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ORIGINAL PAPER

Single and double exhumation of fault blocks in the internal Sesia-Lanzo Zone and the Ivrea-Verbano Zone (Biella, Italy)

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Abstract The combination of magmatic, structural and fission track (FT) data is used to unravel Oligocene/Miocene near-surface tectonics in the internal Western Alps. This includes reburial of parts of the already exhumed Sesia-Lanzo Zone and their subsequent re-exhumation. We define blocks mainly on the base of their Oligocene–Miocene cooling history (FT data) and on published paleomagnetic data. The preservation of a paleosurface allows a detailed reconstruction of the exhumation, burial and re-exhumation of different tectonic blocks. Near-surface, rigid block rotation is responsible for the reburial of the Lower Oligocene paleosurface in part of the Sesia-Lanzo Zone (the Cervo Block) and for the conjugate uplift of deeper portions of the Ivrea-Verbano Zone (the Sessera-Ossola Block). This block rotation around the same horizontal axes produces in the currently exposed portions of the two blocks, quite different temperature/time paths. While the surface of the Cervo Block is buried, the lower part of the Sessera-Ossola Block is uplifted. The rotation is constrained between the age of emplacement of the Biella Volcanic Suite on top of the Sesia-Lanzo Zone (32.5 Ma) and the intrusion of the Valle del Cervo Pluton (30.5 Ma). After this relative fast movements, the concerned blocks remained in (or underneath) the partial annealing zone of zircon until in Aquitanian times they were rapidly uplifted into the partial annealing zone of apatite. The further stage of exhumation out of the partial annealing zone of apatite extends over the entire Miocene. At that time, units of the external Western Alps underwent fast exhumation (external Briançonnais, Valais). In addition to the well-known post-collisional deformation in the axial- and external Western Alps, the internal units (i.e., the upper plate) hold an apparent stable position in terms of exhumation.

Keywords Block rotation · FT ages · Western Alps · Paleosurface

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Introduction

The understanding of collisional mountain belts like the Alps, in our particular case the Western Alps, has been substantially enlightened by studies on the tectonic and metamorphic evolution during subduction and collision (e.g., Compagnoni et al. 1977; Venturini 1995; Schmid and Kissling 2000; Agard et al. 2002; Bucher et al. 2004; Konrad-Schmolke et al. 2006; Babist et al. 2006; Bousquet et al. 2008) as well as investigations into the post-collisional near-surface evolution (e.g., Fügenschuh and Schmid 2003; Agard et al. 2003; Malusá et al. 2005, 2006, 2009; Malusá and Vezzoli 2006; Sue et al. 2007). Neotectonic studies often use structural data of the presently exposed crustal level and thermo-chronological data to reconstruct the exhumation history. In addition, the investigation of the sedimentary record linked to exhumation, and tectonics in the hinterland is another way to investigate this problem (e.g., Di Giulio et al. 2001; Garzanti and

Malusà 2008; Malusá et al. 2011). The latter method requires a detailed inventory of the sediments (e.g., fission track data, provenance analysis), well-constrained stratigraphic age and complete preservation of the sedimentary column. The first requirement is frequently fulfilled in coarse clastic sediments but can be more difficult in fine clastic or chemical sediments. Furthermore, the different preservation of the sedimentary column limits the reconstruction of exhumation and tectonics from the sedimentary record.

Preserved paleosurfaces provide another possibility to constrain near-surface deformation and the relationship to deeper structural levels. This is the case in the internal Western Alps, where the extraordinarily well-preserved Lower Oligocene paleosurface of the Sesia-Lanzo Zone (upper plate during subduction and collision), allows unraveling the Oligocene and Miocene near-surface tectonics and its link to coeval mid-crustal collisional processes in the more external part of the orogen. Our investigation includes (1) the definition of blocks with a consistent thermotectonic evolution and (2) the reconstruction of local temperature–time paths.

Geological setting

The study area is part of the internal Western Alps and includes basement rocks of the Southern Alps and high-pressure rocks of the Austroalpine Sesia-Lanzo Zone (Fig. 1). The Western Alps represent a collisional orogenic belt, where oceanic and continental units are stacked as a consequence of southeast-directed subduction of oceanic and continental units under the Adriatic plate. Subduction and related imbrications occurred in the late Cretaceous in the Sesia-Lanzo Zone and continued into the Oligocene in the Valais units (summary in Berger and Bousquet 2008). The thickened crust is overprinted by post-nappe folding and faulting (e.g., Bucher et al. 2004; LeBayon and Bellevre 2006).

The major units of the internal western Alps are the Sesia-Lanzo and the Ivrea-Verbano Zone (Fig. 1), separated by the Canavese Line (part of the Periadriatic Fault Zone; Schmid et al. 1989), which has been repeatedly active over time (e.g., Ahrendt 1980; Schmid et al. 1989; Handy et al. 2005). The Sesia-Lanzo Zone exposes mid- to upper crustal rocks grouped into three main units (Babist et al. 2006): (1) Mombarone nappe (mostly equivalent to the “Micascisti eclogitici” of Compagnoni et al. 1977), (2) Bonze unit and (3) Bard nappe (nearly equivalent to the “Gneiss minuti” of Compagnoni et al. 1977). The Sesia-Lanzo Zone, generally interpreted as part of the Adriatic margin (e.g., Babist et al. 2006; Lardeaux and Spalla 1991), is dominated by various gneisses intercalated with lenses of basic rocks of variable size and shape. The Sesia-Lanzo Zone underwent HP/LT metamorphism at the Cretaceous/Tertiary boundary (Rubatto et al. 1999). Exhumation of these Sesia-Lanzo Zone rocks occurs mainly in the Eocene (Babist et al. 2006). These authors distinguished five ductile deformation phases during the Alpine evolution of the Sesia-Lanzo Zone. As will be discussed below, a subdivision of the Sesia-Lanzo Zone into rigid blocks characterizes its late-stage brittle evolution. Two Rupelian plutons intrude the southeastern margin of the Sesia-Lanzo Zone: the Valle del Cervo Pluton (Bigioggero et al. 1994 and references herein) and the Traversella Pluton (Zanoni 2010 and references therein). A narrow band of Early Rupelian subaerial volcanic and volcaniclastic rocks (Figs. 1, 2) overlay the metamorphic rocks of the Sesia-Lanzo Zone (Carraro 1966; Callegari et al. 2004; Kapferer et al. 2011).

In the Ivrea-Verbano Zone, evidence for an Alpine metamorphic overprint is weak. The complete crustal section is largely dominated by mafic plutonic rocks, especially gabbros and diorites of Permian age outcropping almost along the Canavese Line and Paleozoic migmatites (Peressini et al. 2007 and literature therein). The migmatites developed in Carboniferous to Permian times and represent the former upper part of this crustal section (i.e., country rocks of the Permian intrusives). Alpine thermal overprint is limited to localized hydrothermal activity, and Alpine overprint on geothermochronometers is only known from the northern and northwestern part of the Sesia-Lanzo Zone (Siegesmund et al. 2008; see section on block definition). The adjacent Strona-Ceneri Zone (or Serie dei Laghi) is generally interpreted as to represent mid-crustal levels, dominated by Paleozoic migmatites, gneisses and granitoids displaying intense pre-Alpine tectonic overprint (e.g., Zurbriggen et al. 1997; Handy et al. 1999). These rocks together with their Mesozoic cover are equivalent to the basement underlying main parts of the Padan basin. The Tertiary sedimentary evolution of this basin is exhaustively described in a series of recent papers (Malusá et al. 2011; Molli et al. 2010; Mosca et al. 2009; Garzanti and Malusà 2008; Di Giulio et al. 2001). An interesting feature of this basin in the Oligocene and Early Miocene times is the presence of an emerged swell with the Rupelian subaeric Mortara volcano overlain only in Langhian times by marine marls and shales (Pieri and Groppi 1981; Di Giulio et al. 2001). The tectonic subdivision of the above described units is based on the crustal scale tectonic evolution of basement units or their sedimentary evolution. In addition to this first-order subdivision, the younger near-surface tectonics cut these units into new blocks. These blocks are defined mainly by their cooling histories and are delimited by reactivated older structures or by late brittle faults (see section on definition of blocks).

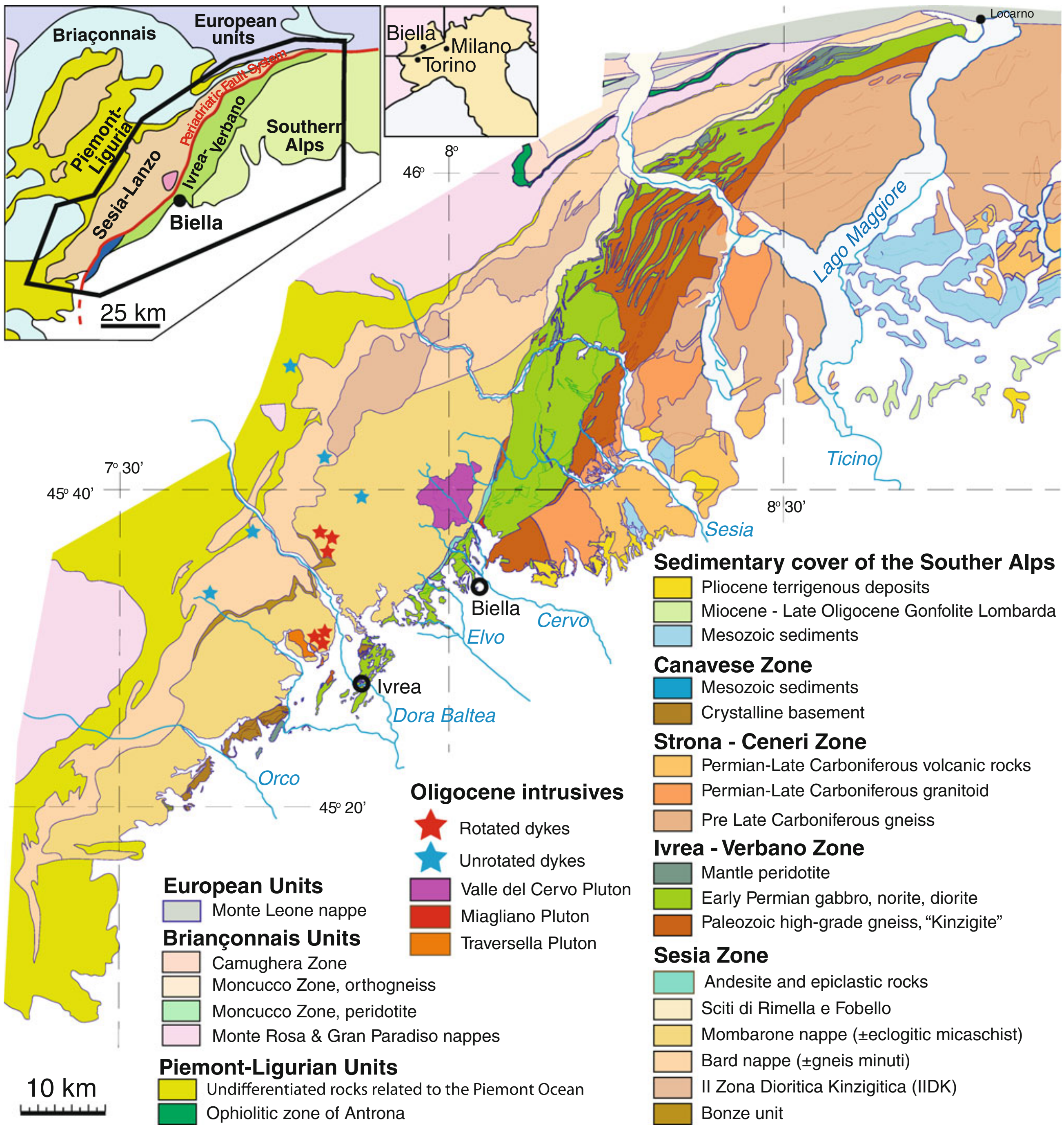

Fig. 1 Geological map compiled after: Bigi et al. (1990) and Babist et al. (2006) and paleomagnetic data from Lanza (1977, 1978)

Fission track data

All fission track samples have been crushed using the *SelFrag* equipment at the University of Bern (Giese et al. 2010). After crushing, sieving, Frantz magnetic separator, heavy liquid separation with bromoform and methylene iodide apatite and zircon were hand-picked. Ages were calculated using the zeta calibration method (Hurford and Green 1983) with a zeta factor of 190.2 ± 9.0 (zircon, CN1 glass) and 357.7 ± 39.8 (apatite, CN5 glass). Samples were analyzed using the external detector method as described by Gleadow (1981). The measurements were taken using a Zeiss Axio Imager A1 m microscope equipped with an AUTOSCAN^{TM} stage. The ages were calculated using the TRACKKEY program, version 4.2.f (Dunkl 2002). Time–temperature (t/T) paths are modeled

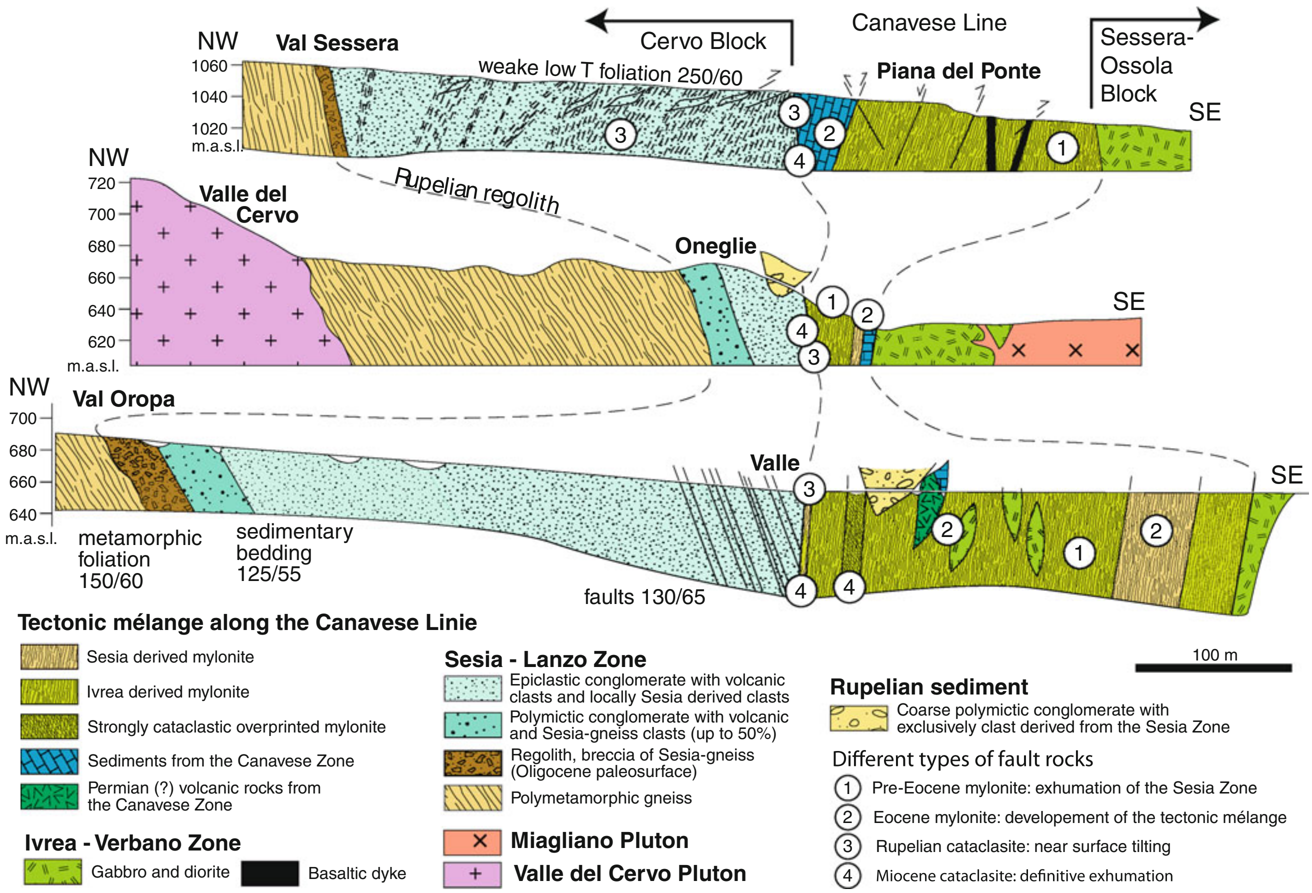

Fig. 2 Detailed profiles through the studied area. **a** Section in Val Sessera showing different deformation zones in the rocks of the Biella Volcanic Suite and of the Ivrea Zone. **b** Section in Valle del Cervo. Note the different thickness of the volcanic rocks in comparison with the other areas. **c** Section in Val Oropa (after Wissmann 1985). The different fault rocks are indicated

Table 1 Positions of the samples used for FT analysis

Samples	Locality	Altitude	Rock type	Measured minerals
Bi0633	Campiglia	730	Monzogranite	A
Bi0634	Balma	650	Syenite	A
Bi0705	Rosazza	900	Monzonite	A + Z
Bi0707	Oriomosso	1185	Monzonite	A + Z
Bi0708	Forgnengo	950	Porphyritic monzogranite	A
Bi0632	Campiglia	750	Granite	Z
Bi0637	Miagliano	530	Miagliano tonalite	A + Z
Bi0635	Passobreve Valle del Cervo	590	Sesia gneis	A + Z
Bi0638	Valle in Valle dellOropa	640	Sesia gneis	A + Z

A, apatite; *Z*, zircon

using the HeFTy® program, version 1.6.7 (Ketcham 2005) including the annealing model of Ketcham et al. (2007).

We have collected a suite of samples for FT dating along the Cervo valley, a NW-SE deep incision into the southern extremity of the Alpine mountain belt (Table 1; Figs. 2, 3). Along this profile (Figs. 2, 3), all units of interest (Sesia-Lanzo Zone, Valle del Cervo Pluton, Biella Volcanic Suite, Ivrea-Verbano Zone and Miagliano Pluton) are exposed along the river allowing sampling at nearly the same altimetric level. Two samples (Bi0707 and Bi0708) have been collected at different altitude (1,185 and 950, respectively; Table 1) to test a possible dependence of the age with the altitude. Fission track ages do not indicate any correlation with sampling altitude (Tables 1, 2, 3). Within the same lithologic unit, the central ages for zircon and apatite from samples of different altitude are within error

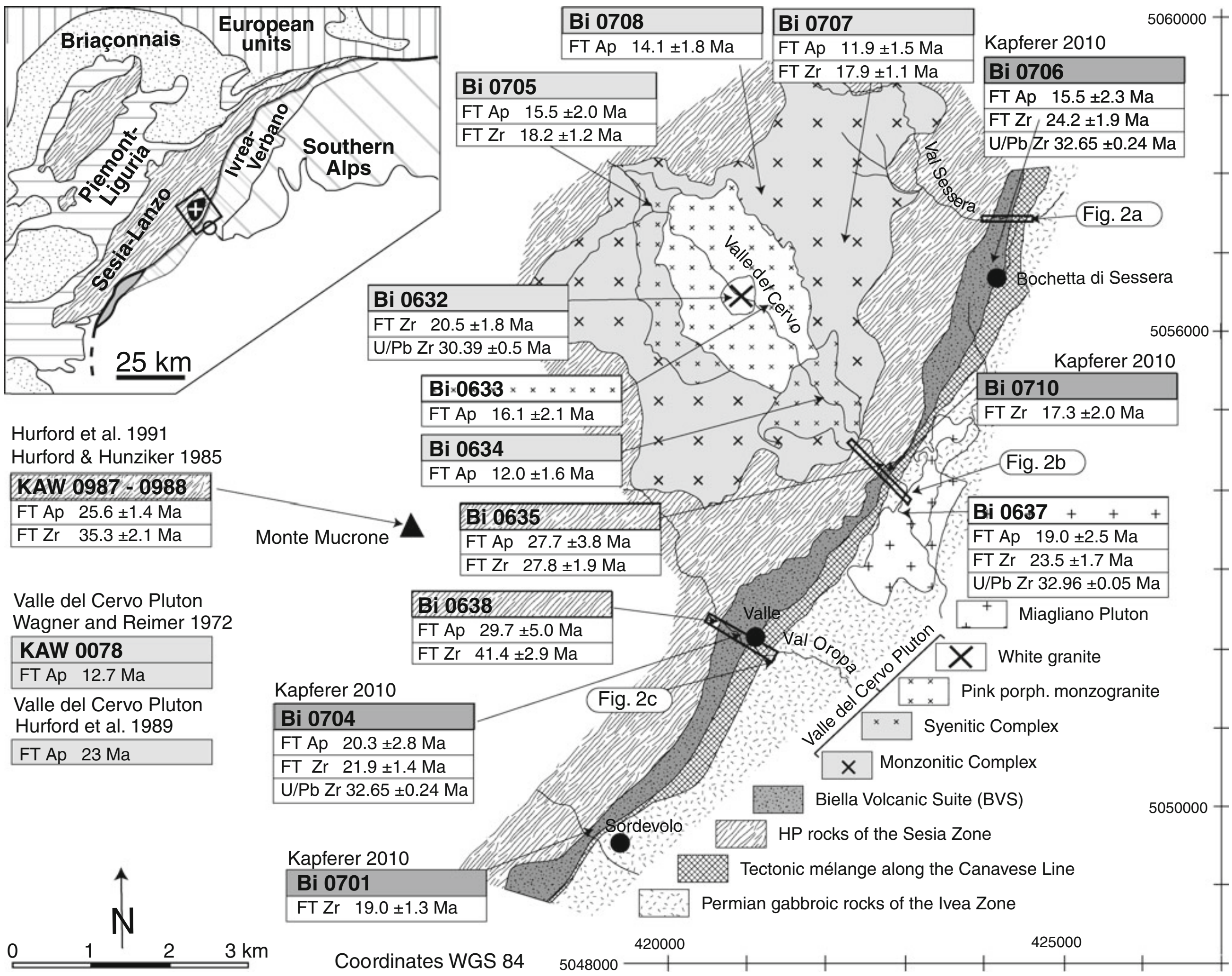

Fig. 3 Map of the studied area with the sample localities for FT (see Table 1, 2, 3, 4)

Table 2 Results from apatite FT analysis

Samples	Counted grains	N_s	Ps (*E5 cm–2)	N_i	Ps (*E5 cm–2)	χ2 (%)	Age (Ma)	Dpar	Mean track length	Counted tracks
Bi0633	20	243	6.262	3,704	95.452	98.91	16.1 ± 2.1	2.18	12.1 ± 2.0	102
Bi0634	20	174	4.845	3,543	98.655	80.88	12.0 ± 1.6	2.38	12.1 ± 1.8	106
Bi0705	16	216	5.766	3,253	86.843	72.53	15.5 ± 2.0	2.34	12.6 ± 1.5	110
Bi0707	21	291	7.158	5,418	133.263	47.09	11.9 ± 1.5	2.11	12.6 ± 1.9	106
Bi0708	20	347	6.601	5,817	110.652	96.61	14.1 ± 1.8	2.19	12.3 ± 1.8	105
Bi0637	21	213	3.599	2,482	41.933	97.49	19.0 ± 2.5	2.68	12.8 ± 1.9	58
Bi0635	28	227	2.856	2,023	25.449	10.85	27.7 ± 3.8	1.86	12.5 ± 2.1	103
Bi0638	18	72	1.408	576	11.268	99.93	29.7 ± 5	1.31	10.7 ± 2	8

equal. A sample was collected in Val Oropa at Valle ca. 5 km west of the Cervo valley (Fig. 3). In the discussion, we will integrate also four samples from the Biella Volcanic Suite (Fig. 3; Kapferer 2010; Kapferer et al. 2012). This spatial distribution of the samples should allow tracing the cooling history of each unit during last stage of exhumation toward the surface.

In the Valle del Cervo Pluton, the central ages can be interpreted as cooling ages as indicated by the small spread in single grain ages and the related high chi-square

Table 3 Results from zircon FT analysis

Sample	Counted grains	N_s	Ps (*E5 cm-2)	N_i	Ps (*E5 cm-2)	χ2 (%)	Age (Ma)
Bi0632	15	857	78.992	2096	193.194	0	20.5 ± 1.8
Bi0705	19	1494	53.337	3802	135.734	0.15	18.2 ± 1.2
Bi0707	20	2505	56.381	6415	144.386	0.06	17.9 ± 1,1
Bi0637	25	932	23.181	1853	46.089	12.26	23.9 ± 1.7
Bi0635	19	964	50.2	1614	84.049	22.34	27.8 ± 1.9
Bi0638	24	2727	62.665	3215	73.879	0	41.4 ± 2.9

probability. The apatite central ages vary between 12 and 16 Ma, but overlap within error. Wagner and Reimer (1972) also obtained an apatite age of 12.7 Ma for a not specified rock sample (KAW78), whereas Hurford et al. (1989) report a considerably older apatite age of 23 Ma without any other specification (Fig. 3). Zircon ages spread between 18 and 20 Ma. Apatite FT and zircon FT ages are distinctly younger than the crystallization age of the Valle del Cervo Pluton of 31.0 ± 0.20 (Romer et al. 1996). The ten million year differences between emplacement and zircon FT ages cannot be related to the post-emplacement cooling of the pluton to ambient host rock temperatures. The modeled temperature/time paths for apatite in different members of the pluton (Fig. 4a–d) indicate post-emplacement cooling to temperatures below the zircon partial annealing zone (PAZ) until the Early Miocene. In Burdigalian times (20–16 Ma), the pluton together with its country rocks rapidly cooled down into the apatite PAZ. The following cooling through the apatite PAZ takes place at significantly lower rates (Fig. 4).

The Miagliano pluton shows internal consistent age populations of apatite and zircon FT ages. This result in central ages for apatite and zircon of 19.0 ± 2.5 Ma and 23.5 ± 1.7 Ma, respectively (Tables 2, 3). In combination with the U/Pb zircon crystallization age of 33 Ma (Kapferer 2010; Berger et al. 2012), the Miagliano pluton represents an excellent marker for the cooling history of the surrounding portion of the Ivrea-Verbano Zone (Sessera-Ossola Block, see below). The apatite cooling model (Fig. 4g) indicates rapid cooling from the zircon PAZ into the apatite PAZ in Aquitanian times followed by a Middle Miocene break in cooling. After this break, the Miagliano Pluton renewed cools down outside the apatite PAZ, relatively rapidly, during the Tortonian and Messinian.

Two samples from the high-pressure metamorphic rocks of the Sesia-Lanzo Zone yield two similar central apatite FT ages of 27.7 ± 3.8 and 29.7 ± 5.0 Ma but two considerably different zircon FT ages of 27.8 ± 1.9 Ma and 41.4 ± 2.9 Ma (Tables 2, 3). Published ages of the HP-gneiss at Monte Mucrone result in 35.3 and 25.6 Ma for zircon and apatite, respectively (Hurford et al. 1991; Hurford and Hunziker 1985). The Chattian zircon age of the sample in Val Cervo (Fig. 3) ca 700 m away from the intrusive contact can be partially explained with a thermal influence of the intrusion. The second sample (Bi0638, Fig. 3) in Val Oropa, showing a Bartonian zircon age, is probably sufficiently distant from the intrusive (at least 2 km). This age is similar to FT ages at Monte Mucrone (Hurford and Hunziker 1985; Malusá et al. 2005 and references herein). More in detail, the single grain ages in sample Bi0638 scatter between 25 and 70 Ma, which make them meaningless in terms of their central age. This scatter is due to the complex Paleogene exhumation history of this portion of the Sesia-Lanzo Zone, as we will discuss later. The two Late Rupelian-Early Chattian apatite ages are similar but much older than the Langhian-Serravallian ages of the Valle del Cervo Pluton. As no localized fault surrounding the pluton as been recognized and missing other geological explanation for a differentiated cooling evolution between the pluton and its direct surroundings, these differences must be related to FT annealing behavior during exhumation, reburial and final exhumation of this part of the Sesia-Lanzo Zone versus the continuously cooling and uplifting plutonic rocks (see below).

Oligocene–Miocene individualization of upper crustal blocks

In order to discuss the near-surface tectonic evolution of the units characterizing the studied area (Sesia-Lanzo Zone and Ivrea-Verbano Zone), it is fundamental to define portions of these units, which we called blocks, based on their distinct late-stage exhumation paths (Figs. 4, 5, 6). Different blocks in the Southern Alps are already defined in light of structural arguments (Schumacher et al. 1997). Malusá et al. (2005) have subdivided the units of the axial domain of the Western Alps into two large blocks (the western and the eastern blocks) on the base of thermochronological criteria. Similarly, Malusá et al. (2006) showed an example of local (km scale) complex segmentation inside the Bard nappe of the Sesia-Lanzo Zone. We extend these suggestions defining some new blocks in the Sesia- and Ivrea Zone (Fig. 5). It is important to keep in

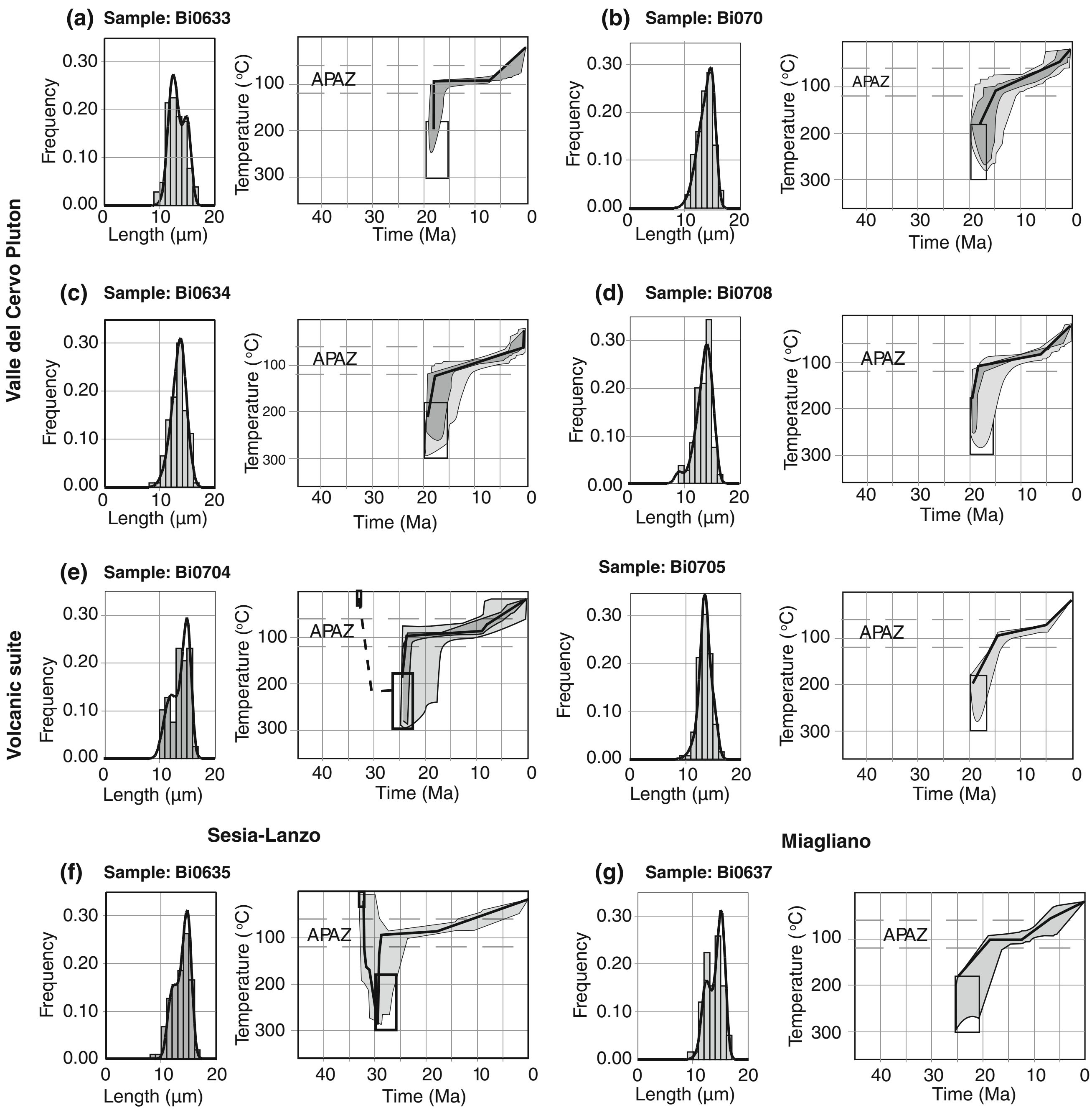

Fig. 4 FT data and modeled cooling curves (see Table 1, 2, 3): **a–d** Val Cervo pluton; **a** sample Bi0633. **b** Sample Bi0633; **c** sample Bi0633; **d** sample Bi0633; **e** sample Bi0704 from the volcanic cover; redrawn after Kapferer (2010): **f** sample Bi0635 from the Sesia-Lanzo zone; **g** sample Bi0737 from the Miagliano pluton

mind that the individualization of these upper crustal blocks starts in the Late Eocene and that some differ notably from earlier subdivisions based on lithological or structural arguments presented in the literature (e.g., Venturini 1995; Babist et al. 2006). Fission track dating is one of the main criteria to define this low-temperature evolution. However, the distribution of FT data is limited and heterogeneously distributed. It is therefore often difficult to interpolate the ages over a large surface. Near-surface blocks are most likely delimited by brittle faults. Therefore, as long as possible, we have utilized currently known tectonic discontinuities (at best brittle faults or brittle reactivated ductile shear zones). Some few other borders have been traced on the base of published lithological criteria (i.e., degree and/or age of metamorphism). Where information is completely missing and no other evident

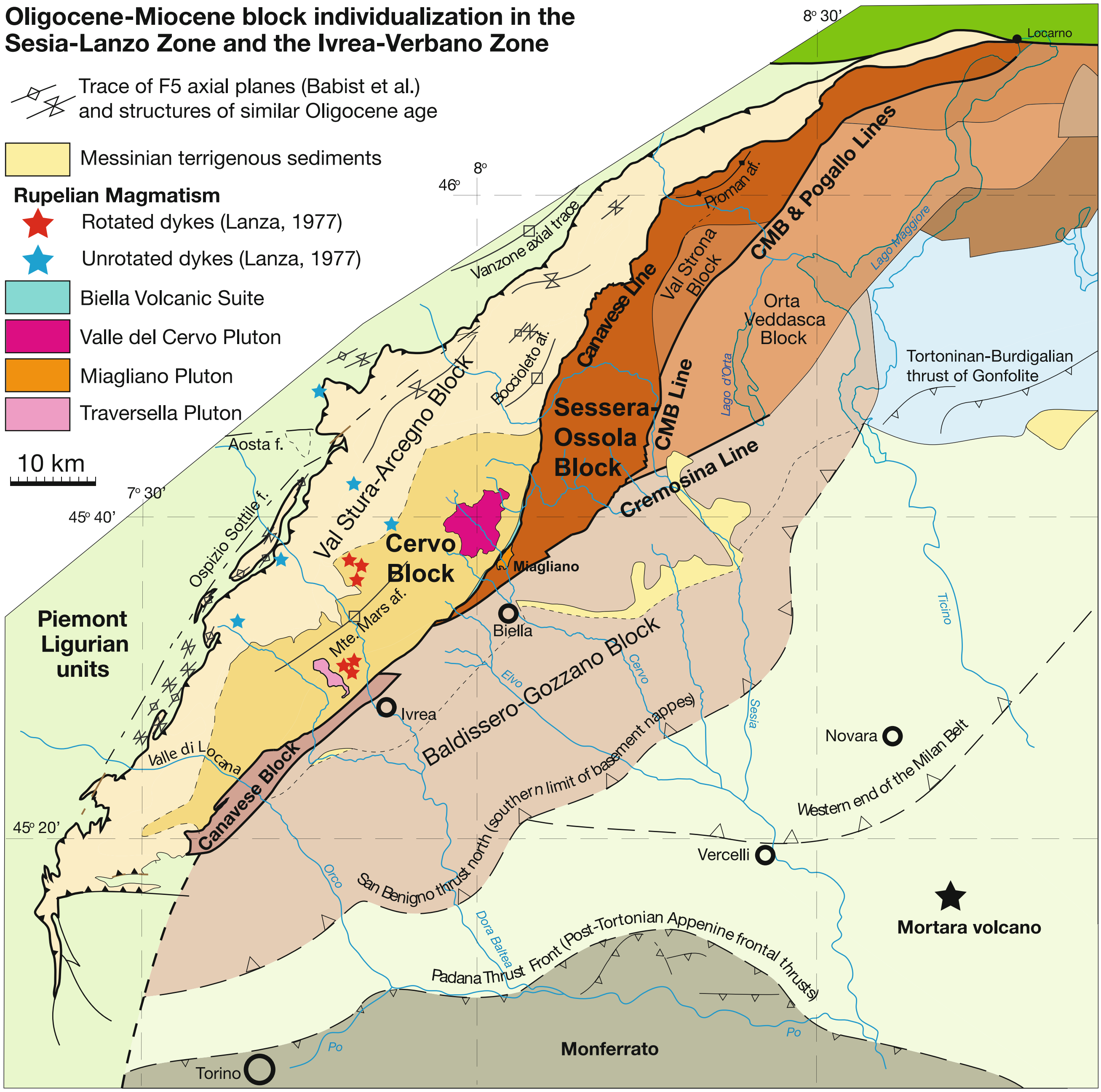

Fig. 5 Delimitation of blocks of similar Oligocene–Miocene near-surface cooling and tectonic history (see also Schumacher et al. 1997). The blocks that discussed detail in this contribution are written in *bold*. See text for discussion

geological boundary has been defined so far, we have traced the boundary arbitrarily across existing subdivisions, in a position that should fit the new constrains. These last boundaries are represented by dashed lines in Fig. 5.

Cervo block

The lenticular-shaped Cervo Block extends from the Valle di Locana (NW of Torino) to the upper Val Sessera (N of Biella; Fig. 5). This block has been named after the river Cervo, where we have collected most information. Toward E and SE, it is delimitated by the Canavese Line between Scopello (Val Sesia) and Curogne (Valle di Locana). The western margin follows the border between the internal and intermediate units of the polycyclic basement complex of Venturini (1995) until it meets the tectonic contact between the Mombarone nappe and the Bonze unit. The northwestern border follows this tectonic contact until it bends into the Mombarone nappe along an arbitrarily defined transition zone between the rotated and un-rotated Oligocene dykes of

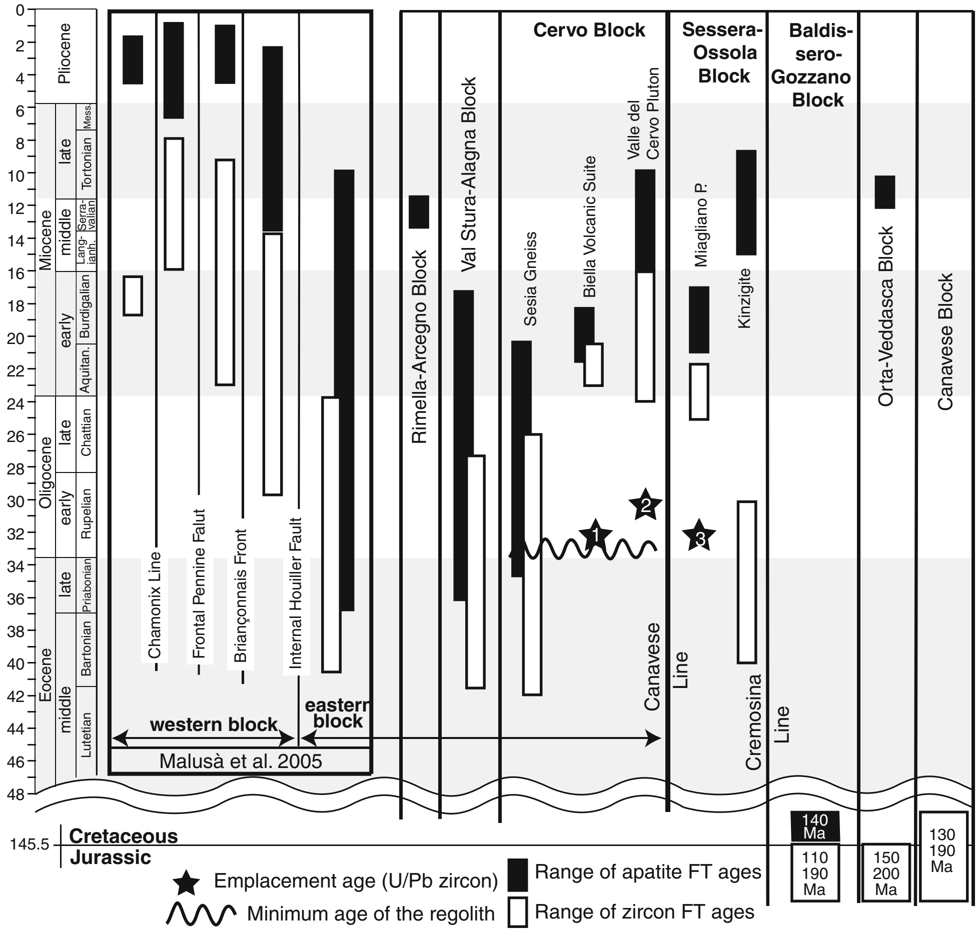

Fig. 6 Table of the magmatic and cooling events in the studied area. *1*, *2* and *3* are magmatic emplacement ages. *Data source*: Bistacchi et al. (2001); Bürgi and Klötzli (1990); Giger (1991); Giger and Hurford (1989); Giger and Hunziker (1985); Hurford et al. (1991); Kapferer (2010); Malusá et al. (2005); Siegesmund et al. (2008); Wagner et al. (1977); Wagner and Reimer (1972); see also Malusá and Vezzoli (2006) for other compilations

Table 4 Summary of published data of the magmatic rocks in the area

Units	Age (Ma)	Reference	Depth (km)	Reference
Valle del Cervo pluton	30.39 ± 0.50	Romer et al. (1996)	4–7	Zanoni et al. (2010)
Miagliano pluton	32.97 ± 0.05	Kapferer (2010)	12–15	Berger et al. (2012)
Biella volcanic compl.	32.44 – 32.89	Kapferer (2010)	Surface	–

Lanza (1977, 1978; Fig. 5). This border could also more or less correspond to the trace of the last ductile folding in the Mombarone nappe (D5; Babist et al. 2006). The northern margin in the upper Val Sessera is again defined by the border between the internal and the intermediate units of the polycyclic basement complex of Venturini (1995). The Cervo Block is bordered by the Sessera-Ossola Block to the east, the Baldissero-Gozzano Block and the Canavese Block to the south and finally the Val Stura-Arcegno Block to the west, northwest and north. The Cervo Block consists essentially of rocks of the Mombarone nappe (Babist et al. 2006). It contains the paleosurface, the overlaying Early Rupelian volcanic and volcanoclastic rocks of the Biella Volcanic Suite (Fig. 5; Kapferer et al. 2011) and the two Rupelian plutons, the Valle del Cervo Pluton and the Traversella Pluton. Zircon and apatite FT ages of the Valle del Cervo Pluton define at best the rapid Aquitanian cooling of the block into the PAZ of apatite, followed, during the whole Miocene (between 20 and 5 Ma), by a slow crossing of the PAZ of apatite (Fig. 4a–c).

A coherent lithologic association forms the Cervo Block. Beside the Oligocene magmatic rocks, it consists of Paleozoic metamorphic and magmatic rocks having suffered Alpine HP-metamorphism and greenschist facies overprint to variable extent. The block forms also a coherent structural domain as it consists of the "Fabric Domain 3a" defined by Babist et al. (2006). Only a small strip along the margin with the Canavese Block belongs to the domain 3b. A large antiform (Monte Mars antiform), as expression of the Fabric Domain 5 of Babist et al. (2006), dominates the central part of the block. Generally E-W and NW-SE striking faults coincide with the block boundaries.

Sessera-Ossola block

The elongated boomerang-shaped Sessera-Ossola Block extends from near Biella to the Valle Dossola and probably until Locarno. It is named after the two rivers (Sessera and Ossola). The Canavese Line bound it to the northwest, whereas the southeastern margin is defined by a patchwork of structural elements. Between Biella and Crevalcuore, it follows the Cremosina Line and the Cossato-Mergozzo-Brissago Line (CMB) until Varallo. From Varallo, a suite of shear zones (Rosarolo shear zone of Siegesmund et al. 2008; Forno-Anzola shear zone of Rutter et al. 2007) forms the limit of the block until Val D'Ossola, where it bends sharply to the East meeting again, near Mergozzo, the CMB Line/Pogallo Line. The Sessera-Ossola Block is bounded by the Cervo Block, the Val Stura-Arcegno Block, the Orta-Veddasca Block, the Val Strona Block and the Baldissero-Gozzano Block.

The Sessera-Ossola Block consists of rocks belonging to the Ivrea-Verbano Zone, i.e., ultramafic and mafic rocks of the Basic Complex and migmatic gneisses of the Kinzigite Formation. The Miagliano Pluton emplaced in the gabbroic rocks of this block in Earlier Rupelian times (33 Ma) at depths around 12–15 km (Table 4, Berger et al. 2012). This indicates that the lower crustal rocks of the Basic Complex were at upper crustal levels at that time, while the two bounding blocks (Cervo and Baldissero-Gozzano Block) already took a near-surface position. In the north, the central part of the block is affected by ductile folding (i.e., Proman antiform) of similar age and kinematics (F4 of Rutter et al. 2007) as the Monte Mars antiform in the Cervo Block. Final exhumation of the Sessera-Ossola Block started in its western part in Aquitanian times as indicated by the zircon FT age of the Miagliano Pluton (Fig. 4g). Zircon FT ages further to the NE range from 57 to 31 Ma (Siegesmund et al. 2008).

Baldissero-Gozzano block

The exposed northern border of the Baldissero-Gozzano Block (the Biella-Gozzano unit of Schumacher et al. 1997) runs along the Cremosina Line from the Lago Maggiore to Biella and further westwards along the Canavese Line, more precisely the southern (or external) branch of the Canavese Line. Sediments of the Padan Basin cover all other margins. Geophysical data (Pieri and Groppi 1981; Fantoni et al. 2003) indicate the "San Benigno thrust-north" (Fig. 5) as southern margin of the block. The Baldissero-Gozzano Block is bounded by the Canavese Block, the Cervo Block, the Sessera-Ossola Block, the Orta-Veddasca Block and the Morcote unit (Schumacher et al. 1997).

The Baldissero-Gozzano Block is composed of rocks of the Ivrea-Verbano Zone and the Strona-Ceneri Zone. It is characterized by Jurassic zircon and apatite FT ages (Fig. 6; Giger 1991; Vance unpublished). Therefore, the block was tilted (as it shows a more or less undisturbed profile from the lowermost crust up to its Mesozoic sedimentary cover) and exhumed near the surface already in Jurassic times. In Early Miocene times, the Baldissero-Gozzano Blocks were thrusted southward onto the Paleogene sediments of the Padan Basin (Pieri and Groppi 1981; Fantoni et al. 2003) along the San Benigno thrust.

Other blocks

The discussion of our local data needs the integration in a larger framework. We will describe a larger framework, even if the criteria are some times heterogeneous and the relationships to the three blocks of major interest are not directly evident. Based on FT data and other tectonic or lithological criteria, we have tentatively outlined other blocks with different behavior during the Oligocene and Miocene.

The rather small Val Strona Block is wedged between the Sessera-Ossola Block and the Orta-Veddasca Block and has been individualized to satisfy zircon FT ages reported by Siegesmund et al. (2008). In Val Strona di Postua, between the Rosarolo shear zone and the CMB, the zircon in rocks of the Ivrea-Verbano Zone yields Late Cretaceous FT ages, clearly older than the Late Oligocene ages in the adjacent Sessera-Ossola Block but younger than the Jurassic ones in the contiguous block to the east. This, the Orta-Veddasca Block coincides with the Veddasca unit of Schumacher et al. (1997) and consists essentially of Paleozoic basement rocks of the Strona-Ceneri Zone. This block has a distinct Alpine cooling history as it southward neighbor, the Baldissero-Gozzano Block. In spite of their similar Jurassic zircon FT ages, the Orta-Veddasca Block shows Late Miocene apatite FT ages (Wagner and Reimer 1972; Wagner et al. 1977), while the Baldissero-Gozzano Block has an apatite age of 141 Ma (Giger 1991). South of the Cervo Block, the Canavese Block coincides with the Canavese Zone, a portion of South-Alpine basement wedged between the Northern (external) and Southern (internal) Canavese Line (e.g., Biino and Compagnoni 1989; Ferrando et al. 2004). The peculiar geological characteristics of this block prevent its integration in other contiguous blocks.

Directly north of the Cervo Block it is more difficult to reconstruct a coherent distribution of published FT data. Malusá et al. (2005) separate a Western block, with Pliocene apatite FT ages and Late Miocene zircon FT ages, from an Eastern one containing all tectonic units from the Internal Houiller Front to the Insubric Fault Zone, showing older but highly variable FT ages of zircon (Bartonian-Aquitanian) and apatite (Priabonian to Serravallian; Fig. 6). Because of the large scattering of the FT data in the external Sesia-Lanzo Zone, it is difficult to design a subdivision in blocks only on this base. We have summarized this part in one block, the Val Stura-Arcegno Block forming the western and northern neighbor of the Cervo Block. The major feature distinguishing this block from the Cervo Block is the wide spread presence of un-rotated Oligocene dykes (Lanza 1977). This implies that this portion of Sesia-Lanzo Zone, and presumably also the more external tectonic units, has not suffered the rotation characterizing the Cervo Block. We have traced as long as possible the border between the two blocks along the discontinuity formed by the Bonze unit, but we were forced to draw an arbitrarily limit between across the Mombarone nappe to respect the distribution of the rotated and un-rotated dykes of Lanza (1977). Zircon FT ages in the Val Stura-Arcegno Block vary considerably 40 and 28 Ma, while the apatite ages vary from 36 to 20 Ma (Fig. 6; Wagner and Reimer 1972; Wagner et al. 1977; Hurford et al. 1991; Bistacchi et al. 2001; Malusá et al. 2005, 2006). It is within this block that Malusá et al. (2006) have outlined differential uplift at a much smaller scale (few km^2). This suggests an important fragmentation of this block during the Miocene exhumation at near surface levels. The Val Stura-Arcegno Block is tectonically very heterogeneous as it contains parts of all the classical units of the Sesia-Lanzo Zone (Bard nappe, Mombarone nappe, II DK and the Scisti di Rimella e Fobello). As since Oligocene times the border between Sesia-Lanzo Zone and the Piemont-Liguria units no longer represents an active plate boundary, the near-surface segmentation of the accreted units will possibly follow new structures in particular the Aosta-Ranzola and Ospizio Sottile fault system (Bistacchi et al. 2001) or related small-scale faults (Malusá et al. 2006).

The Canavese line

The main border faults are essential for the definition of the late near-surface block geometry. We have already briefly mentioned some of these in the previous section by the definition of the blocks (Aosta-Ranzola and Ospizio Sottile fault system, Cremosina Line, Cossato-Mergozzo-Brissago Line), but the extraordinary overlap of different deformation events along the Canavese Line needs a separate discussion. The Canavese Line separates the Sesia-Lanzo Zone from the Ivrea-Verbano Zone (e.g., Ahrendt 1972, 1980; Schmid et al. 1987, 1989; Biino and Compagnoni 1989; Zingg and Hunziker 1990; Handy et al. 2005; Siegesmund et al. 2008). It forms a mylonite belt characterized by a moderate W-dipping foliation carrying a similarly W-dipping stretching lineation, overprinted by brittle faulting. In the segment between Valle dell'Elvo and Val Sessera (Fig. 2), the belt has variable thickness (10–300 m) and is a tectonic melange, where mainly strongly deformed slices of rocks from the Sesia-Lanzo Zone, the Ivrea-Verbano Zone and Canavese Zone are wedged together (Wissmann 1985; Carraro 1966; Carta geologica d'Italia: Foglio 43 Biella, 1:100,000). Omitting the possible Mesozoic precursor structures related to rifting along the margin of the Adriatic Plate (Babist et al. 2006), four major Alpine deformation events are responsible for the formation of different fault rocks (fault rocks 1–4, Fig. 2) along the Canavese line. The fist step is the development of a mylonite belt (fault rocks 1 or *mylonite belt 1* of Schmid et al. 1989) during subduction and exhumation of the Sesia-Lanzo Zone (Late Cretaceous to Paleocene times). Further convergence in the Sesia-Lanzo Zone produces new steeper Sesia-, Ivrea- and Canavese-derived mylonites (Schmid et al. 1987, 1989; fault rocks 2 in Fig. 2). At least during this stage, the definitive wedging of the slices with different tectonic provenance into the tectonic melange must have been completed. This stage must predate the Early Rupelian emplacement of volcanic rocks of the Biella Volcanic Suite as the volcanic rocks are not involved in the tectonic melange and outcrop even after the tilting and burial (see below) always only westward of the melange (Fig. 2). The conformably emplacement of the Biella Volcanic Suite on a preserved paleosurface on top of the gneisses of the Sesia-Lanzo Zone (Kapferer et al. 2011) marks a fundamental step in the evolution of the Canavese Line. After emplacement the volcanic rocks must be buried at depth below the PAZ of zircon as the central age of the zircon is about 10 my younger than the crystallization (Table 4; Kapferer 2010; Kapferer et al. 2012). The current 60° dip of the Biella Volcanic Suite (Figs. 2, 3) is the result of a near-surface block rotation with the Canavese Line acting as southeastern border fault. We suggest that the previously defined Cervo Block represents the portion of Sesia-Lanzo Zone affected by this rotation. Deformation along the Canavese Line active as border fault during the rotation of the Cervo Block affects volcanic rocks as well as the older mylonites in the tectonic melange (fault rock group 3). A clear evidence for this deformation during block rotation is the development of a weak foliation in the fine-grained chloritic matrix of the andesites in Val Sessera (Fig. 2). The more massive volcaniclastic sequences in Valle del Cervo, Val Oropa and Valle dell'Elvo remain undeformed until the brittle fault marking the sharp transition to the mylonites of the tectonic melange. The latest deformation event is related to second-stage exhumation and taken up by brittle faulting. The cataclasites belonging to this deformation stage form the group 4 fault rocks (Fig. 2; Schmid et al. 1989).

Discussion

In the following, we will describe the geometrical/tectonic relations during near-surface tectonics and connect these deformation processes to the main geodynamic context. In a first step, we will describe the rigid rotation of the Cervo Block, where precise dating of the magmatic events allows reconstructing accurately its reburial after a first Rupelian exhumation to the surface (Table 4). This process is then discussed in relation to the exhumation history of the Sessera-Ossola block. Finally, we will try to compare this local evolution to the surrounding blocks in order to integrate this history into a larger geodynamic framework.

Block rotation and double exhumation in the Cervo block (Sesia-Lanzo zone)

The evolution of Cervo Block serves as a key for the reconstruction of the temporal evolution of the block tectonics (Figs. 4, 6, 7). This reconstruction is mainly based on the preservation of the Early Rupelian paleosurface on top of the gneisses of the Sesia-Lanzo Zone (Carraro 1966; Kapferer et al. 2011) and the precisely dated magmatic activity inside this block (Valle del Cervo Pluton and volcanic-subaeric cover; Bigioggero et al. 1994; Romer et al. 1996; Kapferer et al. 2011; Fig. 6). The andesitic rocks extruded at 32.5 Ma on a regolith of HP-rocks of the Sesia-Lanzo Zone (Table 4). The subsequent burial of these surface rocks to depths compatible with the PAZ of zircon (180–300°C) is indicated by the rejuvenation of the fission tracks in zircon and apatite (Figs. 3, 4, 6) and by the very low-grade metamorphic overprint of the rocks (Zingg et al. 1976; Kapferer et al. 2011). The timing of this fast burial is constrained between the age of the volcanic rocks (32.5 Ma) and the intrusion age of the Valle del Cervo Pluton (30.5 Ma; Table 4). The burial of the volcanic rocks before the intrusion of the Valle del Cervo Pluton is also evident from the exposed geometry of the two units (Fig. 3). In fact, the present day shortest distance between the pluton and the volcanic rocks is 0.7 km (Valle del Cervo; Figs. 2, 3). This is much less as the estimated intrusion depth of 5–7 km for the Valle del Cervo pluton (Zanoni et al. 2007, 2010). This can only be explained by re-burial of the Sesia-Lanzo Zone and their volcanic cover to depths of around 5 km before the intrusion of the pluton. Furthermore, the close vicinity of the two magmatic units is outlined by the observation that the volcanic rocks are crosscut by a network of mineralized veins related to the emplacement of the pluton (Bernardelli et al. 2000; Rosetti et al. 2007). Ongoing tilting of this block could also explain the minor difference in contact metamorphic conditions in the eastern and western part of the pluton (Zanoni et al. 2010). This re-burial of the Cervo block paleosurface is caused by rigid block rotation around horizontal axes. The previously mentioned field relations, geothermo-barometry and FT ages (Zanoni et al. 2010; Kapferer et al. 2011, 2012) are consistent with a tilting of ca. 60° around a flat lying axes oriented 20°N (Fig. 7). This was already proposed by Lanza (1977) on the base of the paleomagnetic orientation of the dykes and volcanic rocks. This rotation should concern the upper 8–10 km of the crust, as the paleosurface is sinked down to 5 km. The uncertainty on the rotation angle is relative small, because independent

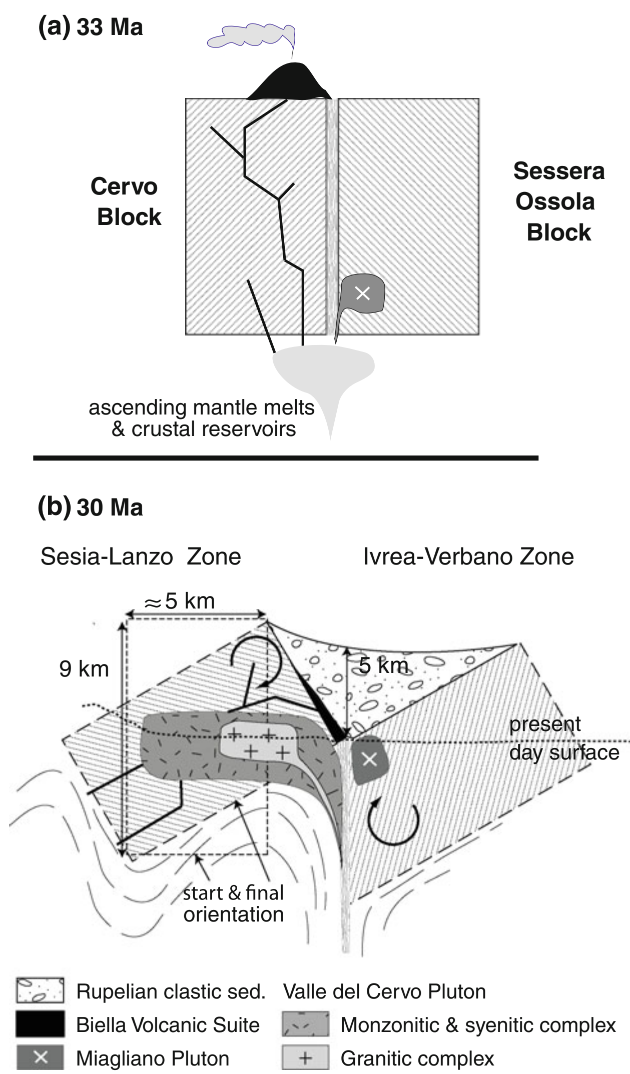

Fig. 7 Sketches illustrating the evolution of block rotation and magmatism. **a** Situation before block rotation of the Cervo block with the volcanoes on top of the Sesia Zone. **b** The geometrical relationships just after block rotation. The approximate size of the block is indicated

observations as the dip of the paleosurface (Fig. 2) and the paleomagnetic data of Lanza (1977) indicate a similar value around 60°. More complicated is an estimation of the block size, which defines amount of offset during such rotations at the different positions (e.g., Moretti et al. 1988). Therefore, in the previous chapter, we have tried to define, the size of the blocks (Fig. 7). The definition of block size is particularly difficult inside basement units, because small brittle faults can be easily overlooked and, lacking better information, we have traced approximately the blocks margins following known lithologic or tectonic boundaries. For the Cervo Block, only its southeastern border fault can be clearly related to faults within the tectonic melange along the Canavese Line (Fig. 2) and the fault rocks of type 3 (Fig. 2) are the expression of this tectonic activity. Along a NW-SE profile perpendicular to the Canavese Line (and nearly perpendicular to the direction of the rotation axes indicated by the paleomagnetic data), the Cervo Block is about 10 km wide (Fig. 3). If we assume this dimension as the approximate diagonal of a rectangle representing surface and depth of the Cervo Block along the profile after rotation, the short and long edges of the rectangle will be ca. 5 and 9 km long, respectively (Fig. 7). These dimensions would correspond to the wide and the depth of the Cervo Block. The total length of the outcrops of the volcanic rocks, ca. 25 km (Callegari et al. 2004), represents the minimal length of the block. If our assumption to include the whole Fabric Domain 3a of Babist et al. (2006) is meaningful, its third dimension could reach 50 km. The cartographic evidence that the Biella Volcanic Suite outcrops in a small strip along the Canavese Line eastward from its substratum (HP-gneisses of the Sesia-Lanzo Zone) indicates a clockwise rotation of the blocks in agreement with the mean 60° SE dip of the primary bedding of the volcaniclastic rocks. The transition to more ductile deformation at the bottom of the block is hardly constrained. However, the coeval D5 folding described by Babist et al. (2006) is a possible transition from localized brittle faulting to ductile folding.

Exhumation of the Sessera-Ossola block (Ivrea-Verbano zone)

The Cremosina Line delimits the Sessera-Ossola Block between Biella and Borgosesia from the Baldissero-Gozzano Block. It is a major tectonic boundary in the Southern Alps (e.g., Boriani and Sacchi 1973) separating the Ivrea-Verbano Zone into two parts as also shown by gravimetric data (Berckhemer 1968). The Miagliano Pluton offers the best arguments to reconstruct cooling and exhumation of the Sessera-Ossola Block. The Aquitanian zircon FT ages are too young to be related to post-emplacement cooling of the pluton intruded in the Early Rupelian (Table 1; Figs. 3, 5) and are therefore reflecting the cooling history of the Sessera-Ossola Block. The Burdigalian apatite FT ages of the pluton confirm the Miocene cooling of this block. The Miagliano Pluton emplaced at depth between 12 and 15 km at 33 Ma (Table 1; Kapferer 2010; Berger et al. 2012). After the cooling of the pluton at depths deeper than the PAZ of zircon, the Sessera-Ossola Block is uplifted in the PAZ of zircon in Early Aquitanian times (Fig. 4g). We suggest that this uplift is intimately related to the rotational movement of the Cervo Block. In this case, the clockwise rotation of the two blocks will produce along the border fault (the tectonic melange along the Canavese Line) the subsidence of the surface of the Cervo Block and the conjugate uplift of the base of the Sessera-Ossola Block. Such a movement will produce two symmetric T/t paths, one describing the cooling of the uplifting lower part of the Sessera-Ossola Block and the other describing the heating by the burial of the surface region of the Cervo Block (less constrained part is dashed in Fig. 4). The preserved evidence for the deeper position of the Sessera-Ossola Block is limited to the estimated intrusion depth of the Miagliano Pluton (Table 1) and the dominant presence of epidote in the hydrothermal overprint of rocks of the Sessera-Ossola Block. The rotation of this portion of the Ivrea-Verbano Zone has been already postulated by Schmid et al. (1989) on the bases of the paleomagnetic data from a basaltic dyke crosscutting Ivrea-derived mylonite along the Canavese Line in Val Sessera (Fig. 3). These paleomagnetic results indicate a rotation with the same axes and the same sense of rotation as that of the Cervo Block suggested by the data of

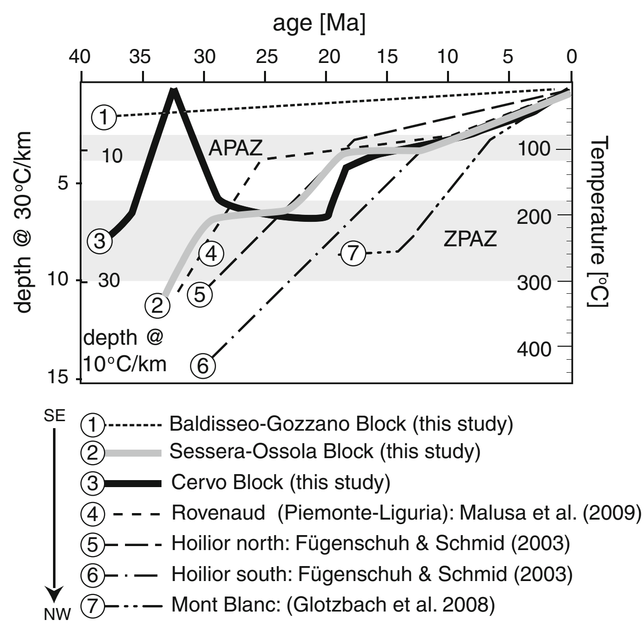

Fig. 8 Cooling/heating curves for the blocks defined in this contribution and other units of the Western Alps from the literature

Lanza (1977). Also, Schumacher et al. (1997) have discussed a similar rotation for the whole Ivrea-Verbano, Strona-Ceneri complex. After rotation, the block remains at depths within the PAZ of zircon during Chattian and Aquitanian when it is exhumed in the PAZ of apatite (Figs. 4, 5, 6). The Sessera-Ossola Block remains at this depth during Burdigalian and Langhian and reaches the uppermost crustal levels in the Late Miocene (Figs. 4, 5, 6). Thus, the Cervo Block and the Sessera-Ossola Block seem to share the same Rupelian tectonic fate, characterized by rapid clockwise rotational movement of ca. 60° along an horizontal axes during ca. 2 my. This movement induces the conjugate burial of the surface of the Cervo Block and the uplift of deeper portion of the Sessera-Ossola Block containing the Miagliano Pluton. Therefore, in Late Rupelian times, these two different crustal levels are juxtaposed at the same crustal level (ca. 5 km depth; Fig. 5). From now on, the two blocks behave in a similar way during the following exhumation. This clearly indicates that this portion of the Canavese Line become passive in the Middle Oligocene.

The relationships to the adjacent blocks

The Cervo Block is partly bordered by the Baldissero-Gozzano Block, which resides since Jurassic times at uppermost crustal levels as indicated by the Jurassic FT ages in apatite and zircon (Fig. 6). Also, the currently exposed part of the Canavese Block resides near the surface since the Earlier Cretaceous (youngest sediments: Argille a Palombini, Ferrando et al. 2004). Thus, these two southern blocks must be considered as passive during the Rupelian near-surface tectonics of the described more northern blocks. The border faults sustaining the differential movement between the different blocks are the Internal and External Canavese Lines and the Cremosina Line. North of the Cervo Block, the Val Stura-Arcegno Block behaves differently. The fundamental difference remains also in this case of the lack of a Rupelian rotation. Later on, since the Aquitanian, the entire portion of Western Alps comprised between the Canavese Line and the Frontal Penninic Faults with the addition of the Sessera-Ossola Block, seems to exhume in a more or less coherently way throughout the entire Miocene (compare cross-section A–A′ and B–B′ of Fig. 8 in Malusá et al. 2005). Therefore, the individualization of the Cervo Block and Sessera-Ossola Block is confined in Rupelian times with the crystallization age of the Valle del Cervo Pluton (30.5 Ma) as terminal age for the rotation.

Local tectonics in the framework of the Western Alps

The Lower Oligocene is a crucial time in the evolution of the Western Alps. Large-scale plate reorganization initiates the complex exhumation history of the different crustal

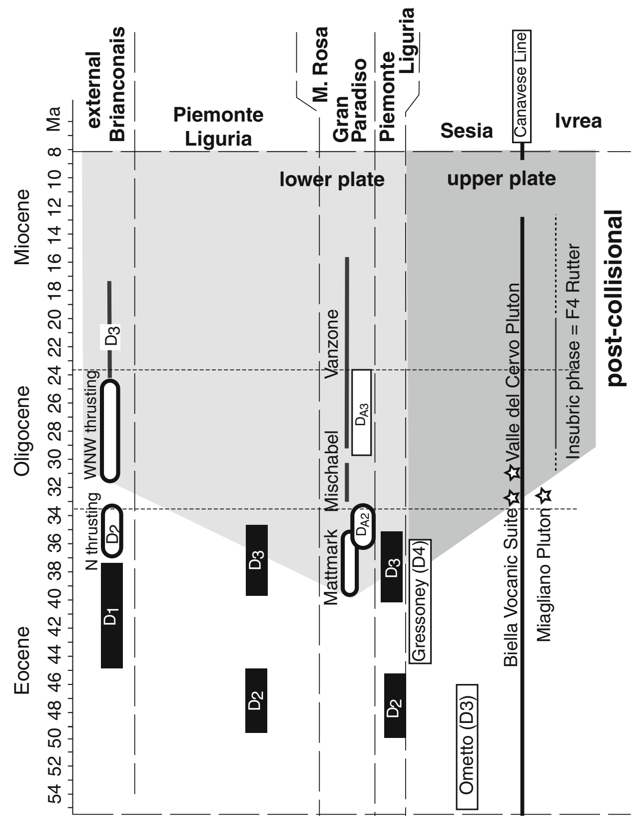

Fig. 9 Correlation table of deformation phases in the Western Alps. *Data Source*: Ceriani and Schmid (2004); Bucher et al. (2004); Babist et al. (2006); LeBayon and Bellevre (2006); Agard et al. (2002); Pleuger et al. (2008); Rutter et al. (2007)

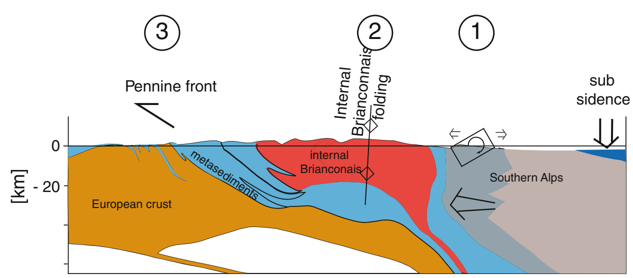

Fig. 10 Schematic cross-section through the Western Alps. The locations of the main discussed areas are indicated. (*1*) Nearsurface tectonics (this study); (*2*) exhumation of the internal Brianconais like the Gran Paradiso or Monte Rosa; (*3*) thrusting in the external Brianconais and Valais units

levels (e.g., Malusá et al. 2009; Handy et al. 2010; Dumont et al. 2011). In the following discussion, we will focus on the evolution of uppermost crustal levels. Some aspects of the post-metamorphic history of the axial zone of the Western Alps have already been discussed (Bistacchi et al. 2001; Malusá et al. 2005, 2006, 2009). We would like to stress the role of local rigid block rotation during upper crustal deformation. In this context, one first question is related to the opening of two dihedral volumes at the top and bottom between neighboring rotating blocks (e.g., Ramsay and Huber 1987; Moretti et al. 1988). In the case of the Cervo Block, we assume that the volume opening at the bottom between the Cervo Block and the Sessera-Ossola Block is progressively filled by proto-plutons related to the magmatism of the area (Fig. 7). The portion of space created at top by the subsiding surface is most likely filled by clastic sediments issued from the denudation of the uplifting uppermost edge of the block. Scarce relicts of a coarse grained conglomerate outcrops in Valle del Cervo und Val Oropa (Fig. 2). A second important consequence of rigid block rotation concerns the distribution of uplift and cooling evolution within the block itself. The geometric position within the block in relation to the rotation axes will define its uplift rate. This means that rocks located near the axes will move imperceptibly relative to the surface, whereas increasing distance from the axes will induce the rocks to move up- or downwards at very different rates (Fig. 7). The near-surface rocks will be used to constrain the geometry of these processes and related heating and cooling. In our example, this results in a rapid burial rates, in the range of 3 mm/y (by a geothermal gradient of 30°/km), followed, after ca. 10 my residence in the PAZ of zircon, by an average slower cooling rate in the range of 8°/Ma (Figs. 4, 6, 7).

The above-discussed rigid block rotation affect the uppermost $\sim$10 km of two blocks (Cervo Block and Sessera-Ossola Block) in the most internal part of the Western Alps, whereas in the adjacent areas, the near-surface deformation is dominated by brittle faulting (e.g., Malusá et al. 2006). At the same time, the more external and deeper units (e.g., Piemonte Liguria, Briançonnais and Valais units) experienced ductile post-nappe deformation (Figs. 8, 9; Bucher et al. 2004, Ceriani and Schmid 2004). The main expression of this deformation is the WNW-directed Pennine front, Houiller thrust and post-nappe folding, which are active under greenschist facies conditions in the lower Oligocene (e.g., Simon-Labric et al. 2009; Bucher and Bousquet 2007; Fig. 9, 10). More complex is the situation for the internal Briançonnais (Gran Paradiso, Monte Rosa). These units with their granitoid cores underwent large-scale folding (Monte Rosa folding: Pleuger et al. 2008; Gran Paradiso doming: LeBayon and Bellevre 2006). This occurs in the temperature range of the PAZ of zircon FT and in a time frame from the Oligocene to middle Miocene. In summary, a NW-SE a transect from Biella to Chamonix trough the Western Alps in Oligocene times illustrates the evolutionary stage of the different tectonic units (Figs. 8, 9):

- Pre-uplift position for the external massifs (e.g., Mont Blanc massif).
- Greenschist facies in the external Briançonnais (Pennine frontal thrust, Hoillior thrust).
- Folding of the internal Briançonnais (Gran Paradiso, Monte Rosa).
- Above-discussed rigid upper crustal block rotation in Sesia/Ivrea units.
- Marl to sandy sedimentation in the southward adjacent basin.

These inferred different depths from the external to the internal Western Alps are related to different exhumation histories, while the Sesia-Lanzo Zone and Ivrea-Verbano Zone show slow overall exhumation starting in the Oligocene (Figs. 4, 8). Cooling and exhumation started progressively later toward more external units (Fig. 8; Fügenschuh and Schmid 2003; Malusá et al. 2005, 2011; Glotzbach et al. 2008), as already discussed by Malusá et al. (2009). Excluding the internal Briançonnais (Gran Paradiso, Monte Rosa), the exhumation follows a trend from internal to external units. This includes a young and partly fast exhumation of the external units (Mont Blanc), while the most internal ones (Sesia and Ivrea-Verbano Zone) show slow uplift rates. The described rigid block rotation near the surface and the adjacent subsidence in the basins indicates local upper crustal extension. At the same time, main shortening occur in middle crustal levels and in a further external part of the Western Alps (Figs. 8, 9, 10). This combination would be consistent with a wedge-shape intender tectonics as indicated by the geophysical Ivrea body. Another change in the tectonics is indicated in the Miocene by the outward moving exhumation (Fig. 8).

Conclusion and outlook

Our new data on the cooling and exhumation histories of the Cervo and the Sessera-Ossola Block highlight some important aspects of the Oligocene–Miocene near-surface tectonics:

Uppermost crustal block individualization occurred within the Sesia-Lanzo Zone and the Ivrea-Verbano Zone in Rupelian times.

- Rigid block rotation is related to localized deformation oriented broadly NNW-SSE.
- This deformation terminated with the intrusion of the Valle del Cervo Pluton at around 30 Ma.
- The just northwards surrounding block behaves differently, with NW-SE compression in the Rupelian and nearly NS extension in the Chattian.
- Different blocks of the Ivrea-Verbano Zone show a different Alpine tectono-thermal history.

Interpretation of FT ages is highly dependent to the recognition of the geological events responsible for the respective time–temperature evolution. The preservation of the Rupelian paleosurface of the Cervo Block (Kapferer et al. 2011) has essentially contributed to unravel a complex local burial and exhumation history. Without this observation, it would have been impossible to reconstruct the role of rigid block rotation in this evolution. In turn, rotational movements lead to strongly contrasted uplift/burial paths of each point within a singular block and consequently the lack of information about such a mechanism will seriously affect the interpretation of FT ages and their correlation over large regions.

The exhumation history of the Sessera-Ossola Block has emphasized the need of a subdivision of the Ivrea-Verbano Zone and Strona-Ceneri Zone in blocks with different Oligocene–Miocene cooling evolution. The tilting of the Ivrea-Verbano Zone, as a whole, has been already discussed intensively (see summary in Handy et al. 1999). The different viewpoints are based on extrapolation of local observations (e.g., paleomagnetic data of a dykes, magmatic layering, orientation of sediment layers), disregarding their different positions. Accepting a subdivision in independently moving near-surface blocks in Oligocene–Miocene times, some of the apparent controversial observations appear to be related to the different amount of movements inside these blocks.

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