona-Ceneri Zone, Sesia-Lanzo Zone and Lower Penninic nappes are included in the study to derive a broader picture of the low-temperature history of the area.

In the Strona profile of the Ivrea-Verbano unit the biotite K/Ar, zircon fission track and (U-Th)/He geochronometers show well preserved, but unusually wide partial retention zones. The youngest ages, representing the formerly deepest position, are situated along the Insubric Line.

The main foliation of the Ivrea-Verbano Zone is vertical. The exhumation of the Ivrea-Verbano Zone, which section has a horizontal position on the surface now – took place in three steps. During Jurassic time the Ivrea-Verbano Zone was exhumed to a shallow to mid-crustal position by continental-scale extension. In this displacement the Pogallo Line probably played a dominant role. The studied section occupied an oblique position with a calculated angle of ca. 15 to 23° in the Jurassic. Later the Ivrea-Verbano Zone experienced a minor cooling event in the Late Eocene (~38 Ma zircon fission track ages) that was probably related to thrusting and erosion. The final exhumation towards the surface took place in the mid-Miocene as documented by the ca. 14 Ma zircon (U-Th)/He ages and a 12.8 Ma K/Ar fault gouge age. The magnitude and the high rate of final exhumation suggest orogen-parallel extension as a driving force, which is widespread in the Alps in the Lower to Middle Miocene and is most probably connected to orogenic collapse.

1. Introduction

The Ivrea-Verbano Zone (IVZ) spreads between Locarno in Switzerland and Ivrea in the Southern Alps of Italy. The IVZ (Fig. 1) is interpreted as a tilted section of the lower continental crust of the Southern Alps, which makes it a significant region for examining a profile through the continental crust to lenses of the upper mantle (e.g. Berckhemer, 1969; Fountain, 1976; Fountain and Salisbury, 1981; Mehnert, 1975; Rabbel et al., 1998; Weiss et al., 1999). Separated by the Cossato-Mergozzo-Brissago (CMB) Line the Strona-Ceneri Zone (SCZ) is part of the upper crust of this profile. The Southern Alps were affected by the Permian high temperature metamorphism and magmatism, but not by the regional Alpine metamorphism. Separated by the Insubric Line the Penninic units including the Sesia-Lanzo Zone (SLZ) are the units, which were underthrust below the Southern Alps during the Alpine orogeny.

The adjacent units in the Ivrea area differ significantly in their tectonometamorphic histories. During the Late Cretaceous (80 to 65 Ma, Babist et al., 2006) the SLZ underwent high pressure metamorphism at a depth of 60 km (Compagnoni, 1977; Dal Piaz et al., 1972), while the IVZ and the SCZ were already cooled below greenschist facies conditions (Zingg et al., 1990). Due to rotation and exhumation along the Insubric Line and minor fault zones, these units with very different time-temperature histories are now adjacent to each other. The emplacement kinematics and timing of the tectonic movements, which lead to the vertical position of the main foliation is still a subject of ongoing debates (Handy and Zingg, 1991; Handy et al., 1999; Hurford et al., 1991; Schmid, 1993; Schmid et al., 1987; Siegesmund et al., 2008). According to Schmid et al. (1987; 1989), the rotation of the IVZ into its vertical position adjacent to the Insubric Line is post-Oligocene and related to the Oligocene back-thrusting, which was synchronous with the back-folding of the Central Alps

Abbreviations: IVZ, Ivrea-Verbano Zone; SCZ, Strona-Ceneri Zone; SLZ, Sesia-Lanzo Zone; CMB, Cossato-Mergozzo-Brissago; ZFT, line, zircon fission track; ZHe, zircon (U-Th)/He; PAZ, partial annealing zone; PRZ, partial retention zone.

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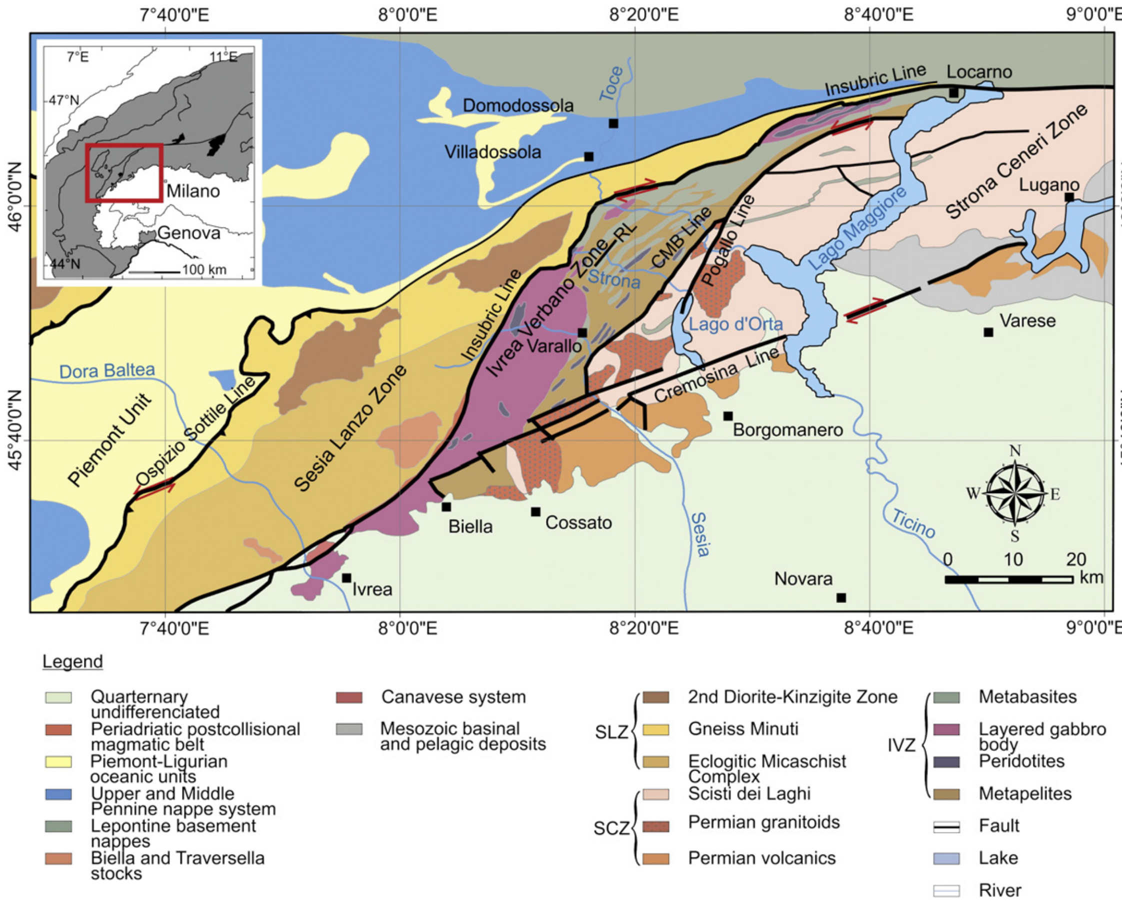

Fig. 1. Geological map of the Ivrea area, RL = Rosarolo shear zone (modified after the structural map of Italy, Bigi et al., 1983).

combined with a minor sinistral strike-slip component. The back-thrusting and the differential uplift of the SLZ led to mylonitization under greenschist-facies conditions along the Insubric Line. Based on the data of Hurford (1986), Schmid et al. (1987) concluded that back-thrusting started between 30 Ma and 23 Ma.

Paleomagnetic analyses in the IVZ (Schmid et al., 1989) suggest independently a post-Oligocene rotation of 60° around a horizontal axis striking parallel to the Insubric Line in a clockwise sense viewed to the north. According to Zingg et al. (1990), the IVZ rotated during the Oligocene-Miocene dextral transpression into its present attitude. The rotation of the IVZ was possibly due to the combination of the inherited Paleozoic crustal setting and the change from early Mesozoic extension to Cretaceous shortening, which caused a SE dipping of the MOHO.

Boriani and Giobbi (2004) argued, however, that the basement of the western Southern Alps is not a tilted section. Their main arguments are: in the Early Permian, the IVZ to the SCZ were already in contact through the CMB Line. Later the Permian Baveno granite intruded the SCZ at a depth of about 4 km (Boriani et al., 1990b). Because the Baveno pluton shows a layering, dipping less than 20° (Boriani et al., 1990a), the IVZ and the SCZ have not been tilted more than 20° in post-Permian time. Furthermore, the SCZ was at least in part exhumed in Permian times. Additionally, vertical dykes with chilled margins intruded in the Permian along the CMB Line. These dykes are still vertical, they have not been rotated. However, these dykes are debated rather being concordant sills than dykes (Handy and Streit, 1999). The interpretation of the Ivrea-Verbano Zone as a tilted section is criticized in favour of a trans-tensional model (Boriani and Giobbi, 2004).

Handy et al. (1999) considered that banding and foliation of the IVZ were sub-horizontal prior to the Paleogene period. Insubric faulting and brittle folding accompanied the rotation of this crustal section. However, while the IVZ was rotated by around 90°, the SCZ underwent only minor to moderate Alpine rotation. Brittle reactivation of the Pogallo Line likely accommodated the differential rotation of the crustal blocks.

Rutter et al. (2007) argued that the IVZ formed a large monoclinal kink during the Alpine orogenesis, in which the main compositional banding was tilted to the vertical. Siegesmund et al. (2008) interpreted the lower break in slope of the zircon fission track ages along a profile in the Val Strona di Omegna at 50 Ma. This break emerges during or immediately after the rotation of the IVZ, because the part closest to the Insubric Line has been exhumed already tilted at this time.

The cooling and exhumation history of the Ivrea-Verbano Zone is important for the proper understanding of the timing and magnitude of the Mesozoic extension and the Paleogene to Neogene shortening events. In this paper we present new mica K/Ar, zircon fission track (ZFT) and zircon (U-Th)/He (shortly ZHe) ages. The ZHe method is sensitive to the low-temperature events in the shallow crust. Combined with the other thermochronometers these new age constraints are suitable for setting up a refined model on the cooling and exhumation history of the IVZ.

2. Geological setting

The Southern Alps are characterised by south verging fold and thrust belts (Schmid et al., 2004). According to the seismic profiles (ECORS-CROP, Roure et al., 1996) this fold and thrust belt continues towards the south below the Po plain and up to the area of Milan. The *'Seengebirge'* (Schmid, 1967) spreads between Biella and Lago di Como in the western part of the Southern Alps and is also called

Massiccio dei Laghi (Boriani and Sacchi, 1973). It combines the Ivrea-Verbano Zone and the SCZ, which is also named Serie dei Laghi.

The Ivrea-Verbano Zone comprises metapelites, quartz-feldspar gneisses with garnet, biotite, sillimanite and graphite. In older literature the metapelites are divided into 'kinzigites' and 'stronalites'; the metamorphic grade of the IVZ decreases from granulite grade in the NW towards the high-temperature amphibolite grade in the SE (Schmid, 1967). Because of this decrease in metamorphism, together with the pressure gradient (Henk et al., 1997), the paleomagnetic evidences and the lenses of upper mantle, the IVZ is interpreted as a 90° tilted and shortened section. The Mafic complex at the SW part of the IVZ is of Permian age (288 Ma; Pin, 1986; Peressini et al., 2007) and represents an example of lower crustal underplating (Fountain, 1989). This range of ages brackets the growth of the Mafic complex, from its inset by sporadic pulses to the final caldera collapse (Sinigoi et al., 2011). The Early Permian thermal overprint caused by the intrusion of the Mafic complex obscured the ages of the earliest events of the IVZ (Henk et al., 1997; Peressini et al., 2007).

Continuing to the southeast the Strona-Ceneri Zone dips 15°–30° SE and represents the former upper crust capped by Permian volcanites (Handy et al., 1999). These volcanites are interpreted as part of a supervolcano. The volcanic field underwent the collapse of a caldera; the plumbing system is represented by both the IVZ Mafic complex and the coeval granitic plutons (Quick et al., 2009). The SCZ comprises a series of metasedimentary schists and gneisses with occasional amphibolite sheets, which are cut by orthogneisses of Ordovician protolith age. During the Carboniferous uplift, retrograde greenschist facies paragneisses are formed. In the SCZ large granite plutons and mafic-intermediate stocks and dykes were emplaced during the Permian. These so-called Graniti dei Laghi form a batholith system, comprising the Valle Mosso (Valsessera-Biellese), Alzo-Roccapietra, Quarna, Mottarone-Baveno, and Montorfano plutons (Boriani and Giobbi, 2004). A shallow intrusion depth of less than ~4 km is inferred by miarolithic cavities in the Baveno granite, which can only develop under low pressure conditions (Boriani et al., 1990b). In addition, Boriani et al. (1990b) suggested that the SCZ was, at least in part, exposed in the Permian. Accordingly, the Baveno granite has already cooled down in the Permian. The contact between the miarolithic and non-miarolithic granites indicate, that the Baveno pluton has been rotated 15°–20° eastwards after its emplacement (Boriani et al., 1990b). The Permian emplacement is constrained by Pinarelli et al. (1988) with Rb-Sr whole-rock ages of 276 ± 7 Ma and Schaltegger and Brack (2007) with zircon U-Pb ages of 281 ± 1 Ma. Siegesmund et al. (2008) dated the Baveno granite to 291 Ma and 284 Ma with biotite K/Ar. In contrast, Pinarelli et al. (1988) reported younger Rb/Sr biotite ages (170 Ma) close to the CMB Line. This younger age could be due to a thermal event in the Middle Jurassic. In Mesozoic times the SCZ was dissected by extensional faults, also the CMB Line and the Pogallo Line were reactivated (Boriani et al., 1990b). During the alpine compression the SCZ was affected by S-verging cataclastic overthrusting (Boriani et al., 1990b).

The Sesia-Lanzo Zone is located north of the Insubric Line and belongs to the distal part of the Adriatic continental margin lithosphere. It represents the highest nappe of the western alpine belt and is located on top of the Penninic nappes, which crop out northwest of the SLZ. According to Compagnoni (1977), the SLZ comprises three basement nappes, which underwent eclogite-facies conditions due to subduction during the Late Cretaceous between 80 Ma and 65 Ma (Babist et al., 2006). The exhumation was isothermal to a depth of 20 km (Babist et al., 2006). Thereafter in the Eocene the exhumation proceeded together with extensional shearing. The high pressure rocks cooled slowly from 40 Ma to 30 Ma (Babist et al., 2006) and were intruded by shallow granitic plutons (Biella and Traversella plutons, 30 Ma; Krummenacher and Evernden, 1960), when they were already exposed to erosion at the surface. Only the NE part of the SLZ remained below 10 km depth until its exhumation due to back-folding and thrusting of the Insubric Line in the Tertiary and brittle faulting in the post-Oligocene (Babist et al., 2006).

The Periadriatic lineament marks the northern and western boundary of the Southern Alps and the southern limit of the Tertiary metamorphism, excluding the segment south of the Tauern window (Ahrendt, 1980). The protoliths tectonically incorporated into this mylonitic belt are derived from the IVZ, SLZ and from the Permo-Mesozoic sediments of the Canavese Zone in the study area (Ahrendt, 1980). Its segments are called from west to east, the Insubric-(Canavese- and Tonale-), Giudicarie-, Pustertal- and Gailtal Lines (Schmid et al., 1987). The shear zone at the Insubric Line accommodated the back-thrusting synchronously with the back-folding of the Central Alpine nappes. This was followed and partly synchronous with the dextral strike slip of ~100 km along the E–W striking Periadriatic lineament (Schmid and Kissling, 2000; Schmid et al., 1987). In the study area this ~1 km thick greenschist-facies mylonite belt is called the Insubric Line, which separates the SLZ and the IVZ (Fig. 1). Wemmer (1991) determined the last reactivation of the Insubric Line at Rimella to 22 Ma ± 0.7 Ma by K/Ar fault gouge dating. The total NW side-up displacement between the Oligocene and present was 10 to 20 km, which means the SLZ was uplifted with respect to the IVZ (Hurford, 1986; Schmid et al., 1987).

The IVZ and the SCZ were adjacent since the Early Permian and shared the same metamorphic history (Boriani et al., 1990a). The shear zone dividing the IVZ and the SCZ is the Cossato-Mergozzo-Brissago Line (Boriani and Sacchi, 1973). The CMB Line forms the main contact southwest of the Val d'Ossola, where the Pogallo Line breaks away from the lithological contact. This Permian contact is a subject of ongoing debates (Boriani et al., 1990a; Handy, 1987; Handy et al., 1999; Mulch et al., 2002). Boriani et al. (1990a) and Mulch et al. (2002) define the CMB Line as the major tectonic contact between the IVZ and the SCZ, while in earlier literature the Triassic Pogallo Line was defined as a contact (Hodges and Fountain, 1984; Schmid et al., 1987). The CMB Line is a sub-vertical high temperature ductile shear zone that was active until the Early Permian. The mylonitic shear activity went along with the intrusion of gabbro-dioritic bodies called Appinites (Boriani and Giobbi, 2004). The vertical displacement along the CMB Line is negligible (Handy et al., 1999). The Pogallo Line displaces the CMB Line north of the Valle d'Ossola (Mulch et al., 2002). It is interpreted as a low angle normal fault due to crustal thinning (Hodges and Fountain, 1984), which was active between 210 Ma and 170 Ma (Zingg et al., 1990). The extension from Late Triassic to mid Jurassic correlates with the opening of the Piemont Ocean (Zingg et al., 1990). The northern part of the Pogallo Line formed under amphibolite facies conditions, whereas at the same time, to the south, shear occurred in greenschist facies conditions (Handy, 1987). The fault plane of the Pogallo Line strikes NNE and dips 80° towards the WNW (Zingg et al., 1990). It is concordant with the attitude of the kinzingites of the IVZ but discordant with the SCZ (Boriani et al., 1990a).

To the south the Cremosina Line crosscuts the CMB Line. It was suggested, that this fault zone was active during Carboniferous to Permian times by Boriani et al. (1990a) and Giglia et al. (1996). However, according to the evolution of the Sesia magmatic system, the Permian Graniti dei Laghi were emplaced besides and separated by the Cremosina line. Thus the activity has to be shifted into post-Permian time (pers. Comm. Quick and Sinigoi). It was reactivated as a dextral strike-slip fault during post-Oligocene times (Boriani et al., 1990a).

In the north the Ospizio Sottile fault locally separates the Piemont Unit and the SLZ. This sinistral fault zone was reactivated from Miocene to the present, which was triggered by the escape of the Penninic Unit from the Simplon detachment (Bistacchi et al., 2001).

Hunziker et al. (1992) presented a collection of the available geochronological data of the Central and Western Alps. In this paper their data set is used and complemented with the geochronological results from the following studies: Jäger and Faul, 1960; Krummenacher and Evernden, 1960; Carraro and Ferrara, 1968; McDowell and Schmid, 1968; McDowell, 1970; Wagner and Reimer, 1972; Hunziker, 1974; Frey et al., 1976; Zingg et al., 1976; Monié, 1985; Oberhänsli et al., 1985; Diamond and Wiedenbeck, 1986; Hurford, 1986; Stähle et al., 1986; Stöckhert et al., 1986; Hurford et al., 1991; Wemmer, 1991; Inger et al., 1996; Vance, 1999; Keller et al., 2005; Malusà et al., 2005; Malusà et al., 2006; Siegesmund et al., 2008.

3. Sampling and sample preparation

Forty-five samples were collected in six parallel profiles across the SCZ, IVZ, SLZ and the adjacent Piemont Unit (Fig. 2). The profiles are oriented NW–SE and roughly perpendicular to the general strike of the IVZ. The geographical positions and the petrography of the analysed samples are summarised in Table EA. 1. The samples were selected for the different geochronological methods according to their structural positions along the profiles and according to the quality of the datable mineral phases. The shape, pureness and paragenesis of micaceous minerals were controlled in thin sections. Mica separation was performed by standard techniques such as sieving, using the Frantz magnetic separator and by hand-picking. Pure micas were ground in alcohol and sieved to remove altered rims, which might have suffered argon loss. The zircon crystals were concentrated by standard mineral separation processes such as sieving, density and magnetic separation steps and final selections were done by hand.

4. Methods

4.1. K-Ar geochronology

The argon isotopic composition was measured in a Pyrex glass extraction and purification line coupled to a VG 1200C noble gas mass spectrometer operating in static mode. The amount of radiogenic ^{40}Ar was determined by isotope dilution method using a highly enriched ^{38}Ar spike from Schumacher, Bern (Schumacher, 1975). The spike was calibrated against the biotite standard HD-B1 (Fuhrmann et al., 1987). Age calculations are based on the constants recommended by the IUGS quoted in Steiger and Jäger (1997). Potassium was determined in duplicate by an Eppendorf Elex 63/61 flame photometer. The samples were dissolved in a mixture of HF and HNO_3 according to the technique of Heinrichs and Herrmann (1990). CsCl and LiCl were added as an ionisation buffer and internal standard, respectively. The analytical error for the K/Ar age calculations is given on a 95% confidence level (2σ). Details of argon and potassium analyses are given in Wemmer (1991). The fault gouges were analysed in the lab of the Geoscience Center Göttingen as described in Löbens et al. (2011) and Bense et al. (submitted for publication).

4.2. Zircon fission track thermochronology

The zircon crystals were embedded in PFA Teflon and polished in five steps by diamond suspensions and etched by the eutectic melt of NaOH-KOH at a temperature of 220 °C. Neutron irradiations were performed at the research reactor of the Technical University of Munich (Garching). The external detector method was used (Gleadow, 1981). After irradiation the induced fission tracks in the mica detectors were revealed by etching in 40% HF for 40 min at 21 °C. Track counting was made with a Zeiss-Axioskop microscope computer-controlled stage system (Dumitru, 1993) with 1000× magnification. The fission track (FT) ages were determined by the zeta method (Hurford and Green, 1983) using age standards listed in Hurford (1998). The error was calculated by using the classical procedure, i.e., by Poisson dispersion (Green, 1981). Calculations and plots were made with the TRACKKEY program (Dunkl, 2002).

4.3. Zircon (U-Th)/He thermochronology

For zircon (U-Th)/He chronology single crystals were dated; only intact, euhedral crystals with minor inclusions were selected. The shape parameters were determined and archived by multiple microphotographs and used for the correction of alpha ejection (Farley et al., 1996) using the constants of Hourigan et al. (2005). The crystals were wrapped in ca. 1×1 mm-sized platinum capsules and degassed under high vacuum by heating with an infrared diode laser. The extracted gas was purified using a SAES Ti-Zr getter at 450 °C. The chemically inert noble gases and a minor amount of other rest gases were then

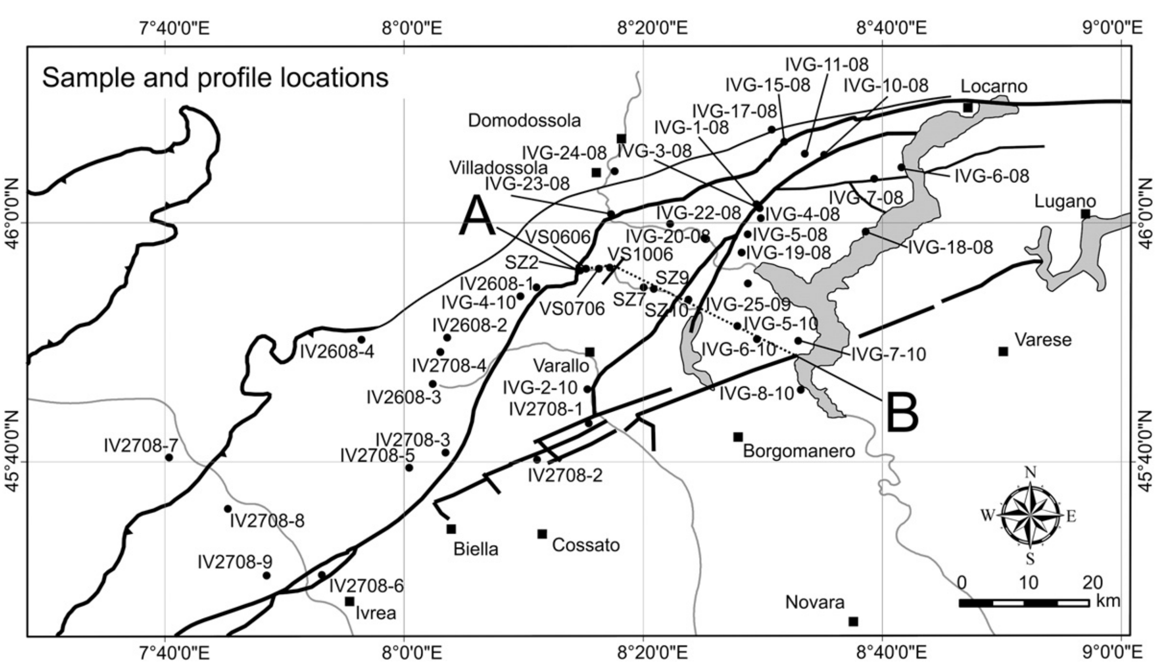

Fig. 2. Sample locations in the Ivrea area. The Strona profile is shown by the dotted line (A–B). For details of the regional geology see Fig. 1.

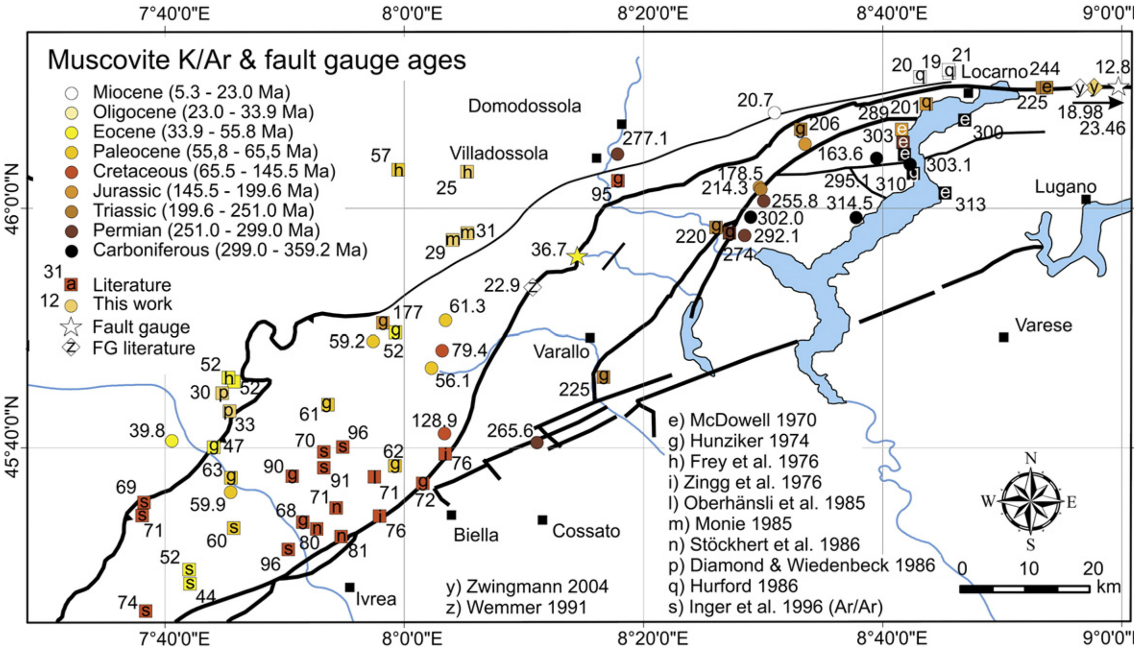

Fig. 3. Compilation of white mica K/Ar and Ar/Ar ages and K/Ar illite ages from fault gouges in the study area. The colour code refers to the age and the references are labelled with a letter code. Circles: samples analysed in this work; squares: cited from other studies. The fault gouges next to the arrow are located outside of the map to the E (Table EA. 1 and Chapter 6.2.3).

expanded into a Hiden triple-filter quadrupol mass spectrometer equipped with a positive ion counting detector. Crystals were checked for degassing of helium by sequential reheating and helium measurement. Following degassing, samples were retrieved from the gas extraction line, spiked with calibrated ^{230}Th and ^{233}U solutions and dissolved in pressurized teflon bombs using distilled 48% HF + 65% HNO_3 in five days at 220 °C. Spiked solutions were analyzed by the isotope dilution method using a Perkin Elmer Elan DRC II ICP-MS equipped with an APEX micro-flow nebulizer.

5. Results

5.1. K/Ar ages

Eighteen new muscovite K/Ar ages and seven new biotite K/Ar ages are presented together with two K/Ar fine fraction ages of fault gouges (Tables EA.2 and EA.3). Muscovite K/Ar ages range between 314.5 Ma ± 3.3 Ma in the Scisti dei Laghi at the Lago Maggiore and 20.7 Ma ± 0.3 Ma in the augengneiss of the Monte Rosa Unit. Biotite

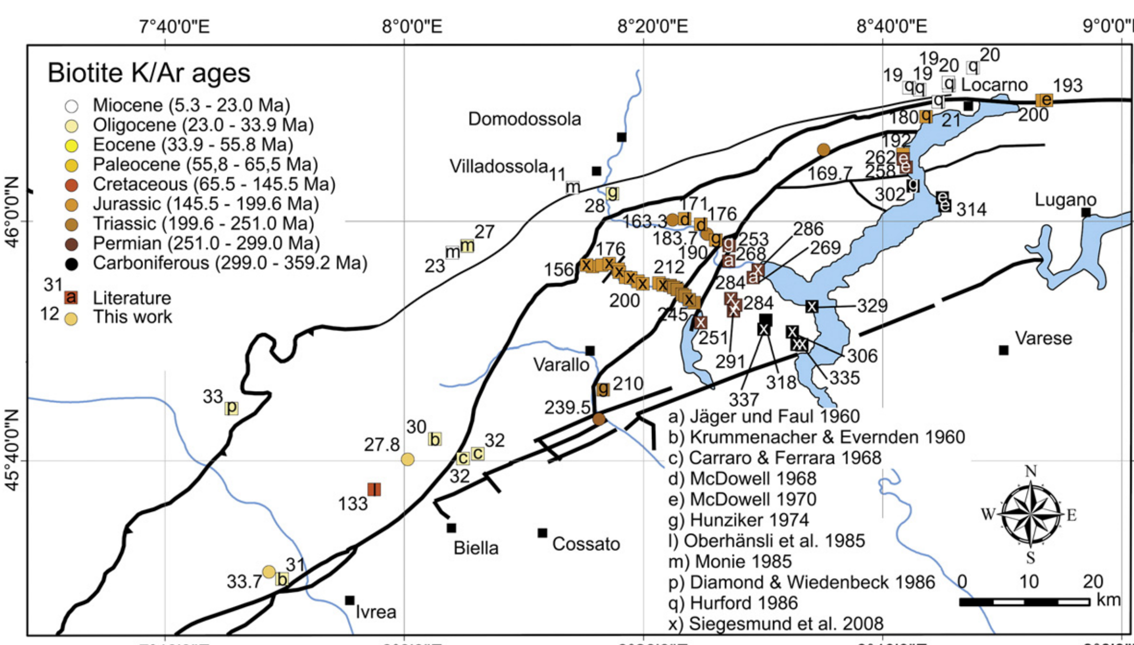

Fig. 4. Compilation of biotite K/Ar ages in the study area. Circles: samples analysed in this work; squares: cited from other studies.

K/Ar ages range between 239.9 Ma ± 3.6 Ma in the Graniti dei Laghi and 27.8 Ma ± 0.5 Ma in the Biella stock. Mica ages are shown in Figs. 3 and 4. The fault gouge at the northern tip of the Lago di Como (not on the map) yielded a K/Ar fine fraction age of 12.8 Ma ± 0.7 Ma for the <0.2 µm fraction, the second from the village Rimella, an age of 36.7 Ma ± 1.0 Ma.

5.2. Fission track ages

Twenty-six new ZFT ages are presented, 10 of which passed the χ^2-Test (see Table EA. 4 and EA. 4a–4j). The ages range from 225.6 Ma ± 13.0 Ma to 18.5 Ma ± 1.0 Ma. These new data are depicted in Fig. 5 together with a compilation of published data from the literature. In Fig. 7 the apatite fission track ages are taken from the literature.

5.3. ZHe ages

One hundred and thirty single crystal ZHe ages have been measured from 30 samples. The analytical details and the unweighted sample averages are listed in Table EA. 5 and plotted in Fig. 6. The ages vary between 227.8 Ma ± 50.3 Ma for the rhyolite at the Lago Maggiore and 9.3 Ma ± 0.9 Ma for the augengneiss from Beura.

6. Discussion

6.1. Areal distribution of cooling events

The Ivrea area west of Locarno comprises units of different tectonometamorphic and exhumation histories. The units are divided by three major faults: the CMB Line, the Pogallo Line and the Insubric Line, which were active during different geologic periods. The juxtaposition of the SLZ, the IVZ and the SCZ, happened at different times. For an overview of the data, the results in this study were grouped together with the AFT ages from Wagner and Reimer (1972), Hurford (1991) and Keller et al. (2005) into three units of different cooling histories, called ‘cooling patterns’ (Fig. 8).

6.1.1. Pre-Alpine cooling pattern

The pre-Alpine cooling pattern spreads within the SCZ between Verbania, the Lago Maggiore, the Lago d'Orta, the Baveno granite and the CMB Line. The first group of apparent cooling paths is defined by the K/Ar mica ages older than 225 Ma, ZFT ages of 225–145 Ma and ZHe ages of 215–130 Ma (Fig. 8). The most characteristic feature of this cooling pattern is that the ZHe ages were not reset during the Alpine orogeny. Hence, this unit stayed in thermal conditions below the closure temperature of the ZHe thermochronometer (ca. 185 °C according to Reiners et al., 2004) since at least 130 Ma.

6.1.2. Eo-Alpine cooling pattern

The Eo-Alpine cooling pattern spreads in the IVZ and the northern SCZ, between the Lago Maggiore and the Insubric Line. The K/Ar mica ages range between 300 Ma and 130 Ma, the ZFT ages between 150 Ma and 35 Ma and the ZHe ages between 75 Ma and 15 Ma. Hence, this unit stayed below the closure temperature of white mica since 140 Ma. The Alpine orogeny has only reset the ZFT and ZHe ages.

6.1.3. Tertiary cooling pattern

The Tertiary cooling pattern is located in the SLZ. The K/Ar mica ages range from 80 Ma to 20 Ma, the ZFT ages between 45 Ma and 20 Ma and the ZHe ages between 24 Ma and 14 Ma. This unit has been affected by Tertiary metamorphism, followed by a fast cooling.

These patterns mark coherent areas in the western Southern Alps and indicate the migration of the exhumation through time (see map sketches in the right panels of Fig. 8). However, the ‘patterns’ outlined above show internal trends and they are not homogeneous. Thus, the apparent cooling paths need a more detailed evaluation. In the discussion below a more refined exhumation history of the Ivrea area is presented based on the new low-temperature geochronological data.

6.2. Major steps and thermal conditions in the post-Permian evolution

6.2.1. Post-Permian cooling

The presented dataset contains information about the cooling and exhumation history of the Ivrea area after the Permian underplating event. This history is based on the tectonic movements of the main units along the major contacts, the Insubric Line and the CMB Line. The dataset shows a joint exhumation history of the IVZ and the SCZ after the Permian underplating without any offset in the data crossing

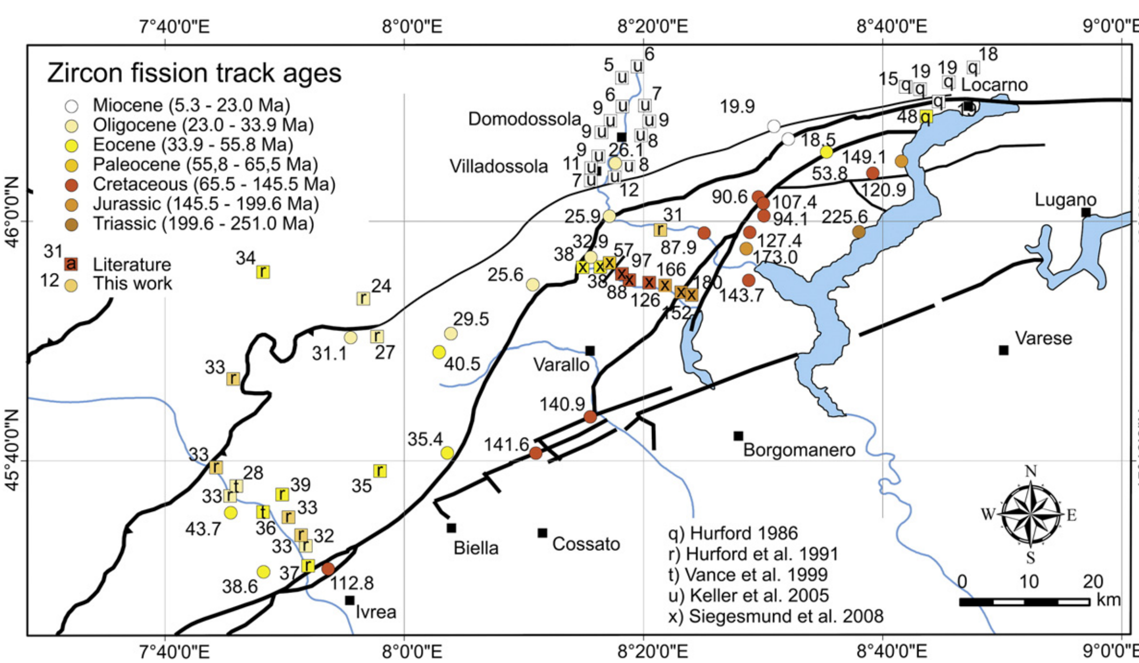

Fig. 5. Compilation of zircon fission track ages in the study area. Circles: samples analysed in this work; squares: cited from other studies.

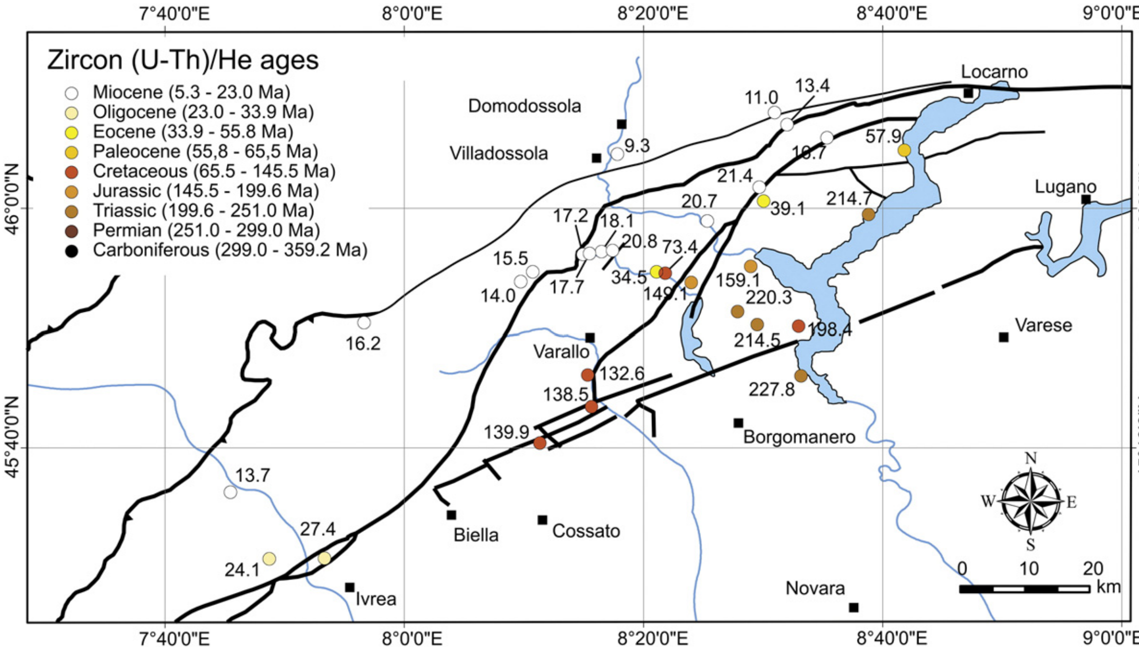

Fig. 6. Distribution of the new zircon (U-Th)/He ages.

the CMB Line (Fig. 9). Neither the monotonic increasing trend of K/Ar (Siegesmund et al., 2008), nor the trend of ZHe ages indicate abrupt changes at the crossing of the CMB Line.

6.2.2. Metamorphic conditions along the Pogallo Line

The Pogallo Line displaces the CMB Line and is interpreted as a low angle normal fault due to crustal thinning (Hodges and Fountain, 1984), which was active between 210 Ma and 170 Ma (Zingg et al., 1990). The extensional activity from Late Triassic to Middle Jurassic coincides with the opening of the Piemont Ocean (Zingg et al., 1990). Metamorphic conditions along the Pogallo Line change from ductile (north of the Val d'Ossola) to brittle deformation further to the south (Handy, 1987). The multi-method thermochronology allows a more precise determination of the temperature conditions along the Pogallo Line (Fig. 10). The cooling paths of the samples in the northern and southern parts of the Pogallo Line yield temperatures of 290 to 350 °C and 220 to 310 °C, respectively, in the time span of the fault activity.

6.2.3. Insubric phase

The main exhumation and tilting of the IVZ was governed by the activity of the Insubric Line. Units which suffered alpine metamorphism and those which did not (Ahrendt, 1980) are now adjacent after the 10 to 20 km of post-Early Oligocene vertical uplift along the

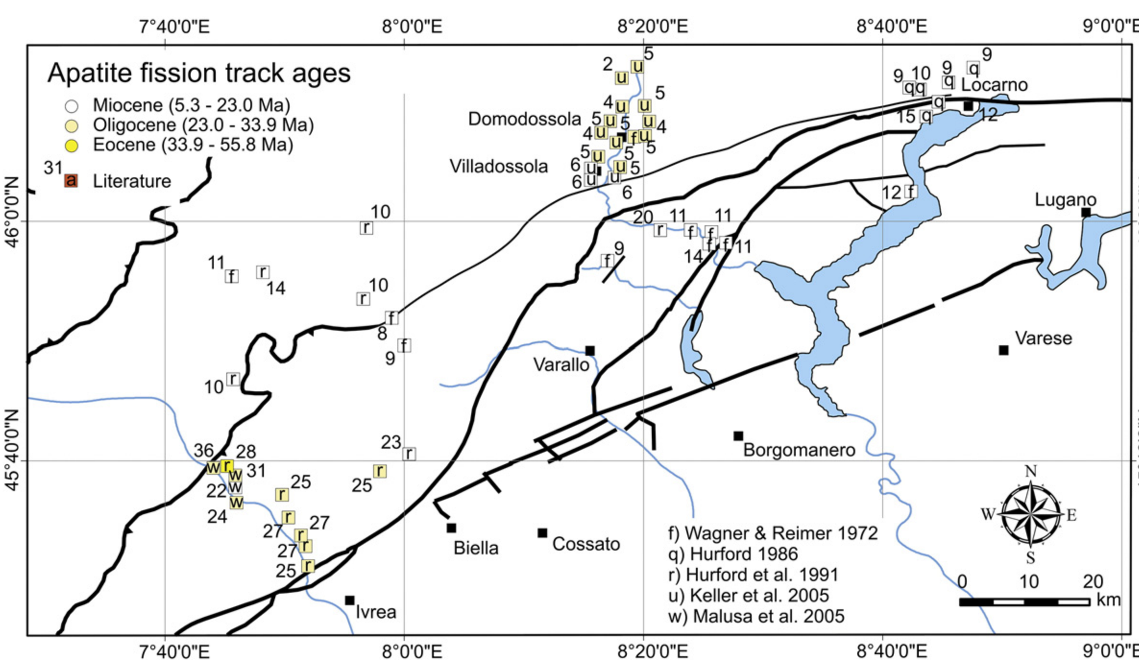

Fig. 7. Compilation of apatite fission track ages in the study area.

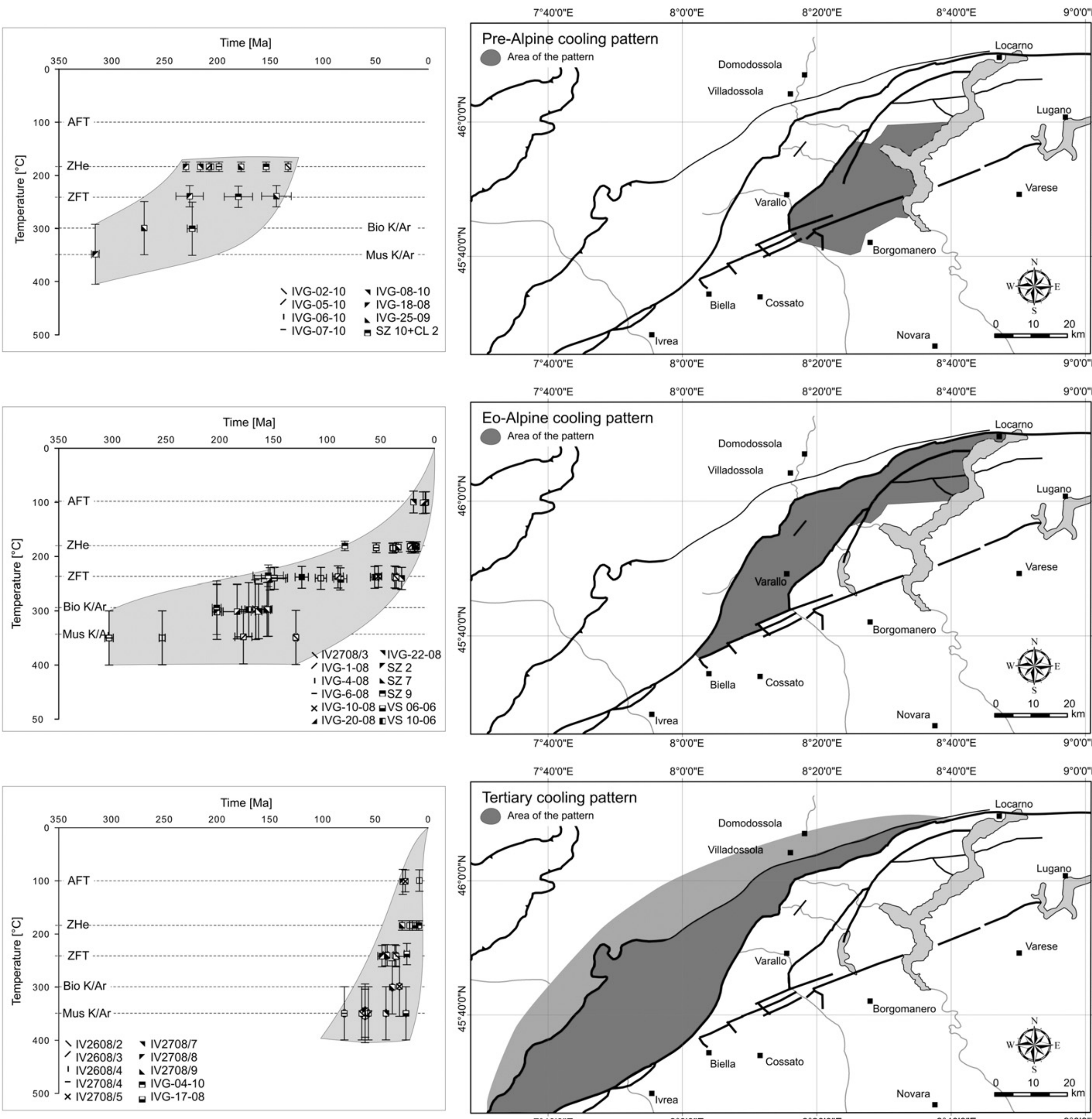

Fig. 8. (Left) The samples were analysed with multi-method geochronology and were grouped according to their apparent cooling paths. (Right) The geographic spread of the three different grouped samples is marked on the map. (A) Pre-Alpine cooling trend: mica K/Ar ages, ZFT and ZHe ages are typically older than 150 Ma. (B) Eo-Alpine cooling trend: the mica K/Ar ages range from Variscan times to the Jurassic, the ZFT ages are typically Cretaceous and Tertiary, while the ZHE ages are exclusively Tertiary. (C) Tertiary cooling trend: the oldest mica K/Ar ages are Late Cretaceous, but all other thermochronometers having lower closure temperatures yield Tertiary ages. Shaded area is unconfined. Data from this study but the AFT ages are from Wagner and Reimer (1972), Hurford (1991) and Keller et al. (2005).

Insubric Line (Frey et al., 1974). According to Schmid et al. (1987; 1989), the rotation of the IVZ occurred during the back-thrusting event, which was synchronous with the back-folding of the Central Alps and combined with a minor sinistral strike-slip component. The back-thrusting and the differential uplift of the SLZ led to mylonitization under greenschist facies conditions along the Insubric Line. Based on the data of Hurford (1986), Schmid et al. (1987) concluded that the back-thrusting started between 30 Ma and 23 Ma. Later dextral strike slip related to transcurrent displacements also lead to mylonitization. The K/Ar fault gouge ages along the Insubric Line bracket this activation history between the Miocene and the Eocene. The ages along the Insubric Line range between 36.7 ± 1.0 Ma and 12.8 ± 0.7 Ma west and east of Locarno, respectively (this paper). They complement the data from Wemmer (1991) yielding 22.9 ± 0.7 Ma at Rimella, Zwingmann and Mancktelow (2004) yielding 19.0 ± 0.5 Ma and 23.5 ± 0.5 Ma east of Bellinzona and Zingg et al. (1976) ranging between 37.8 ± 2.2 Ma and 19.5 ± 3.7 Ma ages between Biella and Valle d'Ossola. The following section is focussing on a profile perpendicular to the general strike of the IVZ through the Val Strona.

6.3. Exhumation history of the Ivrea zone using the new thermochronological data

The new thermochronological data on the Strona profile (A–B on Fig. 2) allows a closer examination of the exhumation history. Fourteen zircon (U-Th)/He ages were generated along a ca. 30 km long, nearly strait NW–SE profile (Fig. 9). In combination with 30 biotite K/Ar and nine zircon fission track ages by Siegesmund et al. (2008), all three geochronometers show a monotonous rejuvenation trend towards the Insubric Line in the north-western direction (Fig. 9). No detectable offset in the ages occurs when crossing the Rosarolo shear zone (Siegesmund et al., 2008), the CMB Line and the Pogallo Line. The biotite K/Ar ages range from 335 Ma to 156 Ma. The ages increase steadily with increasing distance from the Insubric Line, but the slope is low at the beginning and the end and steeper in between 8 and 25 km. The ZFT ages range between 180 Ma and 38 Ma. The two nearest samples to the Insubric Line (at 0.2 and 3 km distances) show similar ages, then the ages increase rapidly to 180 Ma at 13 km distance. The ZHe ages vary between 228 Ma and 14 Ma. The first seven samples in between 0 and 8.5 km distance have ages of 14, 15.5, 17.2, 17.7, 18.1, 20.8 and 35.5 Ma. The following ages increase up to 220 Ma at 19 km distance and then show similar ages again up to the most distal sample at 30 km distance.

The monotonic increase of the ages of the different thermochronometers across the Ivrea-Verbano Zone is interpreted as exhumed and tilted partial reset zones (Fig. 9). These individual ages do not express cooling events or episodes of mineral growth; they are the result of the equilibrium between radioactive decay and the diffusion of decay products (or annealing of fission tracks). Such static partial reset zones develop everywhere in the Earth's crust along profiles having a vertical component. A complete vertical profile with a monotonic transition of ages is composed of three sections (e.g. Fitzgerald et al., 1991): (i) the oldest ages are situated in the upper part of the profile, and expressing the cooling after the oldest thermal event documented by the given thermochronometer. (ii) In the middle section the ages gradually decrease downward. Here the ages were developed in temperature conditions where the products of the radioactive decay only partially disappear by annealing or by diffusion. This transitional zone is defined as the partial annealing zone (PAZ; Fitzgerald et al., 1991) in fission track thermochronology and as the partial retention zone (PRZ; House et al., 1999) in argon and (U-Th)/He thermochronology. (iii) The youngest ages are situated at the base of the profile. If the bottom of the profile is still in the temperature zone where the decay products of the given thermochronometer reset 'geologically instantaneously', then the youngest ages are zero ages. If the youngest ages at the bottom of the profile are non-zero ages, then they express the age of cooling from the former total reset zone to lower temperature conditions, where the decay products are already stable. These youngest data typically register valuable information about the age and rate of the latest exhumation event (Fitzgerald et al., 1991; Kamp and Hegarty, 1989).

In the Strona profile the upper and lower asymptotes of the age curves (Fig. 9) match well with the major known thermotectonic events of the region. The oldest biotite K/Ar ages in the SE of the profile covering the SCZ point to the Carboniferous and clearly mark the age of the Variscan metamorphism, which was a determinant period in the development of the Southern Alpine metamorphic basement (e.g. Boriani and Villa, 1997). The youngest part of the biotite K/Ar age trend towards the Insubric Line is not completely developed, but it is obvious that the ages are converging to ca. 150 Ma. This age actually matches well with the period of relaxation of the isotherms after Early-Mid Jurassic rifting (Stampfli et al., 2002) that caused thinning and increased heat flow in the entire Southern Alps (Bertotti et al., 1997).

The zircon fission track ages indicate a well developed lower part of a fossil partial annealing zone, but unfortunately the oldest (topmost) part of the section was not preserved. However, the oldest ages of the ZHe thermochronometer gives a minimum age of ca. 200 Ma for the oldest ZFT ages because the fission tracks closure temperature is higher than the ZHe closure temperature (e.g. Reiners et al., 2004). The youngest ages are around 38 Ma, indicating a rapid cooling event in the Late Eocene. This event can be related to the so-called 'pre-Oligocene thrusting' phase outlined by Schmid et al. (1989) and documented by numerous field observations and geochronological data in the Western Alps and in the area of Bellinzona (Ahrendt, 1980; Nagel et al., 2002).

The zircon (U-Th)/He data indicate a completely preserved partial retention profile with well documented young and old asymptotes. In the upper part of the profile the thermal conditions allowed complete

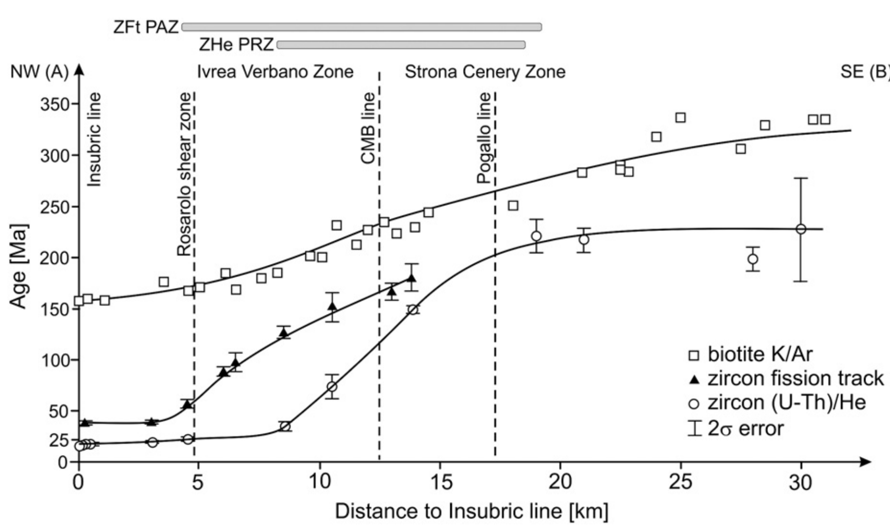

Fig. 9. The trend of biotite K/Ar, ZFT and ZHe ages along the Strona profile (A–B on Fig. 2) between the Insubric Line and Lesa at the Lago Maggiore at ca. 30 km distance (K/Ar and ZFT analysis from Siegesmund et al., 2008). Empty squares: biotite K/Ar, filled triangles: ZFT, empty circles: ZHe. The 2σ uncertainty of the Cenozoic ZHe ages is smaller than the symbol.

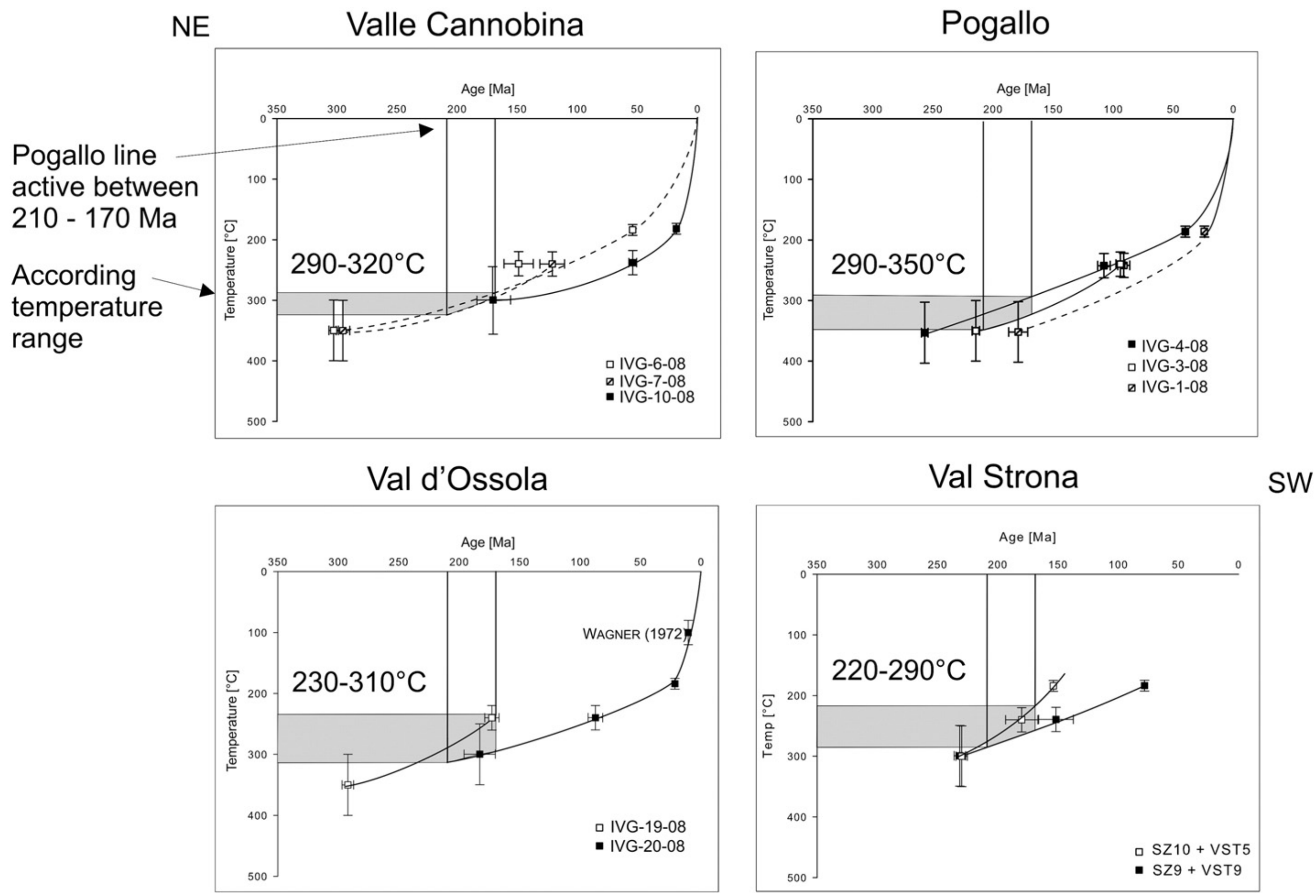

Fig. 10. Apparent cooling paths from samples along the Pogallo Line sorted from the northeast (top left) to the southwest (bottom right). These multi-method thermal histories can be used to determine the temperature (coloured in grey) of the dated rock volumes during the activity period of the Pogallo Line (210 Ma–170 Ma). The temperature decreases from 290 °C to 350 °C in the northeast and ranges 220 °C to 310 °C in the southwest.

helium retention in the zircon crystals during the last ca. 200 Ma. Accordingly, this section occupied a shallow position in the upper crust, above the 100 °C isotherm (for explanation see Fig. 1a in Reiners and Brandon, 2006). This age coincides well with the extension in Early Jurassic time (Hodges and Fountain, 1984; Lemoine and Trümpy, 1987; Santantonio and Carminati, 2010; Zingg et al., 1990). This heating resulted in the reset of the ZHe thermochronometer in the Baveno granite that cooled down already in Permian time after its emplacement in shallow depth. In the young part of the profile (close to Insubric Line) the ZHe ages converge to ca. 14 Ma. These ages indicate that the final exhumation only took place in the Middle Miocene. Along a ca. 5 km section in the vicinity of the Insubric Line the ZHe ages are very uniform. Thus, the final exhumation from the total reset thermal conditions (>~185 °C) took place at a high slip rate.

6.4. Pre-exhumation position of the Ivrea-Verbano Zone

According to the geothermometry and geobarometry data, the Ivrea-Verbano Zone experienced a ca. 90° horizontal axis rotation; however, the timing of this movement is debated (for more details refer to the Introduction and Geology above). The new facts that can be expressed from the thermochronological data and which are relevant for the detection of the pre-exhumation position of the IVZ will be summarized below.

The widths of the detected partial reset zones play a key role in this reconstruction. In the Strona profile the zircon fission track partial annealing zone is as wide as 15 km, while the zircon helium retention zone is ca. 10 km wide (Fig. 9). Worldwide there are only a few complete documentations available on the thickness of the static partial reset zones. Zaun and Wagner (1985) reported the first indications of a zircon PAZ in a borehole. The Urach deep drill hole in southern Germany could not penetrate the entire PAZ, but according to the downhole trend of ZFT ages the thickness of the zone is not more than ca. 2.5 to 3 km. Stockli et al. (2000) studied a naturally exhumed and tilted PAZ in the western Basin and Range province and found a similar thickness for the zircon PAZ, ca. 3 km, while Bernet (2009) documented a thickness of ca. 4 km. For the thickness of the static PRZ of the ZHe thermochronometer Stockli et al. (2000) and Wolfe and Stockli (2010) determined a thickness of ca. 2.5 km. The partial reset zones of all these studied sites are thinner than the detected thicknesses of the PAZ and PRZ in the Strona profile.

Since the zircon helium partial retention zone is perfectly preserved in the Strona profile, a robust calculation with the results of the ZHe method can be undertaken. Modelling of the ZHe ages along a vertical profile have been performed using the HeFTy (Ketcham, 2005). The parameters used for the modelling are:

- Radius of zircon grains: 55 μm (average of the calculated radius for crystals measured in the Strona profile),
- Uranium content of zircon grains: 390 ppm (median of the U concentration measured in the dated crystals).
- The assumed thermal histories are composed of three or four parts:

(i) Thermal stagnation since 200 Ma until the onset of rapid cooling (argument: Late Mesozoic passive margin sedimentation proves that there was no significant modification in the post-Early Jurassic thermal regime of the Southern Alps during Late Mesozoic time).

(ii) Short and rapid cooling event in the Eocene or Miocene or a combination of two cooling events (argument: these cooling events are well constrained by the new data).

(iii) Slow cooling since the major Tertiary exhumation (argument: apatite FT ages indicate a moderate post-14 Ma exhumation rate (see compilation of apatite ages in Fig. 7).

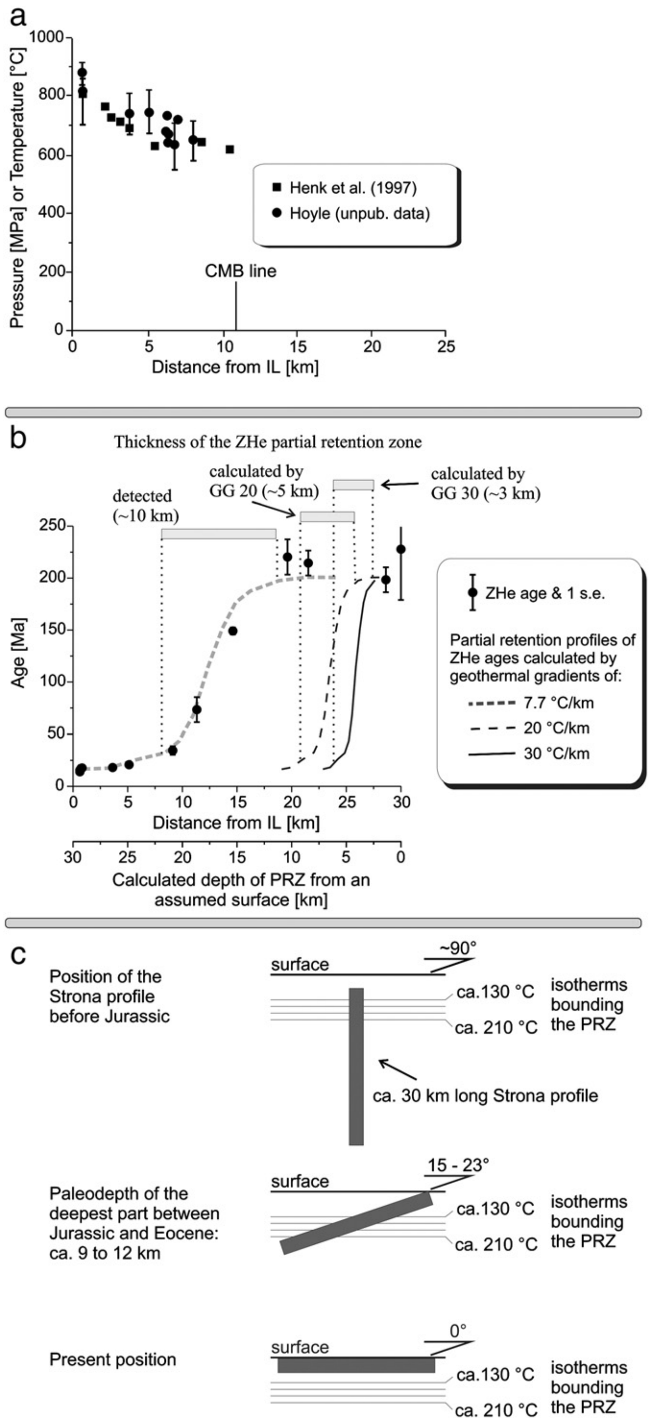

Fig. 11. (a): Peak metamorphic temperature along the Strona profile (from Henk et al., 1997, and Hoyle, unpubl.1999, this laboratory). (b): Measured zircon (U-Th)/He ages plotted across the Ivrea-Verbano Zone and the calculated shape of the ZHe partial retention profiles assuming that (1) the originally vertical profiles are rotated to a horizontal position, (2) the top of the profile is at ca. 30 km distance from the Insubric Line and (3) different geothermal gradients. Assuming a geothermal gradient of 7.7 °C/km results in the best-fit of the measured ages and the calculated curve. Details of the modelling are given in the text. The thickness of the detected PRZ and the calculated ones using gradients of 20 and 30 °C/km (GG 20 and GG 30) are indicated at the top of the figure. (c): Simplified sketch showing the position of the currently exhumed Ivrea-Verbano Zone between the Jurassic and Eocene. Assumption of this position is necessary to get the stretched partial retention zone demonstrated in (b). Angles indicate the dip relative to the present orientation of the profile.

During the modelling the age and rate of cooling events were optimized by multiple iterations in order to obtain the best match of the calculated age profile and the measured ZHe age profile across the IVZ. The best approximation of the age trend (especially in the young part of the Strona profile) was acquired by a two-step cooling model. In these modelling runs the thermal conditions in the uppermost part of the lithosphere were considered as constant between 200 Ma and 38 Ma. Afterwards an episode of ca. 30 °C cooling until 30 Ma took place, where a final, quick cooling step exhumed the profile to surface temperatures between 15 and 12 Ma. For this assumed thermal history the modelling resulted in a partial retention zone between ca. 120 and 180 °C. The conversion of this temperature range to depth depends on the geothermal gradient. The only available geothermal gradient in the studied tectonic unit derives from the geothermometric data determined on the amphibolite to granulite facies metamorphic rocks along the Strona Valley profile (Henk et al., 1997). These data yielded a geothermal gradient of ca. 22 °C/km (calculated from Fig. 11a), but we should consider that the metamorphic paragenesis was formed in Permian time during the thermal climax. If we review the factors determining the post-Permian geothermal gradient of the western Southern Alps in the surrounding area of the IVZ then we should keep in mind two major facts: (i) Jurassic rifting increased the heat flow, but the relaxation should happen in a few 10 Ma, thus this event had no long lasting effect on the ca. 200 to 38 Ma time span. (ii) The proportion of mafic lithologies in the Ivrea body is high and in this Mafic complex the radioactive element content is low (Peressini et al., 2007). Thus, the near-surface radiogenic heat production is reduced in this structural unit, and that the plausible geothermal gradient can be estimated to be between 20 and 30 °C/km during the late Mesozoic and early Cenozoic times. Assuming this gradient the calculated thickness of the ZHe PRZ should be 3 to 5 km, which is close to the detected thickness of the exhumed static partial retention zones in the case studies mentioned above (e.g. Stockli et al., 2000).

The detected helium partial retention zone in the Strona profile is much thicker than the calculated thickness of the retention zone assuming a 20 to 30 °C/km geothermal gradient (Fig. 11b). The best match of measured and calculated profiles can be achieved by assuming a thermal gradient of 7.7 °C/km. This figure is an unrealistic value in an orogen. The problem is probably rooted in the assumed simple geometry of the vertical axis rotation. There are two possible solutions:

(1) The wide PRZ can result from the modification of the geometry of the Ivrea body by stretching. This deformation should happen after the formation of the entire 'normal width' of the zircon PRZ, and under brittle conditions, since the closure temperature of ZHe chronometer is below 200 °C. However, field observations do not prove such an overall and homogeneously distributed stretching. Moreover, the assumption of stretching would also contradict the 'normal' (~22 °C/km) geothermal gradient detected by the Permian mineral assemblages along the profile.

(2) The alternative – and more plausible – solution is the assumption that the exhumed part of the Ivrea body is intact, it has not experienced significant penetrative deformation in brittle conditions, but its initial position before the Miocene exhumation was not vertical. If it occupied an oblique position, dipping at low

angle, before the final exhumation, then the partial retention zone could have developed in an apparently stretched length (see Fig. 11c). If a 20 or 30 °C/km pre-exhumation geothermal gradient is assumed, then the subsurface angle of the currently exhumed and practically horizontal Strona profile was 23° or 15°, respectively. The Ivrea body should be inclined at a low angle already in the Jurassic, because the development of the zircon PRZ has started ca. 200 Ma ago (see the oldest ZFT and ZHe ages in Fig. 9). The most plausible process for this tilting at low angle of the IVZ is the normal faulting partly along the Pogallo Line in the Late Triassic to Middle Jurassic (Hodges and Fountain, 1984; Manatschal et al., 2007; and see Fig. 7 in Zingg et al., 1990).

6.5. Driving forces of the Miocene exhumation in the western Southern Alps

The new results indicate that a significant horizontal axis rotation of the IVZ took place in the Jurassic and acquired its final position only in the Middle Miocene, considerably later than the earlier models postulate: Permian rotation was assumed by Boriani and Giobbi (2004) and Oligocene by Schmid et al. (1987, 1989). The low gradient in the ages close to the Insubric Line proves that the final, Middle Miocene exhumation of the IVZ took place at a high slip rate. Only a few apatite FT ages are known from the region, but they are close to the youngest ZHe ages measured along the Insubric Line (14 to 9 Ma AFT vs. 14 Ma ZHe; see Fig. 7). This minor age difference indicates very quick cooling and subsequently minor post-Middle Miocene erosion.

Such rapid exhumations of flat-lying mid-crustal sections may typically be generated by extensional processes (Coney, 1980; Wernicke and Axen, 1988). It generates quick cooling and exposes the formerly buried static partial retention zones of the different thermochronometers (Dokka et al., 1986; Fitzgerald, et al., 1991; Stockli et al., 2000).

We propose that this newly dated Middle Miocene exhumation phase in the western Southern Alps was also linked to extensional tectonics. The detected flat, oblique pre-exhumation position of the Ivrea body also fits this assumption. During the evolution of the Alpine chain, the building up of the relief occurred in the Eocene in the Western Alps and in the Oligocene in the Eastern Alps. The orogenic collapse followed the development of the thickened crustal structure and resulted in several manifestations of orogen-parallel extensions in the Miocene. In the Western Alps numerous brittle faults indicate extension in the Miocene (e.g. Champagnac et al., 2006; Surace, 2004; Surace et al., 2011). In the Central Alps the Miocene extension along the Simplon fault is well documented under both ductile and brittle conditions (e.g. Grosjean et al., 2004; Mancktelow, 1992). In the Eastern Alps the significant Middle Miocene stretching was localized mainly along the Brenner and Katschberg low angle faults (e.g. Frisch et al., 2000). The major displacement pulse along the Lavanttal faults also took place between 14 and 12 Ma (Wölfler et al., 2010). In the eastern continuation of the Eastern Alps the Miocene extension is much more pronounced: the western Pannonian Basin experienced significant vertical thinning in the same time (Tari et al., 1999). In the eastern Southern Alps before the Late Miocene development of the current montaneous relief the southern Dolomites were buried by molasse sediments. In the Langhian (16–13 Ma) a rapid deepening of the Venetian basin to bathial conditions took place (Mellere et al., 2000).

Thus, this study concludes that the detected time range of the final exhumation of the IVZ matches well to the overall orogen parallel extension of the entire Alps (Mancktelow, 1992; Ratschbacher et al., 1989; Selverstone, 2005). Furthermore it may also be a result of the continental scale extension.

7. Conclusions

Based on the new results from this study and combined with previously published thermochronologic data, the understanding of cooling and exhumation of the Ivrea-Verbano Zone, as well as the adjacent SCZ, SLZ and Lower Penninic nappes, can be significantly refined. The upper part of the Ivrea-Verbano Zone and the SCZ had already occupied a near-surface position (below ca. 100 °C) in the Early Jurassic. In contrast, during the Late Cretaceous (80 to 65 Ma; Babist et al., 2006) the SLZ suffered high pressure metamorphism at ca. 60 km depth (Compagnoni, 1977; Dal Piaz et al., 1972). These different histories are illustrated as cooling patterns, which mark intact areas in the western Southern Alps and indicate the migration of exhumation through time (Fig. 8). The Ivrea-Verbano Zone yields the most complete and coherent geochronological data set, and the evolution of this block can be summarized in the following steps:

— The presently exposed part of the Ivrea-Verbano Zone reached its thermal climax in the Permian (Henk et al., 1997; Peressini et al., 2007; Sinigoi et al., 2011). The geobarometric and geothermometric data indicate a Permian geothermal gradient of ca. 22 °C/km (Henk et al., 1997).
— During the Triassic only some thermal relaxation and subsidence may be considered, without significant modification in the thermal structure of the Southern Alpine crust.
— The Early Jurassic rifting increased the heat flow all over the Southern Alps. This heating resulted in the reset of the ZHe thermochronometer in the Baveno granite that already cooled down in the Permian after its emplacement at shallow depth.
— The Jurassic extension uplifted the Ivrea-Verbano body to a shallow to -mid crustal position. The currently exposed section in the Strona Valley occupied an oblique position of ca. 15 to 23° tilt already at the beginning of the Jurassic. The southeastern part of the section was in a near surface position, while the belt along the Insubric Line was in ca. 9–12 km depth, corresponding to temperature conditions of ca. 300 °C and marked by the partial reset of the biotite K/Ar, ZFT and zircon helium ages.
— After Early Jurassic rifting the Mesozoic thermal history of the Southern Alps was presumably static; steady state thermal conditions can be considered for the time span from 200 Ma to ca. 38 Ma. Late Mesozoic passive margin sedimentation proves that there was no significant modification in the post-Early Jurassic thermal regime of the Southern Alps during Late Mesozoic time.
— During the Eocene a rapid exhumation took place. The deepest part of the currently exposed Ivrea-Verbano Zone (ca. 3 km long section) cooled from the ZFT total annealing zone (from ca. 300 °C) at ~38 Ma. This event was probably related to a Paleogene thrusting phase affecting the entire Western Alps (Schmid et al., 1989).
— The final exhumation and tilting of the Ivrea-Verbano Zone is reflected by 14 Ma ZHe ages and can be related to a rapid and pronounced Middle Miocene event. The latest documentation of these movements is the 12.8 Ma illite K/Ar age obtained on fault gouges of the Insubric Line. Apatite fission track data (Hurford, 1991; Wagner and Reimer, 1972) do not show any trend across the IVZ, indicating that further exhumation took place 'en bloc'.
— The final exhumation phase cannot be excluded as being related to the overall orogen-parallel stretching of the Alps. Moreover, this large-scale process is responsible for the exhumation of the Ivrea body from the shallow and oblique position that was already occupied in the Early Jurassic.

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