The central Lepontine Alps : notes accompanying tectonic and petrographic map sheet Sopra Ceneri (1:100'000)

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This paper is dedicated to the memory of Professor Volkmar Trommsdorff – mentor and tireless pioneer of modern studies in the Lepontine Alps

The central Lepontine Alps: Notes accompanying the tectonic and petrographic map sheet Sopra Ceneri (1:100'000)

Alfons Berger[1], *Ivan Mercolli*[1] and *Martin Engi*[1]

Abstract

This paper accompanies the new map sheet (1:100'000) of the Swiss-Italian Central Alps, introducing the tectonic units in condensed form. The map sheet "Sopra Ceneri" of this core part of the Alps integrates a wealth of classical field studies from the Lepontine Alps with numerous detailed investigations made over the past decades. In the present notes the main tectonic units distinguished on the map are individually characterized, and the dominant rock types surfacing are described. All of the main units that make up the crystalline nappe stack of the Central Alps are comprised in this inventory. Their polyphase deformation is reviewed, and the metamorphic structure exposed in this classic orogen is presented. Particular emphasis is placed upon recent work on the exposed nappe- and plate-boundaries, inasmuch as these results bear directly on the map. The recognition of several tectonic mélange units, their internal make-up and their role within the orogen are key elements of this study. Implications on the tectono-metamorphic evolution of the Central Alps are outlined, and some of the main controversies and remaining questions are spelled out. The map and this condensed text thus assemble an up-to-date introduction to the geology of the Central Alps.

Contents

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1. Introduction

This text accompanies the tectonic-petrographic map (1:100'000) of the Central Lepontine Alps, since the end of the 19th century a key area for studies on the Alpine orogeny. The map coincides with the topographic map „Sopra Ceneri" (sheet 43 of Swisstopo; Fig. 1). The map summarizes: (a) The tectonic units of this area, which include several classical crystalline thrust sheets, as well as a newly defined mélange superunit (Fig. 2); (b) Major rock types characterizing the different tectonic units, as detailed as the map scale and the currently available documentation permit.

This map is the eastern continuation of the tectonic map 1:100'000 sheet "Oberwallis" by Steck et al. (1999). Presentations of the geology and tectonic interpretations of the Lepontine area have long been discussed, most intensely in the early parts of the 20th century (e.g. Figs. 2, 3; summaries by Bossard, 1925; Niggli et al., 1936). Geological research in the Lepontine Alps started with survey scale mapping, followed by decades of more detailed work, often as PhD theses. In recent years, detailed studies on the petrology and geochronology have been added (recent references in Frey et al., 1999; Frey and Ferreiro-Mählmann 1999). However, despite some eighty years of intense research, several fundamental questions of the tectonic evolution are still under debate, questions which address much of the nappe stack and involve, for example, the recognition of former plate boundaries (Fig. 3). Early in the 20th century, different proposals were made regarding the lateral correlation of nappes and their geodynamic significance (see summary in Kündig, 1936); these questions have still not been fully resolved (Fig. 3). Major discrepancies are related to the identification of so-called „nappe divides" (e.g. Mesozoic metasediments and dismembered ophiolitic trails), the role of former plate boundaries during the orogeny cycle, and the relative paleogeographic position of some of the units.

Several recent representations of the tectonic and metamorphic evolution of central parts of the Alps are available. These include new versions of the 1:500'000 "Tectonic Map of Switzerland" and "Geological Map of Switzerland" (2005); the new map "Metamorphic Structure of the Alps" (Oberhänsli et al., 2004; Engi et al., 2004); the "Tectonic Map of the Alps" (Schmid et al., 2004); and contributions in Pfiffner et al. (1997). Collectively these publications complement the brief introduction given here.

2. Concepts and sources used in constructing the map

The need for a new map derives from the requirement to update the illustration of tectonic relationships in the Central Lepontine Alps in the light of new tectonic concepts. To apply these consistently, we adopted a series of basic tenets in drawing this map, as spelled out below. Some of these assumptions are pragmatic enough to be easily accepted, whereas others may be more controversial. However, we are convinced that the strengths and weaknesses of any tectonic interpretation are best visible if the underlying concepts are fully explored and presented as clearly as possible, rather than obscuring difficulties. At the present state of understanding, this map certainly cannot claim to represent the definitive solution to all of the tectonic problems in the Lepontine area. However, the map does represent an up-to-date compilation of the current knowledge, an illustration of recent hypotheses, and thus a basis for further work.

The tectonic units have been grouped following their position in the plate tectonic framework just prior to or during convergence and nappe stacking. We distinguish three continental domains (Europe, Briançonnais, and Adria), two oceanic domains (Piemont-Liguria and Valais), a tectonic mélange domain (no uniform paleogeographic position), and Tertiary intrusives. This major subdivision is reflected in the colours used on the map. Each domain has a basic colour, and individual units of each domain are distinguished by different tones of the respective colour. The legend on the map and the description of the units in this text are grouped according to this same subdivision. The units are ordered from tectonic top to the base, i.e. Adriatic units first, European units last. To the extent possible, the same top-down order has been used in presenting units within each domain. This relies on the recognized structural position for the crystalline nappes, the stratigraphic age for sedimentary sequences, and the lithostratigraphic position, where relative ages or radiometric dates are available.

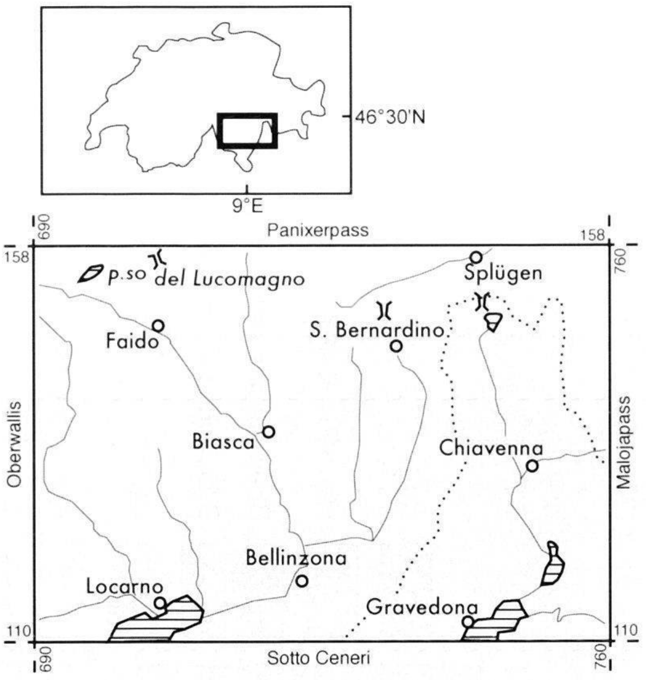

Fig. 1 Geographic position of the map. Principal rivers and towns are shown on the map sheet "Sopra Ceneri". Swiss topographic coordinates are given. At the bottom of the map, the northern parts of Lago Maggiore and Lago di Como are shown.

In compiling the map, we aimed generally to reduce the number of terms for units and avoid names of merely local importance, so as to simplify the presentation for the uninitiated reader. The paleogeographic domains used for this map are those established in the current literature (e.g. Stampfli et al., 2002); the respective terms are briefly characterized here and related to alternative terms (in brackets) commonly used in the Alpine literature: The *European domain* consists of polycyclic crystalline continental crust with its marginal sedimentary cover. During the Upper Jurassic an ocean basin, termed *Valais Ocean*, developed in the southern parts of the European continent. This basin was bordered to the south by the *Briançonnais domain*, a microcontinent. (Most units related to the Valais Ocean have traditionally been grouped into the Northern Pennine or Lower Pennine, a few of them have been denominated Ultrahelvetic). The Briançonnais domain again includes a continental basement and its sedimentary cover. (The term Briançonnais is equivalent to the term Middle Pennine.) The Piemont-Liguria Ocean was situated between Europe – and subsequently the Briançonnais domain – and Adria. This paleogeographic unit includes passive margin sediments, deep-sea sediments, and a predominantly magmatic basement. (The term Piemont-Liguria Ocean is nearly synonymous with Southern Pennine or Upper Pennine). The dimensions and position of the southern continent – and the name used for it – change with the different steps of the Alpine evolution. This problem is related to the closure of the Meliata Ocean and to the tectonic evolution in Oligo-Miocene times (see Stampfli et al., 2002 for a discussion of the Apulia-Adria problem). The Adria continent, initially situated south of the Piemont-Liguria Ocean, includes continental basement, marginal sediments, and relics of the Meliata Ocean. Figure 4a shows the tectonostratigraphic relations as used in this contribution (other possibilities are shown in Fig. 3). As a consequence of the above-described general organisation of the map, we have abandoned the term Pennine. Schmid et al. (2004, p. 108) exposed the difficulties arising from the use of this term, and we

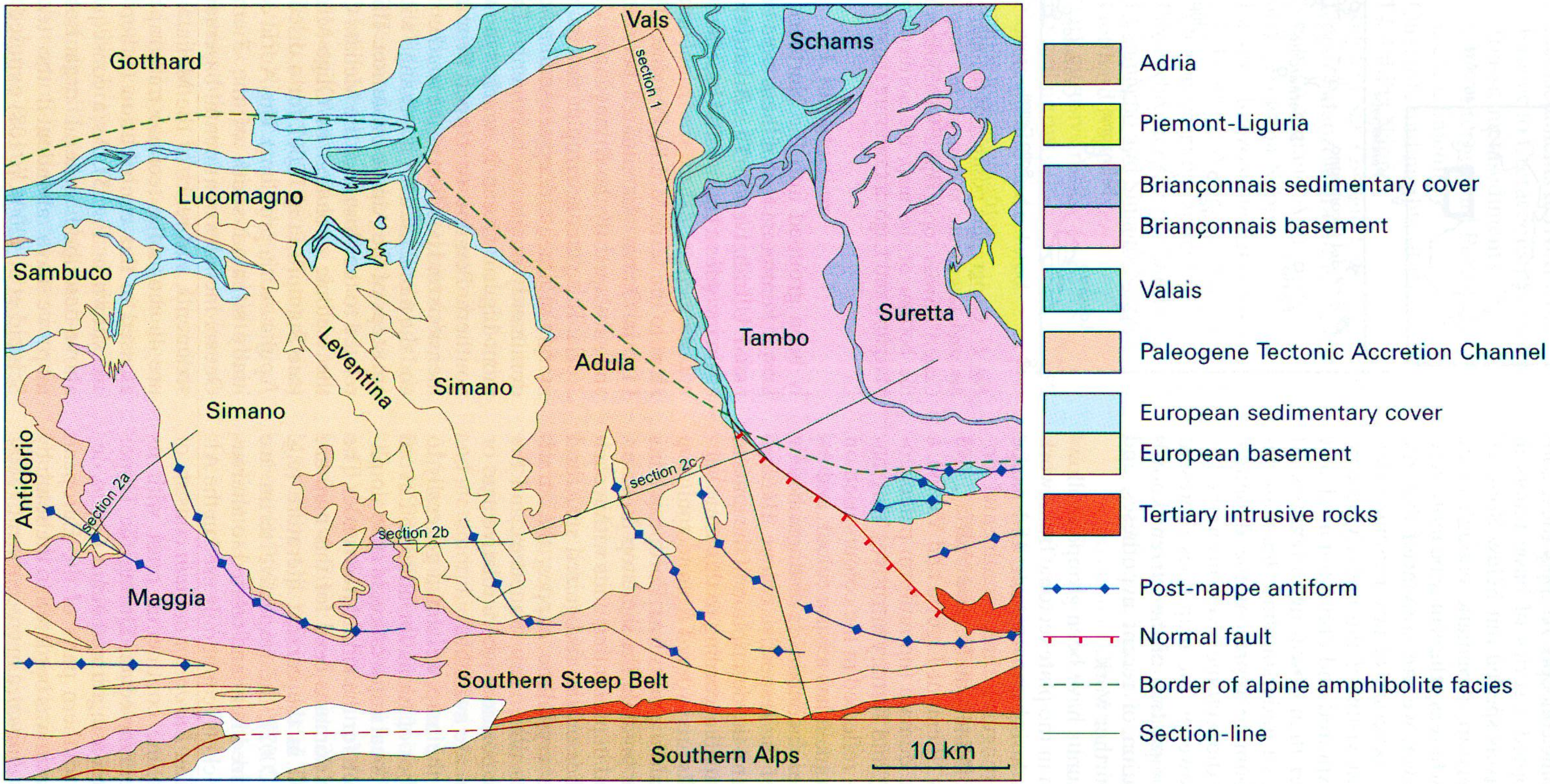

Fig. 2 Tectonic map of the Central Lepontine Alps. Simplified from the 1:100'000 map, with additional information from Steinmann (1994) and Schmid et al. (2004). An extended legend for this map is presented in figure 6.

adopt their suggestion to avoid it.

The tectonic mélange units – including the Adula Nappe Complex, Cima Lunga Unit, and a major part of the Southern Steep Belt (SSB) – formed during convergence and collision, thus they *cannot* be attributed to any one paleogeographic position; instead they represent a *purely* tectonic unit of mixed provenance. These mélange units are a crucial element, inasmuch as they are taken to represent the contact between the down-going and the upper plate. It is one of the objectives of this map to illustrate the spatial distribution of lithospheric tectonic mélange units (e.g. Trommsdorff, 1990) interpreted as remnants of a tectonic accretion channel (TAC, Engi et al., 2001a). Our map presents them as a separate tectonic element. Detailed field studies in the area between Val Maggia and Val Leventina (e.g. Grond et al. 1996; Pfiffner and Trommsdorff, 1998; Pfiffner, 1999; Gruskovnjak, 2002; Leonardi, 2003; Burri, 2005) show that this complex mixture of rock types of variable provenance (i.e. mélange containing eclogite relics) results from the dynamics along the plate boundary (or boundaries) and not just from thrusting within the same continental block. Traditionally, plate boundaries have been traced by following (meta)sediments and ophiolite members of well defined age and paleogeographic provenance. Problems arise where, as in the Central Alps, such typical markers are ambiguous or absent. In this case, mélange units (or TAC fragments) resulting from the deformation dynamics at the interface between subducting or colliding plates represent a useful marker. We propose that TAC units can be used in the Central Alps to distinguish units belonging to the lower plate, i.e. part of the down-going European margin, from those attributed to the upper plate, i.e. part of the Briançonnais or the Adriatic plate. As the TAC unit is thought to play such a fundamental role in the tectonic reconstruction, its identification represents an important update with respect to previous maps of the Lepontine area.

The map is based upon lithological, metamorphic, and structural information. Geological and tectonic boundaries have been adopted from published and unpublished geological maps, as detailed below. The quaternary cover was disregarded wherever possible, which forced us locally to interpret the underlying units beyond the original maps. To the limits imposed by the scale of the map, we have attempted to retain units, which had been identified petrographically and/or tectonically. For instance, in some tectonic units (e.g. the Cima Lunga Unit) very detailed maps of small fragments exist, e.g. ophiolitic lenses in a heterogeneous mélange matrix; these had to be summarized, and only a few of the larger mafic and ultramafic bodies within such units could be represented on the map.

The eastern part of the map has been taken mainly from Huber (1998), Marquer et al. (1996), and Montrasio and Sciesa (1988), whose compilation includes numerous detailed maps, notably those by Blanc (1965), Blattner (1965), Fumasoli (1974), Gansser (1937), Heitzmann (1975), Lardelli (1981), Milnes and Schmutz (1978), Schmutz (1976), Strohbach (1962), Weber (1965), and Zurfluh (1961). The main change compared to previous maps is due to the representation of part of the SSB as a mélange unit. This interpretation is perfectly consistent with the excellent original maps available for this zone (Bächlin et al., 1974; Fumasoli, 1974; Knoblauch et al., 1939; Pfeifer et al., 1989; Pfeifer et al., in prep.; Graeter and Wenk, in prep.). Important data sources in the central part of the Lepontine are by Casasopra (1939), Codoni (1981), and Bruggmann (1965). In the northern part of the map, we used the maps of Preiswerk et al. (1934), Jenny et al. (1923) and Probst (1980). In addition, more detailed studies by Bianconi (1971), Buchmann (1953), Etter (1987), and Keller (1980) have been included as well. The area between the southern parts of Val Verzasca and Val Leventina has only recently been mapped in detail (Gruskovnjak, 2002; Leonardi, 2003; this study), and we used these results and have reinterpreted unpublished maps by Graeter and Wenk (in prep.) in compiling the new map.

3. Description of the units

Most of the rock units have been investigated in some detail by several authors. The following descriptions attempt to summarize briefly the major characteristics found; references are given to relevant publications containing more complete accounts. Rock types now found in different tectonic units, but sharing a common pre-Alpine history, have been documented jointly. The following descriptions essentially follow the organisation of the legend on the map. In order to avoid repetitions, descriptions of closely similar lithological relationships in the crystalline units of the European domain have been grouped following lithological criteria rather than their tectonic units. Similarly, sedimentary sequences of the European margin are discussed in their stratigraphic order. Table 1 serves as a link between the map and the descriptions and provides for easy consultation of these notes.

The unequal levels of knowledge about each unit and our aim to provide brief characterisations of them have resulted in disparate lengths and depths of the individual descriptions. For instance, exhaustive details are known about the Paleozoic lithostratigraphic relationships in the Gotthard Nappe because the pre-Alpine evolution of the basement has been found to be well preserved there and has been studied repeatedly. This is not the case for some otherwise comparable units, where strong Alpine deformation has obliterated the pre-Alpine relationships. Similarly, sedimentary units furnish much relevant information about their age, paleogeography, and basin evolution. Finally, units such as the Antigorio, Simano and Leventina Nappes consist mainly of uniform and rather similar metagranitoids, for which long descriptions are not too useful.

3.1. The Adria domain

3.1.1. Sesia Zone

In the area covered by the map, the steeply dipping Sesia Zone enters at the western margin, is less then 1 km thick and definitely disappears between Losone and Locarno. The strong deformation of rocks squeezed between the Insubric Line and the Loana shear zone (Burri et al., 2005) render the task of delimiting tectonic units on the

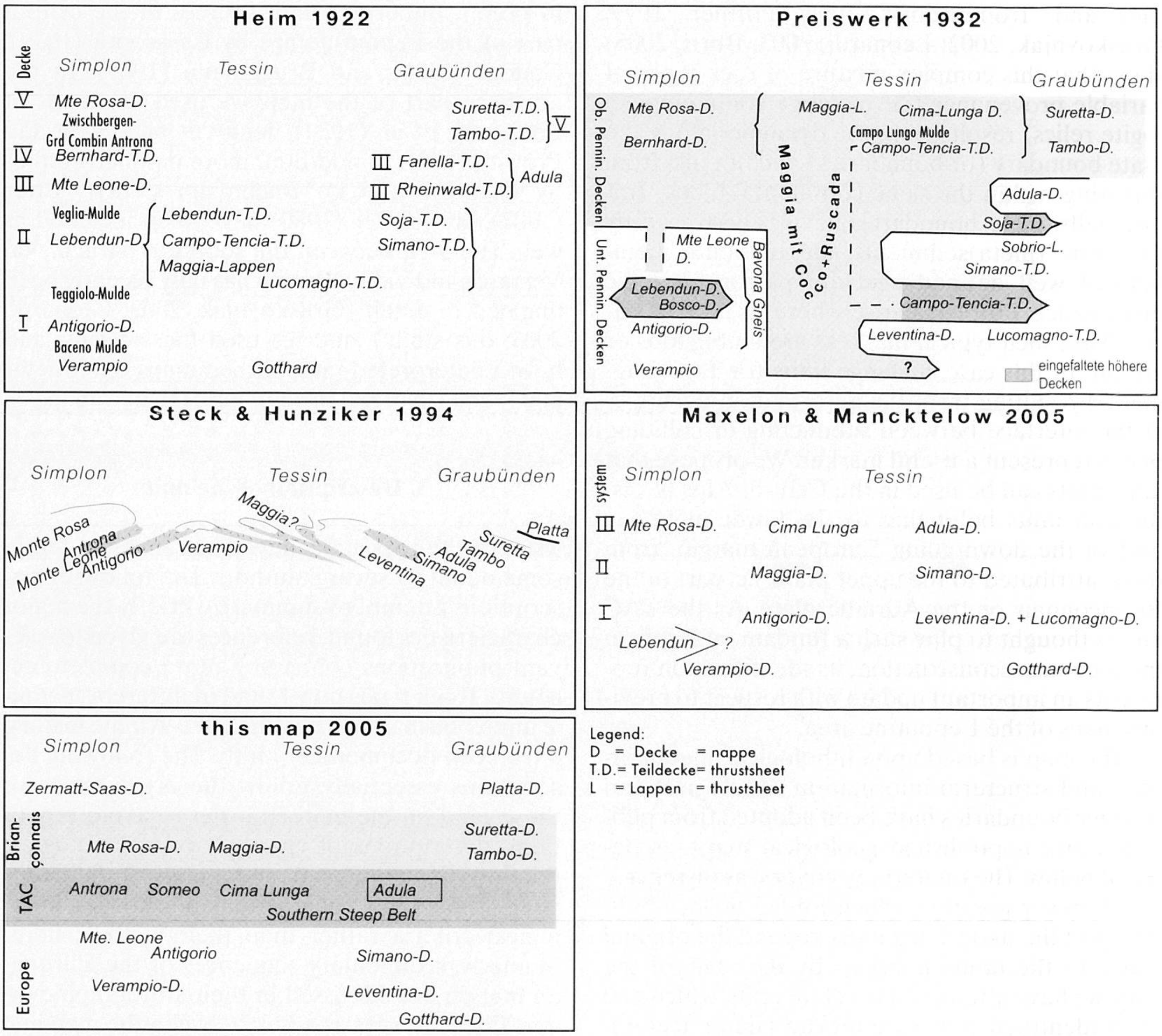

Fig. 3 Historical evolution of the interpretation of the nappe stack in the Central Alps. The style of the scheme follows Kündig (1936). The upper two frames are directly redrawn from Kündig (1936), the central two frames are the interpretations by Steck and Hunziker (1994), and by Maxelon and Mancktelow (2005). The bottom sketch shows our interpretation of the nappe stack (further details in figure 4).

basis of clear lithological criteria difficult. The central part of the thin strip of the Sesia Zone consists of fine-grained biotite gneiss. Towards the north, metadioritic bodies mark the transition to a mélange unit containing amphibolites and various gneiss types (Pfeifer et al., 1989; Colombi, 1989). Locally, these rocks are in contact with granitoid gneisses of the Monte Rosa Nappe or mafic and ultramafic rocks of the Zone of Zermatt-Saas Fee (?). The Sesia Zone increases in size towards the southwest (Steck et al., 2001). Mylonites and fine-grained granitic gneisses form the southern margin of the Sesia Zone juxtaposed against metasediments of the Canavese Zone. Detailed descriptions of Sesia rocks can be found in Walther (1950), Venkayya (1956), and Colombi (1989), whereas tectonic relationships were described by Schmid et al. (1987).

3.1.2. Canavese Zone

The Canavese Zone (defined in the Canavese area, some 120 km SW of Locarno) is a unit comprising a Paleozoic crystalline basement covered by weakly metamorphic to nonmetamorphic Upper Paleozoic volcanic rocks and a Mesozoic sedimentary sequence (e.g. Ahrendt, 1980, Ferrando et al., 2004). The Canavese Zone surfaces to the south of the Sesia Zone and north of the Ivrea Zone; it is separated from the latter by the Canavese Line, a western segment of the Insubric Line. For this reason, these rocks have been traditionally assigned to the Austroalpine domain. In the area covered by the map, the Canavese Zone consists of strongly deformed metasedimentary rocks, i.e. calcareous schists, and metapelites with small lenses of basic rocks (Venkayya, 1956, Walther, 1950). Where strongly deformed along the Canavese Line, these rocks earlier had been linked with mylonites of the Sesia and Ivrea Zones under the name of "scisti di Fobello e Rimella" (Sacchi, 1977) or "südliche Phyllonit-Zone" (Reinhardt, 1966). Outcrops of the Canavese Zone are scarce and discontinuous from the lower Val d'Aosta (type locality) to Locarno (Zingg et al., 1976). For this reason and because of the strong deformation, lithostratigraphic correlation is difficult; instead, the tectonic style and position of the units have frequently been used to delimit this zone.

3.1.3. Tonale Series

The Tonale Series is a mixture of several rock types (schist, amphibolite, calcsilicate, marble, pegmatite and sparse metaperidotite; e.g. Fumasoli, 1974). The metamorphic and structural evolution, mainly related to Variscan amphibolite-facies conditions (Hoinkes et al., 1999), is best exposed further east (outside the map), in less deformed parts. In the area covered by the map, the Tonale Series mainly consists of mylonites exposed just north of the Insubric Line. However, Variscan amphibolite-facies metamorphism has survived locally (e.g., Lardelli, 1981; Fisch, 1989; Schmid et al., 1996a).

3.1.4. Val Colla Zone

On the map, the Val Colla Zone collectively represents the Southalpine basement east of the Strona-Ceneri Zone. However, further tectonic subdivisions into the Val Colla Zone *sensu stricto* and the Musso Zone have been proposed (Schumacher et al., 1997). The different tectonic divisions involve greenschist-facies brittle deformation zones (the Luino Line, Arosio Line, Val Colla Line, Gazzirola Line, Taverne Line, Tesserete-Grona Line, and Musso Line). The Val Colla Zone consists of rock types resembling the Strona-Ceneri Zone, though amphibolites, mica schists, paragneiss and granitic gneisses of the Val Colla Zone have been more strongly overprinted by greenschist-facies metamorphism (Reinhard, 1964). Slices of Triassic cover are wedged along the Insubric Line which, in the area east of Bellinzona, form the northern border to the SSB. The rocks underwent a (very) low-grade thermal overprint in Alpine times, but the precise timing of this weak metamorphism is unclear. The Val Colla Zone represents the transition between two different tectonic styles: the exceptionally thick-skinned Ivrea and Strona-Ceneri complex to the West, and the thin-skinned Orobic Nappes to the East (e.g., Schumacher et al., 1997).

3.1.5. Strona-Ceneri Zone (Serie dei Laghi)

The Strona-Ceneri Zone (Zingg, 1983; Zurbriggen, 1996), also termed Serie dei Laghi (Boriani et al., 1977), is an amphibolite-facies gneiss complex consisting of amphibolites with associated ultramafics, mica schists and mica gneisses. The sedimentary and magmatic protoliths of these rocks are of Precambrian to Cambrian age, and their first evidence of metamorphism is Lower Ordovician in age. This old basement was intruded by Upper Ordovician granitoids and subsequently deformed and metamorphosed during the Upper Paleozoic (Variscan) orogeny. Following erosion, the whole basement complex was unconformably covered by Upper Carboniferous clastic sediments (the "Manno-conglomerate") and Permian volcanic rocks and then intruded by

Table 1 Correlation between the map and chapter 3.

No.	Unit	Key reference	Ch. in 3
1	Sesia Zone		1.1
2	Canavese Zone		1.2
3	Tonale Series	Fumasoli, 1974	1.3
4, 5	Val Colla Zone	Reinhard, 1964	1.4
6	Strona-Ceneri Zone	Zurbriggen, 1996	1.5
7	Ivrea Zone Basica	Zingg et al., 1990	1.6
8	Ivrea Zone Kinzigite		
9	Avers Nappe		2.1
10	Zone of Zermatt Saas-Fee		2.2
11	Schams Nappes	Rück & Schreurs, 1997	3.1
12	Areua-Bruschghorn Zone	Mayerat Demarne, 1994; Gansser, 1937	3.2
13	Knorren Mélange		
	Tambo-Surretta Nappes	Baudin et al., 1993; Blanc 1965	3.3
15, 19	Quartzite		
	Carbonate		
14, 19			
17, 21	Variscan Magmatite	Marquer et al., 1998	
18, 22	Basement		
23	Monte Rosa Nappe	Bearth 1952	3.4
	Maggia Nappe	Preiswerk, 1929	3.5
24	Cocco, Ruscada		
25	Basement		
26	Pertusio Unit	Keller, 1968	3.6
27	Banded Gneiss		
28	Vogorno Unit	Spicher & Wenk, 1981	3.7
	Chiavenna Ophiolite Zone	Schmutz, 1976	4.1
29	Marble		
30a	Metabasalts		
30b	Metagabbros		
31	Metaperidotite		
32	Tomül Nappe	Gansser, 1937; Probst, 1980; Steinmann, 1994	4.2.1
33	Grava Nappe		
34	Grava-Tomül Mélange		
35	Aul Nappe		4.2.2
36	Upper Vals Mélange	Nabholz, 1945	4.2.3
37	Lower Vals Mélange		
	Southern Steep Belt		
38	Zone of Bellinzona-Dascio	Berger et al., 1996; Fumasoli, 1974	5.1
39	Zone of Someo		5.2
40	Cima Lunga Unit		5.3
	Adula Nappe Complex		5.4
41	Fanella Unit	Jenny et al., 1923; Nagel et al., 2002b	
42	Trescolmen Unit		5.4.1
43	Soazza Unit		
44	Zervreila Unit		
45	Gana-Palingera Unit		5.4.2
46	Groven Unit		
47	Claro Unit	Codoni, 1981	
48	Argio Unit		
	Bodengo-Gruf Unit	Hänny, 1972; Bruggmann 1965; Blattner 1965	5.4.3
49	Metasedimentary gneiss		
50	Gneisses with ultramafics, eclogites		
51	Two mica granite		
52	Migmatites and granitic gneiss		
53	San Giacomo Unit	Probst, 1980; Bianconi, 1971	6.1.1
54	Lebendun Nappe		
55	S. Giorgio Molare and Dangio Units		
56	Piz Terri-Lunschania Zone		
57	Gotthard metasedimentary Unit		
58	Triassic metasediments		6.1.2
59	Soja and S. Giorgio Units		6.3
	Sambuco Unit	Günthert, 1956	
60	Granitic gneiss Materello		6.4
61	Polycyclic gneiss		6.6
	Simano Nappe	Preiswerk, 1929	
62	Granitic gneiss Verzasca		6.4
63	Granitic gneiss		6.5
64	Polycylcic gneiss		6.6
	Lucomagno Nappe		
65	Metapsammitic-metapsephitic gneiss	Bossard, 1936	6.1.3
66	Granitic gneiss	Bossard, 1936	6.5
67	Polycyclic basement		6.6
	Leventina Nappe		
68	Metasediment	Casasopra, 1939	6.2
69	Two mica granitic gneiss		6.4
70	Antigorio Nappe		6.4
	Gotthard Nappe	Mercolli et al., 1994; Steiger, 1962	6.7
72	Granitic gneiss		
72	Two mica granite		
73	Paleozoic metasediments		
74	Two mica granitic gneiss „Streifengneis“		
75	Polycyclic gneiss		
	Tertiary intrusive rocks	Schmid et al., 1996a	
N	Novate granite		7.2
G	Bergell granodiorite		7.1
T	Bergell tonalite		

Permian granitoids (the Appinite suite and Baveno suite). The Strona-Ceneri Zone has been interpreted as the middle crustal equivalent of the lower crustal Ivrea Zone (Handy et al., 1999), from which it is separated to the north by the Pogallo Line and by the Cossato-Mergozzo-Brissago Line (CMB). To the south, the Strona-Ceneri Zone is separated from the Val Colla Zone by a suite of SW–NE trending deformation zones (see chapter 3.1.4). Zurbriggen (1996) summarised this situation and proposed a comprehensive concept for the geological evolution (Zurbriggen et al., 1997), the pre-Alpine part of which is practically identical to that of the Gotthard Nappe (cf. chapter 3.6.7).

Table 2 Correlation of the Bündnerschiefer units and related mélange units after Steinmann (1994).

Steinmann (1994) this study	Nabholz (1945) Probst (1980)	Gansser (1937)
Tomül Nappe	Tomüllappen	obere Uccello Zone
Tomül Mélange	basale Schuppenzone des Tomüllappen	Gadriol-Zug
Grava Nappe	Gravaserie	-
Grava Mélange	basale Schuppenzone der Gravaserie	Gadriol-Zug
Aul Nappe	Aullappen	untere Uccello Zone
Upper Vals Mélange	obere Valserschuppen	-
Lower Vals Mélange	untere Valserschuppen	Zone der Adula-Trias

3.1.6. Ivrea Zone

The Ivrea Zone is an exhumed part of the lower crust and uppermost mantle of the Adria continent (Handy et al., 1999; Zingg et al., 1990). Gabbro and diorite intrusives of Upper Paleozoic age ("Basischer Hauptzug", Zingg et al., 1990), and high-grade (largely migmatic) gneisses (e.g. Barboza and Bergantz, 2000) are the main lithological units of the Ivrea Zone; slices of spinel peridotite surface along its northern rim. The lithostratigraphical relationships suggest a largely coherent section through the lower crust. This recognition accounts for the great interest and abundant literature regarding the Ivrea Zone (e.g. Schmid, 1993; Quick et al., 1994; Weyer et al., 2003 and literature therein). The narrow band of Ivrea Zone visible on our map consists mainly of various types of amphibolite (gabbroic to dioritic in composition) with a few spinel-chlorite-metaperidotite lenses. Sillimanite- and garnet-bearing biotite gneisses with abundant layers and lenses of amphibolite rim the mafic rocks (detailed descriptions in Walther, 1950, and Venkayya, 1956). The metamorphism in the Ivrea Zone is mainly Variscan in age (e.g., Vavra et al.; 1999; Mayer et al., 2000), and the Alpine thermal overprint is weak.

3.2. The Piemont-Liguria Ocean

3.2.1. Avers Nappe

The Avers Nappe consists of a monotonous sequence, up to 1500 m thick, of metamorphosed sandy calcschists, shales, greywackes, and marbles, all of Mesozoic protoliths. Members of an ophiolite sequence, comprising metabasaltic greenschists, rare serpentinites and metacherts, are interlayered with the calciclastic metasediments termed Bündnerschiefer. A particular characteristic of these greenschists is the occurrence of alkali-amphibole. Most widespread is sodium-rich actinolitic hornblende, while glaucophane and Mg-riebeckite are rare (Oberhänsli, 1978). In northern sections the greenschists form isolated lenses; towards the south lenses increase in frequency and thickness to form massive, coherent bands (Staub, 1926).

The Avers greenschists were already recognized early in the 19th Century (Escher and Studer, 1839) and have played a key role in the construction of tectonic models. The Avers Nappe with their ophiolitic relics were thrusted over the sedimentary cover of the Suretta Nappe; the Turba normal fault marks its eastern margin (Nievergelt et al., 1996). This unit has been interpreted as parts of an accretionary wedge formed in the Piemont-Liguria Ocean, at the southern margin of the Briançonnais domain (Schmid et al., 1996b).

3.2.2. The Zone of Zermatt-Saas Fee

The Zone of Zermatt-Saas Fee is a classical ophiolite sequence comprising metaperidotite, metagabbro, metabasalt, and metasediments (Bearth, 1967; Pfeifer et al., 1989). This sequence is well preserved in the area of Zermatt and thins out towards the east (Steck et al., 1999, 2001). Its tectonic position is clearly visible in Val d'Ossola, where metabasic and -ultrabasic rocks are located above (and south of) the Monte Rosa Nappe. In the area shown on the map, a few relics of metagabbro and ultramafic bodies are located immediately south of the Monte Rosa Nappe. These metabasic rocks together with some metasediments have thus been interpreted as remnants of the Zone of Zermatt-Saas Fee by Pfeifer et al. (in prep.).

3.3. The Briançonnais domain

3.3.1. Schams Nappes

The Schams Nappes consist of a stack of several tectonic units and subunits (Rück and Schreurs,

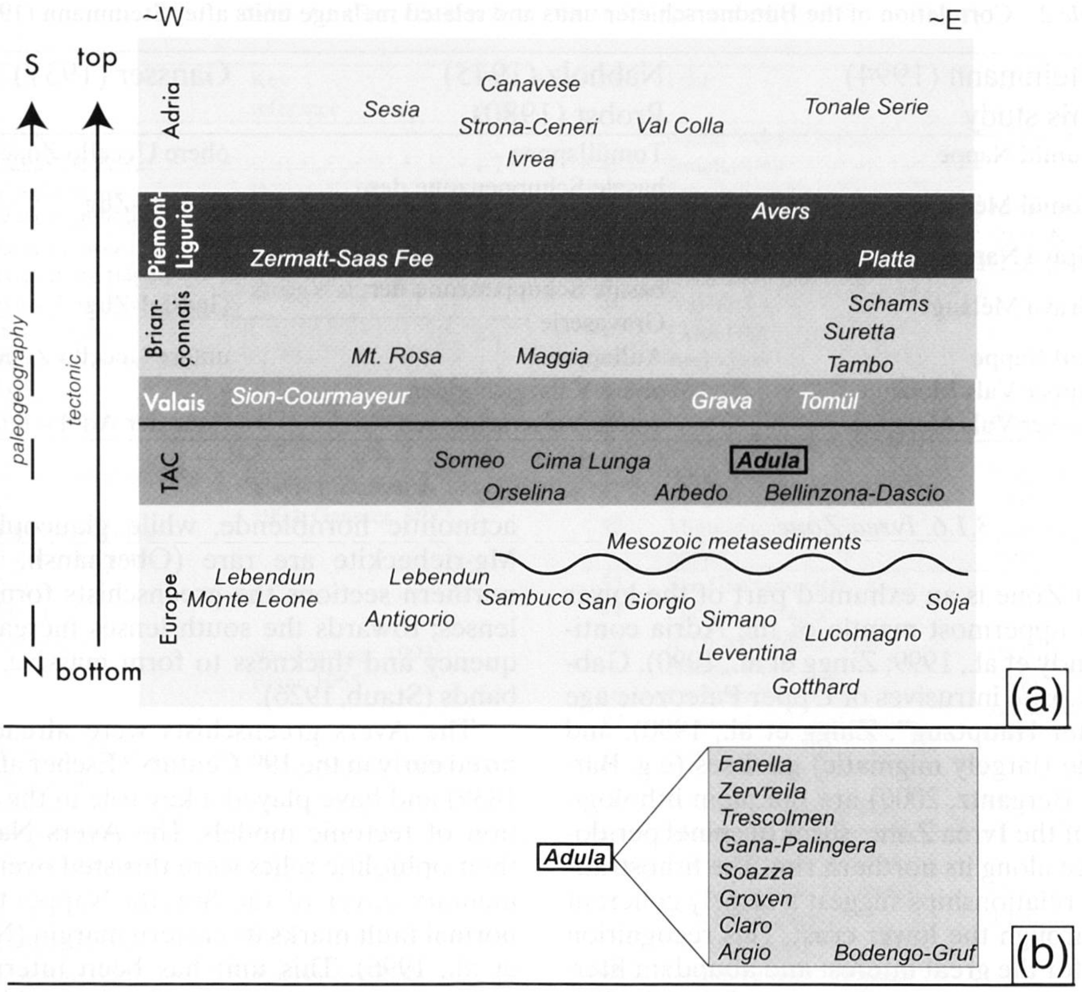

Fig. 4 Tectonostratigraphic units and their E–W correlation. (a) Units present on the map are shown in their respective tectonostratigraphic position. (b) Internal subdivision of the Adula Nappe Complex.

1995). The Gelbhorn and the Tschera-Kalkberg Units are the two major members of this stack. The thrust sheets contain Triassic, Jurassic, Cretaceous and probably even some Paleogene strata (Rück and Schreurs, 1995). These authors assign the Schams (meta)sediments to the Briançonnais domain at the southern margin of the opening Valais Ocean. Stratigraphic equivalents of the Schams sequences have been identified in the Falknis, Sulzfluh and Tasna Nappes. The complete sequence of the Schams Nappes is best exposed between Splügen and Zillis; the map covers but their westernmost parts. These comprise a strongly thinned, overturned limb of the Gelbhorn Unit with its Upper Triassic and Lower Jurassic sediments. In this frontal part of the Tambo Nappe, the Schams Nappes are enveloped by the Areua-Bruschghorn Zone and Knorren Mélange (see below). Mayerat Demarne (1994) and Rück and Schreurs (1995) have stressed the stratigraphic affinity between sequences of the Areua-Bruschghorn Zone and the Schams Nappes. At the northern end of the Splügen Zone the distinction between Schams (meta)sediments and the sedimentary cover of the Tambo Nappe is ambiguous (Mayerat Demarne, 1994, Fig. 5). Although it is difficult to trace mutual borders, Mayerat Demarne (1994) clearly stated that the Mesozoic sediments of the Tambo Nappe do not represent the cover of the Areua-Bruschghorn Zone. Similarly, Rück and Schreurs (1995) separated the Schams Nappes from the Tambo and Suretta sedimentary cover.

Because of post-nappe folding, the original paleogeographic position of the Schams Nappes is difficult to trace. The long debate regarding the Schams Nappes has been termed the "Schams Dilemma" (see Schmid et al., 1990 and literature therein). Two solutions have been proposed: The nappes either originated from below the Tambo and Suretta Nappes (solution termed *Infra:* the nappe was initially located in the Misox Zone); or it originated from above (solution termed *Supra*; the nappe was located on top of the Tambo and Suretta Nappes). Rück and Schreurs (1995) suggested that the Tambo and/or parts of the Suretta basement are possibly the substratum of part of the Schams sediments.

3.3.2. Areua-Bruschghorn Zone and Knorren Mélange

Gansser (1937) proposed a first tectonic subdivision of the units at the front of the Tambo Nappe. Mayerat Demarne (1994) rearranged these and defined the Areua-Bruschghorn Nappe (or Areua-Bruschghorn wedge) as composed of the Areua-Bruschghorn gneiss and the Upper Vignone Zone of Gansser (1937), with an autochthonous cover comprising Permo-Carboniferous sediments and Triassic quartzite. Toward the east these units are a characteristic mélange unit, in which fragments of greenschist and dolomite of the chaotic "Bruschghorn-Schuppe" (Streiff et al., 1971/1976) are interspersed with sheets of Areua-Bruschghorn gneiss. The latter is granitic in composition and similar to (finer grained) gneisses of the Upper Vignone Zone. The Permo-Carboniferous metasediments comprise chlorite-rich schists, graphitic schists and some anthracite lenses, topped by massive quartzites with sparse mica (Gansser, 1937).

The Knorren Mélange (Mayerat Demarne, 1994), a chaotic assemblage of many rock types, differing in size and age, comprises the Knorren Zone and the Lower Vignone Zone (Gansser, 1937). Components of the Knorren Mélange include sericite-rich marble, calcareous sandstone, breccias with gneiss components, conglomerate-gneiss, quartzite, Bündnerschiefer, greenschist, dolomitic marble, and metaevaporite.

3.3.3. Tambo and Suretta Nappes

The Tambo and Suretta Nappes have been assumed to be similar in paleogeographic origin and geodynamic evolution. This relies mainly on the connection with the Schams Nappes during their common deformation, involving thrusting and folding (e.g. Rück and Schreurs, 1995). However, the Tambo and Suretta Nappes are two units separated by the Splügen Zone (Blanc, 1965). This zone as well as the sedimentary cover of the Suretta Nappe shows a sedimentary evolution typical of the Briançonnais domain (Boudin et al., 1993; Boudin and Marquer, 1993). The pre-Variscan basement witnessed a polycyclic metamorphic evolution and subsequent intrusion of late Variscan magmatic bodies. Basement rocks comprise mostly metapsammites and metagreywackes, all characterized by strong pre-Alpine deformation and metamorphism; metapelites contain pre-Alpine staurolite, kyanite, andalusite, and garnet. Trails of mafic and ultramafic lenses occur in the northern part of the Tambo Nappe. Some of the amphibolites preserve relics of pre-Alpine eclogitic assemblages (Biino et al. 1997). The larger intrusive masses are the Truzzo granite in the Tambo Nappe and the Rofna porphyry in the Suretta Nappe. Both magmatic suites follow a calc-alkaline trend, intermediate to acidic in composition. The Rofna porphyry is an acid subvolcanic rock overprinted in greenschist facies. The Truzzo granite is a weakly metamorphosed porphyritic granite with K-feldspar megacrysts (e.g. Marquer et al., 1998). Zircon ages of these rocks show an early Permian magmatic origin (Marquer et al., 1998).

The oldest sedimentary cover of the Tambo and Suretta basement are quartz-conglomerates, overlain by fine-grained quartzite, which is up to several meters thick. Both members are thought to be Permo-Triassic in age (Staub, 1918, 1921). The stratigraphy of the carbonate sequence is Triassic and younger; it is best preserved near Lake Cam, north of Vicosoprano (Val Bregaglia). The carbonates consist of dolomite, limestone, cellular dolomite and carbonate breccia. A characteristic alternation of dolomite and limestone is Ladinian in age (see also Boudin and Marquer, 1993; Streiff et al., 1971/1976). Above the marble, calcareous schists occur; these grade into more sandy and pelitic calcareous schists (Staub, 1921).

The Tambo and Suretta Nappes show Alpine assemblages that range from HP greenschist to blueschist facies. Phengite barometry (based on the calibration of Massone and Schreyer, 1987) yields P~1.0–1.3 GPa (at T~400°C in the N, ~550°C in the central part: Boudin and Marquer, 1993; Ring, 1992), whereas for the Suretta Nappe the results are 0.9–1.2 GPa (at 400–450°C, Nussbaum et al., 1998).

3.3.4. Monte Rosa Nappe

The Monte Rosa orthogneiss is the only unit of the Monte Rosa Nappe in the area of the map. Detailed descriptions of the granite are due to Bearth (1952), who investigated these rocks in the area of the Monte Rosa massif; Knup (1958) characterized them in the Centovalli area. The gneiss is a deformed metagranite with two feldspars, quartz, biotite and characteristic K-feldspar megacrysts. However, variations in petrography and intensity of deformation change the field aspects of the Monte Rosa gneiss. Nearly undeformed granitic textures contrast with strongly foliated and lineated varieties. In the area of the map, the Monte Rosa gneiss has been infiltrated by abundant aplites and pegmatites of Late-Alpine age, which crosscut the Alpine foliation

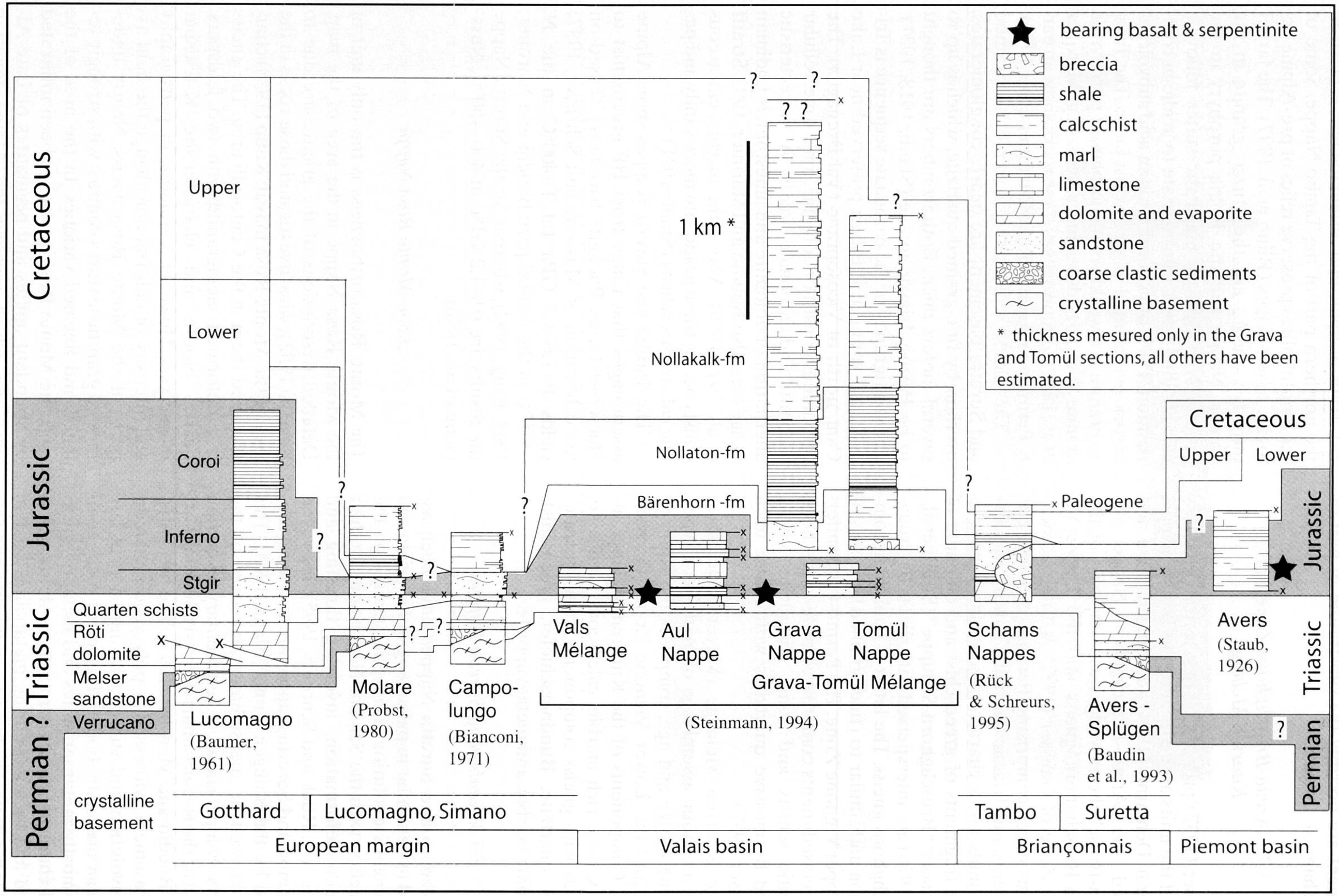

Fig. 5 Stratigraphic summary of the units presented on the map. Data are from Baumer (1961), Bianconi (1971), Probst (1980), Steinmann (1994), Boudin et al. (1993), Rück and Schreurs (1995), and Staub (1926).

(Romer et al., 1996; Schärer et al., 1996; Burri et al., 2005). The granitic protolith of the Monte Rosa gneiss has been dated as 270±4 Ma (cited in Pawlig and Baumgartner, 2001; see also Frey et al., 1976). Sparse pelitic gneiss trails in the Monte Rosa metagranite indicate a two-phase Alpine metamorphic overprint, with an Eocene high-pressure (HP) phase followed by a decompressional overprint, dated at between 38 and 32 Ma (Engi et al., 2001b).

3.3.5. Maggia Nappe

We regard the Maggia Nappe as a pure basement nappe without sedimentary cover. (In contrast to some authors (e.g. Spicher, 1980), we view the Sambuco Unit to the north as a separate unit; see chapter 6.1.). The Maggia Nappe is made up of two crystalline units: a polycyclic pre-Variscan basement complex and the intrusive Cocco Unit, which has been subdivided into the Cocco gneiss and the Ruscada gneiss (Preiswerk, 1931). The former is a mesocratic gneiss with a flaser texture. Granodioritic in composition, it contains plagioclase and minor K-feldspar, quartz, characteristic nests of biotite and, in some localities, amphibole (Preiswerk, 1925, 1929, 1931; Spicher and Wenk, 1981). The Cocco gneiss was intruded by the Ruscada granitoids, now represented by dominantly leucocratic gneisses. These are petrographically and geochemically heterogeneous, commonly showing (pre-Alpine) migmatic textures. Both of these units derive from Variscan calc-alkaline plutonic masses, which intruded an older basement (Burri, 2005). Within the latter, plagioclase-quartz-biotite gneisses dominate, but metasediments, amphibolites, and migmatites are widespread as well.

It is difficult to map the limits of the Maggia Nappe against some of its neighbouring units. In the northeast, the Pertusio Unit (see below) is well established as marking the border against the Simano Nappe (Keller, 1968; Keller et al., 1980). Further south, tectonic delimitations are more ambiguous (Merle and LeGal, 1988; Maxelon, 2004; Maxelon and Mancktelow, 2005). The border of the Maggia Nappe against the Antigorio Nappe is defined by TAC-fragments of the Zone of Someo (see chapter 3.5.3).

3.3.6. Pertusio Unit and related rocks

The Pertusio Unit separates the Simano Nappe from the Maggia Nappe. It consists of clastic metasediments, showing strong deformation and amphibolite-facies metamorphism (Hasler, 1949; Keller, 1968). Within the Pertusio Unit isolated carbonate lenses occur, the origin of which remains unresolved. Towards the south, the Pertusio Unit extends into a strongly deformed unit of slightly different rock types, i.e. the strongly banded gneisses in the upper Val d'Osura (Merle and LeGal, 1988).

3.3.7. Vogorno Unit

The Vogorno Unit consists of a pre-Variscan polycyclic basement intruded by a leucocratic (meta-) granite. The latter is termed Vogorno gneiss, the dominant rock type of the unit and of similar petrography as the Verzasca gneiss (described in chapter 3.6.4). The basement contains various metasedimentary gneisses (in part migmatitic), amphibolites, and granitic layers (Spicher and Wenk, 1981).

3.4. The Valais Ocean

3.4.1. Chiavenna Ophiolite Zone

The Chiavenna Ophiolite Zone has been interpreted as an overturned ophiolitic sequence; it includes mafic and ultramafic rocks, calcsilicates, and marbles (Schmutz, 1976). The Chiavenna Ophiolite Zone is in steep tectonic contact to the Gruf complex and overlain by the Tambo Nappe (e.g. Huber and Marquer, 1998). Only the larger mafic, ultramafic, and carbonate masses could be individually shown on the map. In the restored position, the metaperidotite is overlain by metagabbro and amphibolite. The latter, being massive and fine-grained, is interpreted as metabasalt; its sedimentary cover, comprising marbles and calcsilicates, is locally preserved (Schmutz, 1976). Geochronological data indicate two stages of metamorphic evolution. The first one is possibly of late Eocene age (42 Ma: Talerico, 2001). The second stage, Oligocene in age (37–32 Ma: Liati et al., 2003; Talerico, 2001), reached amphibolite-facies conditions and displays a steep thermal gradient against the Gruf-Bodengo Unit (Schmutz, 1976). This has been interpreted as due to rapid, hot emplacement of the Gruf Unit, juxtaposing it against the Chiavenna Ophiolite Zone (Liati et al., 2003; Schmutz, 1976).

3.4.2. Metasediments derived from the Valais Ocean

Essentially during the Cretaceous, a huge mass of limestone, sandy limestone, shale and marl (Bündnerschiefer) have been deposited in the Valais Ocean (Fig. 5). Sizeable units of these Bündnerschiefer have been imbricated and thrusted northward onto Jurassic units of the European margin (Penninic thrust; Probst, 1980; see also chapter 3.6.1). Steinmann (1994) gave a very detailed account of the sedimentological, stratigraphic and tectonic relationships of these sediments in the section Prättigau – Mesolcina. Only a reduced part of these series is exposed in the area covered by our map. Six of the units defined by Steinmann (1994) are represented, i.e. two nappes (Tomül and Grava) and four mélange zones (Grava-Tomül, Upper Vals and Lower Vals Mélange, and Aul Nappe). Whereas the two nappes contain Cretaceous formations, the sediments in the mélange derive from Upper Triassic and Jurassic strata. Table 2 illustrates the correlation between the units of Steinmann (1994) and older tectonic subdivisions proposed by Gansser (1937) and Nabholz (1945).

3.4.2.1. Tomül and Grava Nappes

These two nappes consist of the same stratigraphic units, i.e. the Bärenhorn Fm., Nollaton Fm., Nollakalk Fm. and Carnusa Fm. (Fig. 5). The nappes show variations in thickness of these formations. In addition to these (meta)sediments, the Tomül Nappe shows a greenstone layer at its base and a flysch sequence at the top; neither occur in the Grava Nappe. Owing to intense internal folding and thrusting, it is difficult to reconstruct the original thickness of the sedimentary sequences. Steinmann (1994) estimated a thickness up to 2000 m for this Cretaceous cycle. The composition of these turbiditic, hemipelagic sediments is characterized by highly variable abundances of three major components: carbonates, quartz and clays. Unfortunately, the entire sequence lacks biostratigraphic markers. Despite these complexities, detailed stratigraphic profiles have been reconstructed and correlated across different tectonic units (Steinmann, 1994). Based on such lithostratigraphic correlations with dated sequences, he proposed the following chronostratigraphic arrangement: (1) Bärenhorn Fm., sandy limestone with few quartzites and shales of Kimmeridgian to Barremian age; (2) Nollaton Fm., essentially shale of Aptian–Albian age, (3) Nollakalk Fm., intense interlayering of limestone, sandy limestone, and marl of Cenomanian age; (4) Carnusa Fm., conglomerate, breccias, quartzite and sandy limestone probably of Turonian age; (5) Tomül Flysch, possibly of Coniacian age. The metabasalts of the greenstone basal layer of the Tomül Nappe are interpreted as relics of the Valais Ocean.

The Tomül Nappe is restricted to the area east of the Mesolcina valley, whereas the Grava Nappe can be followed along the entire Northern Steep Belt (NSB), as far west as Val Bedretto. Beyond the map, the Bündnerschiefer of the Zone Sion-Courmayeur represent the western continuation of the Grava Nappe; Steck et al. (1999). From this main east-west direction of Bündnerschiefer units, two branches separate towards the south: one in Val Blenio (to Dangio), the other one in Val Leventina (to Rodi). Probst (1980) proposed a tectonic unit comprising the Grava Serie to the east and the Lugnez-Sosto schists to the west. He correlated the monotonous successions of calcareous shale with the massive Nollakalk Fm. (up to 1000 m thick) of the Grava Nappe. More tentative is the correlation of some of the shale horizons in the Molare and Blenio areas (Probst, 1980) with those of the Nollaton Fm. The marls of the Bärenhorn Fm. appear to be missing west of Hinterrhein. The top of the Carnusa Fm. is not clearly defined in the Grava Nappe; it is therefore impossible to be sure whether younger sediments (Paleocene/Eocene) are preserved in the NSB, though this seems to be the case both further east and west (Bousquet et al., 2002).

3.4.2.2. Grava-Tomül Mélange

The base of the Tomül and Grava Nappes in the Mesolcina region is marked by two lithologically and tectonically complex sequences termed, respectively, Grava and Tomül Mélange (Steinmann, 1994). In the region of Hinterrhein, where the Grava Nappe thins out, the two basal layers merge to a single unit that can be followed all along the Misox Zone, where it has been termed "Gadriol-Zug" (Gansser, 1937; Table 2). The spectrum of components comprises sedimentary breccias, sandstones with a Liassic guide fossil (*Grypheae arquata*; Nabholz, 1944, 1945), sandy limestones, shales and marls. Intercalations of metabasalt in these sediments are frequent, but the fragments are much smaller than in the Aul Nappe. Rare slices of crystalline basement have been found in the "Gadriol-Zug" only.

3.4.2.3. Aul Nappe

Slices of marble and greenstone dominate this unit, in which the metasediments are thick-bedded, grey to brownish sandy calcitic marbles. Greenstone layers consist mainly of metabasalt; pillow structures have been recognized locally. Serpentinite lenses are locally associated with these metabasalts. Subordinate dolomitic lenses occur, as do a few slices of basement. This unit is also named Aul Schuppenzone (e.g. Steinmann, 1994)

3.5. Paleogene Tectonic Accretion Channel (TAC) Units

Units of the TAC share distinctive characteristics with respect to their lithological contents and metamorphic evolution. The major lithological feature is the small-scale (meter to decameter) diversity of rocks of clearly different origin, i.e. continental upper- and middle crust, oceanic crust, and mantle. Intense deformation of the fragments leads to a characteristically lenticular and banded aspect. In the Central Alps, tectonic zones of this type have long been recognized (e.g. Jenny et al., 1923; Knoblauch et al., 1939; Kobe, 1956; Knup, 1958). Their heterogeneity led earlier workers not to regard these units as parts of the main Alpine thrust sheets or to identify them as individual nappes. Instead, they have been termed "Zones" and given local or regional names, such as, Zone of Bellinzona-Dascio, Zone of Arbedo-Mergoscia, Zone of Orselina, Zone of Someo, Zone of Onsernone, and Cima Lunga Unit. The tectonic significance of these zones collectively has become more evident only recently (e.g. Trommsdorff, 1990; Engi et al., 2001a). In light of the structural position of the "Zones" within the orogen and based on detailed petrological studies, Engi et al. (2001a) proposed a unified interpretation of the mélange units, which links their formation to the interface between the subducting and the hanging plate. A key observation in the Lepontine is that Alpine HP relics, notably eclogite and garnet peridotite lenses, appear to be restricted in their occurrence to TAC units. The term TAC was proposed to link the observed characteristics of these mélange units to known and inferred processes at the tectonic interface of destructive plate margins. The term and concept have been adopted for similar units in other orogens (e.g. Abalos et al., 2003).

3.5.1. Lower and Upper Vals Mélange

Slices of basement gneiss, tectonically wedged in between dolomite layers, are characteristic of these two mélange zones. The gneiss slivers show a strong affinity to those occurring in the Adula Nappe Complex. The Upper Vals Mélange furthermore contains a greater abundance of sandy limestone, shale, marl and mafic rocks, albeit in lower amounts than in the Aul Nappe and the Grava-Tomül Mélange.

3.5.2. TAC Units inside the Southern Steep Belt (SSB)

The SSB extends from Valle della Mera in the east to the Centovalli in the west and corresponds to the old term "Wurzelzone" (root zone), i.e. it is defined by its steep main foliation. The SSB comprises parts of coherent nappes (Simano, Maggia, Monte Rosa) and mélange units (Zone of Bellinzona-Dascio, Zone of Arbedo-Mergoscia, Zone of Orselina, Zone of Onsernone, and the southernmost parts of Zone of Someo and the Cima Lunga Unit; Fig. 2). Kobe (1956), Knup (1958) and Spicher and Wenk (1981) presented further detailed subdivisions. Dominant in the wide range of rock types are two-feldspar orthogneiss and biotite-plagioclase gneiss (e.g. Fumasoli, 1974). These gneisses are repeatedly interlayered with trails of pelitic and calcareous schists, marbles, amphibolites, and lenses of variably retrogressed eclogite and metaperidotite (Knoblauch et al., 1939; Forster, 1947; Fumasoli, 1974; Wenk et al., 1974). The gneisses show intense deformation, with a variety of meso- and microscopic deformation structures and metamorphic fabrics. Subordinate slices and bands of (usually siliceous) marble are interlayered with abundant gneiss bands in several of the TAC zones. Mafic rocks predominantly occur as highly strained amphibolites; local eclogite relics (e.g., Forster, 1947; Colombi and Pfeifer, 1986; Tóth et al., 2000) are found primarily in ovoid lenses showing less internal deformation. The ultramafic lenses have been intensely investigated (e.g., Stucki et al., 2003; Pfeifer et al., 1991; Trommsdorff and Evans, 1969). Some of these are associated with eclogite relics and metarodingites. Basic and ultrabasic lenses vary in size between a few decimeters to hundreds of meters; famed and prominent in the SSB is the garnet peridotite body of Alpe Arami with its eclogitic rim (Moeckel, 1969). The Zones of Bellinzona-Dascio and Arbedo-Mergoscia differ from the Zone of Orselina, which shows a high density of metasediments and metabasic rocks. However, irrespective of local variations in the rock associations, the different zones share their tectonic position in the orogen and testify to a similarly complex geodynamic evolution.

The TAC units inside the SSB underwent different degrees of late-Alpine partial melting (e.g. Burri et al., 2005). Alpine migmatites are almost entirely restricted to the SSB. Partial melting there is related to the infiltration of aqueous fluids and, at least in the central portion (between Bellinzona and Locarno), to white mica dehydration melting. Melts accumulated in different structural positions, such as local patches, discordant dykes and as stromatic migmatites (the "injection gneisses" in older literature; e.g., Wenk, 1970). The types and amounts of partial melting in the SSB are variable, depending on rock composition, temperature, and amounts of fluids at each locality. The highest proportions of leucosomes (25–30%) occur in the central portion of the belt, in rocks of pelitic and granitic to tonalitic bulk composition.

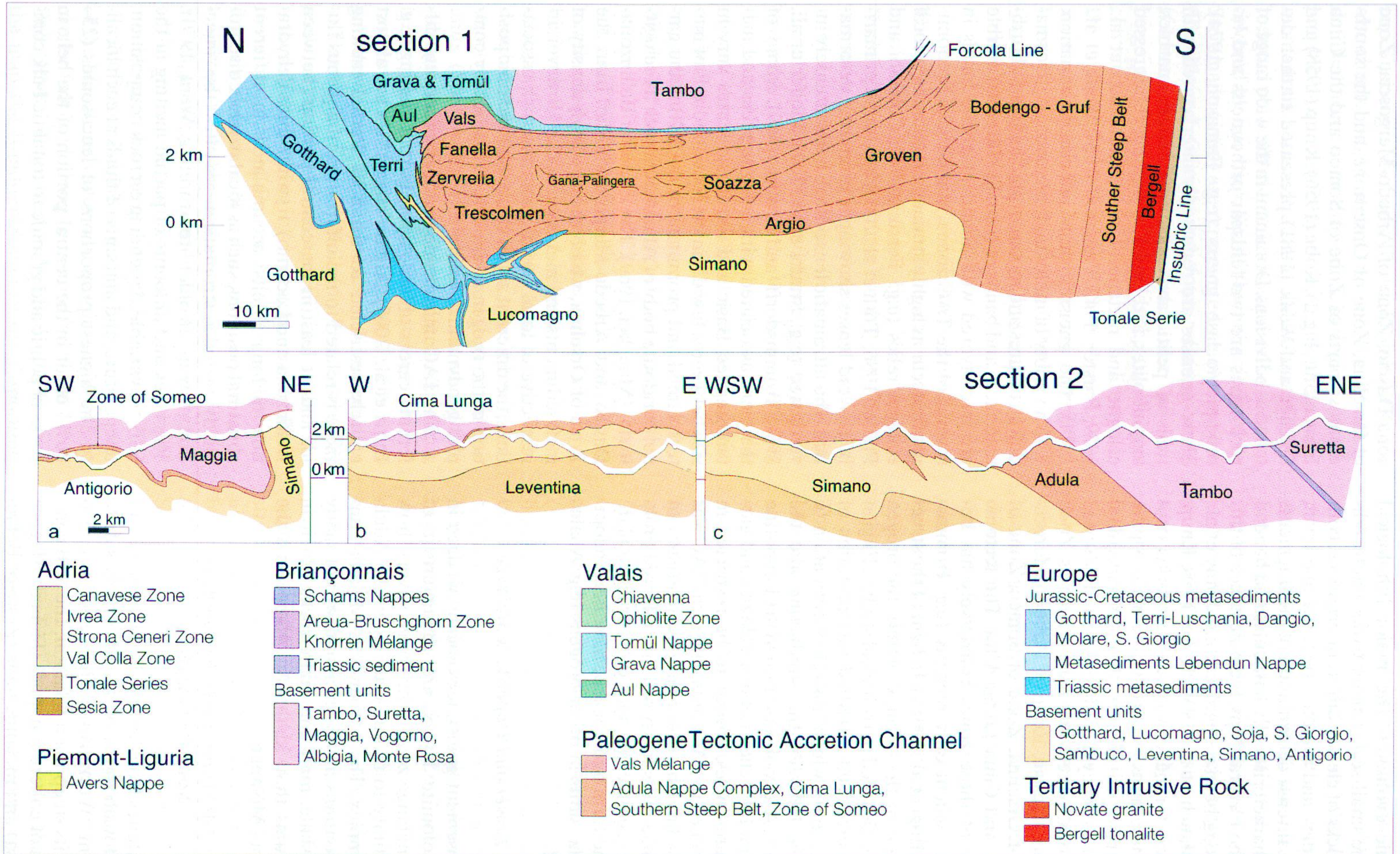

Fig. 6 Schematic sections across the map. (a) N–S section: In part redrawn from Jenny et al. (1923) and Nagel et al. (2002b). Internal subunits of the Adula Nappe Complex are shown. The connection of this thrust sheet to the Bodengo-Gruf Unit is not very clear. (b) E–W section: In part modifed and extended after Nagel et al. (2002b) and Burri (2005).

3.5.3. Zone of Someo

The Zone of Someo is well established as the border between the Antigorio and Maggia Nappes (Knup, 1958; Dal Vesco, 1953); it can be followed from the Centovalli to the northern Valle Maggia. Although characterized by local occurrences of metaperidotite, retrogressed eclogite, and marble, the most abundant rock types in the Zone of Someo are plagioclase-biotite gneiss and two-feldspar-biotite gneiss. The map shows the maximum extent of this zone, drawn so as to include all of the basic and ultrabasic remnants in this area. On earlier maps, only the marble bodies had been taken as the distinctive characteristic of the Zone of Someo, hence this unit was considerably less extensive. The key reasons for delimiting the Zone of Someo as shown on the new map are its similarity in petrography and field occurrence with mélange units in the SSB.

3.5.4. The Cima Lunga Unit

The Cima Lunga Unit principally surfaces along the crests of the mountain range separating Val Verzasca from Val Leventina. Its lithological structure is similar to that of the other TAC units described above, i.e. heterogeneous bands of metabasic and metaultrabasic rocks, and marble lenses together with metaclastic schists and metagranitic gneisses. Several localities in the Cima Lunga Unit have been intensely investigated (e.g. Pfiffner, 1999; Pfiffner and Trommsdorff, 1998; Trommsdorff et al., 1975). The occurrence of metarodingite dykes in some metaperidotites clearly indicates a previous serpentinisation stage. Garnet peridotites locally preserved their HP assemblages, though many have been retrogressed to spinel-chlorite peridotites; eclogitic parageneses are widespread in the metabasaltic rocks. Where in contact with enclosing gneiss, metaperidotite lenses show prominent metasomatic reaction rims, with mineral assemblages characteristic of the regional amphibolite-facies overprint (see also chapter 5). Petrological studies of the metaperidotites indicate a similar range of P and T as for metaperidotites in the SSB (e.g. Heinrich, 1982; Schmidt 1989; Nimis and Trommsdorff, 2001). However, most of these ultramafic lenses retain evidence of prior oceanic metamorphism, which has not been documented at Alpe Arami and has been found in only a few of the metaperidotites in the SSB (e.g. Alpe Albion). The structures observed in the Cima Lunga Unit include a common composite foliation, but an older deformation has been indirectly inferred and appears to be related to fragmentation and the development of an eclogitic foliation (e.g., Grond et al., 1995).

3.5.5. The Adula Nappe Complex

The Adula Nappe Complex is one of the largest elements on the map and certainly a key thrust sheet in the Lepontine. It surfaces extensively between Val Leventina and Val Blenio to the west, and Valle della Mera and Mesolcina to the east. Apart from being impressively exposed, the Adula Nappe Complex is important owing to its unique internal structure, as compared with the other crystalline nappes. Whereas its overall shape resembles most of the other crystalline nappes, it internally comprises several subunits in the shape of individual slices and thrust sheets. We refer to the Adula Nappe Complex, rather than the Adula Nappe, to underline these particular structural features. The exceptional characteristics of this unit have been recognized by Jenny et al. (1923) in their pioneering study. Based on this study, and integrating subsequent work by Kündig (1926), Bellin (1929), Blatter (1965), Bruggman (1965), Hänni (1972), Fumasoli (1974), Codoni (1981) and Nagel et al. (2002b), we have subdivided the Adula Nappe Complex into a series of nine subunits. Subdivisions essentially reflect three lithological associations: Granitic gneiss with minor amounts of banded gneiss dominate the first group; the second group represents true mélange units with basement gneiss wedged against marbles, metabasics with eclogitic relics, and metaultrabasics. Migmatites, gneisses, and metasediments in the region between Val Bodengo and the Bergell form the last group. Where possible, we have retained the names for the subunits as used by Jenny et al. (1923), Kündig (1926), and Nagel et al. (2002b), even where we have seen fit to modify their borders in part.

The first-order structures within the Adula Nappe Complex developed by tectonic intermingling of the above-defined subunits, whereas the assembly of the different units behaved as a coherent block in the subsequent tectonic evolution. The Adula Nappe Complex as a whole rests upon a metasedimentary nappe divide ("Deckenscheider") derived from Triassic sedimentary protoliths in the roof of the Simano Nappe. The contact between the top of the Adula Nappe Complex and the metasediments of the Misox Zone is very difficult to delimit.

3.5.5.1. Mélange units with HP relics

Three tectonic slices within the Adula Nappe Complex, i.e. the Fanella, Trescolmen and Soazza Units contain metabasalt fragments preserving

Alpine eclogite assemblages. These and the commonly associated metaperidotite fragments are regarded as relics of a dismembered ophiolite sequence within the mélange units, which also comprise various types of basement gneiss and metacarbonates. The types, amounts, and sizes of the fragments, as well as their distribution vary locally inside each zone and amongst the various units. Some localities are enriched in eclogite, metaperidotite, and metasediments, whereas in other locations basement gneisses dominate the composition of the unit. Metasedimentary plagioclase-biotite gneisses generally dominate, but granitoid types occur as well. Lower Mesozoic sedimentary protoliths can be inferred for the more coherent sequences in the northern Adula Nappe Complex, whereas in the south the age of typically isolated lenses and trails of various metacarbonates and calcsilicates is unknown. In the last decades, investigations have concentrated on the HP metamorphism inside the Adula Nappe Complex (e.g. Heinrich, 1982; Meyre and Frey, 1998; Zack et al., 2001, 2002); generally increasing pressures have been documented from north to south (Dale and Holland, 2003; Heinrich, 1982, 1983). The best-preserved eclogites occur in the areas of Alpe Trescolmen and Confin, whereas in other locations eclogites show variable degrees of hydration and Barrovian overprint. The P–T conditions of the eclogites and overprinted eclogites range from 1.0 GPa and 550°C in the north to 2.5 GPa and 750°C in the south, but the spatial distribution of P–T data suggests a possibly coherent N–S field gradient only for the northern parts of the Adula section (Dale and Holland, 2003). Apart from mafic bodies, metasediments occurring inside these mélange units also locally preserve the HP stage of metamorphism (Meyre et al., 1999).

The whole sequence has been overprinted by Barrovian metamorphism (e.g. Nagel et al., 2002a; Niggli, 1970), and it has been shown that some of the Barrovian metamorphism in the Adula Nappe Complex developed during decompression from the HP stage (Nagel et al., 2002a). Barrovian assemblages are well recognized in metapelitic rocks and impure carbonates. The mapped mineral zone boundaries (i.e. first occurrence) of staurolite and kyanite and isograds (e.g. diopside-calcite: Trommsdorff, 1966; microcline-sanidine: Bernotat and Bambauer, 1982) crosscut the nappe boundaries of the Adula Nappe Complex (see border of amphibolite facies in Fig. 2). The structurally lowermost Claro Unit exhibits all of the mélange characteristics described above, but is lacking relics of HP metamorphism.

3.5.5.2. Granitic gneiss units without HP relics

Thrust sheets and slices mainly composed of granitic gneisses separate the mélange units just described. To this group belong the Argio Unit (Basal gneiss of Nagel et al, 2002b), the Groven, Gana-Palingera, and Zervreila Units. Individual metagranitoid bodies are uniform in composition, frequently form large portions of a single unit. No evidence of HP metamorphism has been found in these granitic gneisses. It is not clear whether this is due to kinetic problems in equilibrating at HP or to Barrovian reequilibration, or whether the gneiss bodies differ in their (accretion-related) P–T history from the units with HP. The granitic gneisses commonly are two-feldspar-biotite gneisses showing variable types and intensities of deformation (Jenny et al., 1923). Variability of pre-Alpine granites is evident, as two-mica orthogneiss is frequent in some localities, whereas augengneiss dominates elsewhere, indicating initially porphyritic granite. Striking in the field is the well-developed foliation of all of these gneiss units, displaying the main Alpine deformation features (Jenny et al. 1923; p. 23).

3.5.5.3. Bodengo-Gruf Unit

The southeastern part of the Adula Nappe Complex and the rocks between Valle della Mera and Bergell (Gruf complex) have been grouped into a single unit, the Bodengo-Gruf Unit. Migmatic gneisses of different protoliths dominate in this area. These migmatites are strongly folded and deformed jointly with layers of metasedimentary gneiss, amphibolite, ultramafics and marble. It is not possible to show the high variability of these migmatites and gneiss types on the map. However, we have tried to illustrate the complexities by displaying the spatial distribution of four lithologic groups: (I) metasedimentary gneisses with mafic, ultramafic and marble bodies, (II) metasedimentary gneisses without metaigneous intercalations, (III) granitoid gneisses, and (IV) two granitoid bodies (Soe and Garzelli).

In general, the metasedimentary gneisses only locally show evidence of partial melting; muscovite is widespread in them, indicating at most minor dehydration melting. By contrast, substantial parts of the metagranitoids show evidence of partial melting. These observations indicate the major importance of water-assisted melting in this region. Migmatisation in TAC units of the SSB is mostly due to Alpine partial melting (cf. Burri, 2005; Fumasoli, 1974; Hänny, 1972; Blattner, 1965). Very different, however, are the more leucocratic rocks of the Soe and Garzelli domes. These two-mica granites show locally variable An-contents of plagioclase (Blattner, 1965); textures are granitic and only locally display a weak foliation. Zircon U/Pb ages indicate a Variscan origin of these granitoid rocks (Hänny et al., 1975). However, their monazite U/Pb ages overlap with those of the Late-Alpine Novate granite (Hänny et al., 1975; Liati et al., 2000). Also, aplites and pegmatites are widespread in the Bodengo-Gruf Unit, and these are chemically and structurally related to the Novate-type granites (Blattner, 1965; Fumasoli, 1974, Hänny, 1972).

Lenses of granulite-facies rocks are hosted in migmatic gneisses of the Gruf complex. These rocks show assemblages containing sapphirine, cordierite, orthopyroxene, and garnet (Bucher-Nurminen and Droop, 1983).

The lithological difference between metagranitoid and metasedimentary gneisses has been used to reconstruct fold interference (Bruggmann, 1965; Fumasoli, 1974). Especially in the area of the Paina Schlingen Complex these regional folds are visible in map view. As shown by Nagel et al. (2002b), these are mainly interference patterns of two folding phases (Fig. 6).

3.6. The European domain

The European part of the Lepontine Alps consists of a pre-Alpine basement, locally with its sedimentary cover. The basement essentially comprises three groups: (I) rocks having been involved in two or more orogenic cycles, mainly migmatic gneiss, metasedimentary gneiss and amphibolites; we refer to this group as the *polycyclic basement*; (II) older metagranitoids (mainly Lower Paleozoic in age); and (III) Upper Paleozoic metagranitoids. Lithostratigraphic relationships within the European basement are best preserved in the Gotthard Nappe and are therefore described extensively in that context (see chapter 3.6.7). Because of their close lithological similarity, the description of the basement within the other nappes (Leventina, Lucomagno, Simano, Antigorio, Sambuco, San Giorgio, and Soja) is only briefly sketched with some emphasis on local particularities. The (meta)sedimentary cover units include remnants of Upper Paleozoic and Lower Mesozoic series. (Note that only for post-Jurassic strata is it appropriate to speak of a true European margin, separated from the Briançonnais by the Valais Ocean; Fig. 5).

3.6.1. Metasediments derived from the European domain

Intense folding and wedging, and the metamorphic overprint, which reached lower amphibolite-facies conditions, have severely obscured the original lithostratigraphic relationships. Only few of the sequences have been interpreted as autochthonous with respect to their crystalline substratum, whereas the majority are clearly allochthonous. Our map distinguishes the following units (following Bianconi, 1971, Probst, 1980; Etter, 1987; Steinmann, 1994, see also Fig. 5):

– Allochthonous Jurassic to Cretaceous calcareous micaschist units (Bündnerschiefer) of the San Giacomo, Lebendun, San Giorgio–Molare–Dangio, Piz Terri-Lunschania and Gotthard Units.

– Autochthonous and allochthonous Triassic metasediments related to the European basement (Gotthard, Lucomagno, Simano, Sambuco, Antigorio, San Giorgio and Soja Units)

– Autochthonous clastic metasediments of probable Upper Carboniferous and Permian age.

3.6.1.1. Metasediments derived from Jurassic to Cretaceous protoliths

Lower Jurassic sequences were deposited on the subsiding European plate. Their substrate is made up of large-scale tilted blocks, which developed during rifting (Baumer et al., 1961; Probst, 1980; Etter, 1987; Steinmann, 1994; Stampfli and Marchant, 1997). The map distinguishes three units (cf. Probst, 1980):

– Jurassic metasediments (calcareous micaschist) associated with the Gotthard Nappe (termed "Gotthardmassivischer Lias").

– Jurassic metasediments (Bündnerschiefer) associated with the Lucomagno, San Giorgio, and Soja Units (the "Molare-, Dangio- and Lucomagno-Bündnerschiefer" and the "Formazora-Series").

– Jurassic (and younger?) metasediments associated with the Sambuco Unit and/or the Lebendun Nappe (termed "Lebendun-Mesozoic").

These three units show a broad affinity with non-metamorphic sequences in the Helvetic realm. The sedimentary sequences related to the Gotthard Nappe (Scopi, Piora and Nufenen areas; Probst, 1980) show the best preserved stratigraphic relationships. The Jurassic strata are subdivided into three series: Stgir, Inferno and Coroi (Baumer et al., 1961). Correlations with well-dated Helvetic strata indicate a Lower Jurassic age for the entire sequence (fossils reported by Bernoulli, 1942). The Stgir Serie consists of a complex of shaly, sandy and carbonaceous sediments, locally rich in Crinoid fragments, and oolithic limestone. The Inferno Series represents a rather monotonous succession, up to 400 m thick, of dark calcareous shales intercalated with cm-thin sandstone and limestone layers (Etter, 1987). Relics of crinoids and belemnites point to a Middle Liassic age (Baumer et al., 1961; Etter, 1987). The Coroi Series consists of more than 100 m of shales with variable amounts of sandy and carbonate components. Lithostratigraphic correlations (Opalinus clay) suggest an Aalenian (lowermost Middle Jurassic) age (Baumer et al., 1961). These Middle Jurassic rocks seem to be the youngest sediments preserved in autochthonous position over the entire area.

The great variability in modal ratios between the three main sedimentary components (shale, sand, and carbonate) has resulted in a corresponding variability of metamorphic assemblages. The overprint reached lower amphibolite-facies conditions and produced rocks containing variable amounts of chloritoid, staurolite, kyanite, garnet, hornblende, zoisite/clinozoisite, biotite, muscovite, calcite, dolomite and quartz. Details on the metamorphic evolution of these rocks were described by Engi et al. (1995 and references therein).

3.6.1.2. Triassic metasediments

Triassic metasediments on top of the polycyclic basement traditionally have been subdivided into three lithostratigraphic units (Niggli, 1912; Baumer et al., 1961; Frey, 1969; Probst, 1980; Etter, 1987), by lithostratigraphic analogy with sections in the Helvetic nappes (Mürtschen and Axen Nappes):

– Arkose and quartzite (Melser sandstone): Alkali-feldspar-bearing quartzite, muscovite-quartzite, calcite and biotite-bearing muscovite-quartzite (Bianconi, 1971; Frey, 1969).

– Dolomitic marble and metaevaporite (Röti dolomite): dolomitic marble with a saccharoidal texture, talc- and/or tremolite-bearing dolomitic marble, phlogopite-bearing dolomitic marble, graphite-bearing dolomitic marble, gypsum- and/or anhydrite-bearing calcite and dolomite marble (Bianconi, 1971).

– Intense alternation of quartzite, metapelite, metamarl and thin dolomitic layers (Quartenschiefer): margarite-bearing biotite-chlorite schist, biotite-hornblende schist, kyanite- and staurolite-bearing chloritoid-two-mica schist, garnet-staurolite-kyanite-two-mica schist and garnet-biotite-plagioclase-hornblende schist (Frey, 1969).

The scarcity of useful biostratigraphic markers, even in well-preserved profiles of the Helvetic nappes, prevents an accurate chronostratigraphic allocation of the units. The quartzite (Melser sandstone) has been assigned to the Triassic and frequently represents the transition from the polymetamorphic crystalline basement to the carbonate units. The overlying dolomite and the evaporite are considered to be of Middle to Upper Triassic age. Finally, the pelitic and marly strata (Quartenschiefer) are upper Triassic in age. This stratigraphic sequence has been interpreted as the start of a marine transgression; such a paleoenvironmental evolution is characteristic of the Germanic Triassic. Locally it is difficult to distinguish the clastic Triassic from the Upper Paleozoic (Permian?) clastic metasediments topping the polymetamorphic basement.

The Triassic lithostratigraphy is generally similar in the following areas: Lucomagno, Piora, Molare, Campolungo and Dangio. The Triassic successions in contact with the basement of the Gotthard and Lucomagno Nappe (Lucomagno, Piora and Molare regions) are identical, except for changes in thickness due to tectonics. Some differences are nevertheless noteworthy. In metasediments overlying the Simano Nappe (Campolungo region), the Upper Triassic metapelites (Quartenschiefer) are absent (Bianconi, 1971; Probst, 1980), and dolomitic marbles dominate (Fig. 5). Bianconi (1971) emphasised the similarity of the Campolungo sequence with the Triassic of the Binntal area (Valais). He further indicated a link between the Triassic units on top of the Sambuco (Piz Meda) and Soja (Dangio) Units. These two Triassic sections bear unusual calcite marbles, whereas the evaporitic and the shale members are missing. These changes in depositional facies indicate a slightly different paleogeographic position for the underlying basement blocks.

Major outcrops of Triassic rocks are concentrated in the northwestern part of the map, where the Alpine metamorphism has attained conditions at the transition from greenschist to amphibolite facies. It is important to note that many classical studies on Alpine metamorphism have focussed on these rock sequences (Engi et al., 1995, and references therein).

3.6.1.3. Carboniferous and Permian metasediments

Metapsephitic and metapsammitic rocks frequently occur at the transition between the polycyclic basement and Triassic metacarbonates; they occur in different tectonic units, but they have been distinguished mostly in the Lucomagno Nappe. Quartz-rich sericitic schist, conglomeratic muscovite schist to gneiss with quartz pebbles up to 10 cm in size, graphitic quartz-rich two-mica gneiss and graphitic garnet-biotite phyllite are the main rock types. Minor kyanite and local enrichments of tourmaline complete the mineral association of these rocks; intense crenulation of fine-grained layers are structural characteristics.

Grütter and Preiswerk (1936) and Bossard (1936) proposed to relate the sericitic quartzite and conglomeratic gneiss to Permian deposits (Verrucano), whereas the graphitic schist is attributed to a Carboniferous protolith.

3.6.2. Quartzite and marble of the Leventina Nappe

Along the border to the Simano and Lucomagno Nappes, a discontinuous layer of quartzitic rocks rims the top of the granitic Leventina gneiss (Bossard, 1936; Grütter and Preiswerk, 1936; Casasopra, 1939; Bianconi, 1971; Rütti et al., 2005). Bossard (1936) interpreted these rocks as derived from Triassic sediments, whereas Grütter and Preiswerk (1936), Casasopra (1939), and Bianconi (1971) questioned their sedimentary origin, emphasizing the clear mineralogical differences between the Lower Triassic quartzite and the feldspar-rich mylonitic quartzite (containing up to 35% alkali-feldspar and 20% plagioclase) in the top of the Leventina Nappe. Similarly, two thin intercalations of calcite marble (at Freggio and Monte Piottino; Bossard, 1936; Bianconi, 1971) do not resemble Triassic carbonates. All of the authors agree, however, that the characteristic quartzite and the mylonitic zone between the Leventina and the Simano Nappe represents an important mechanical discontinuity between these two thrust sheets (Rütti et al., 2005, Timar-Geng et al., 2004). Its role as a nappe separator is most evident in the frontal parts, where the mylonitic layer extends into the Lower Triassic sequence of Rodi-Prato-Cornone (Bianconi, 1971). The same mylonitic quartzites also separate the Leventina gneiss from the Lucomagno Nappe.

3.6.3. Soja and San Giorgio Units

These units show comparable rock associations and tectonic positions, hence they are described jointly. Both units consist of metasedimentary gneisses with some amphibolite layers (polycyclic basement) followed by metapsephitic and metapsammitic schists and gneisses (detailed descriptions in Bossard, 1929, 1936; Grütter, 1928, 1936; Egli, 1966; Bianconi, 1971). The clastic metasediments – the peculiar lithostratigraphic characteristic of the two units – locally grade into clastic and dolomitic sediments of the Triassic. The Soja and San Giorgio Units have been correlated with the Lebendun Nappe (Burkhardt, 1942; Egli, 1966; Bianconi, 1971). Preiswerk (1917) emphasised lithological similarities of the San Giorgio rocks with the Tremola Serie of the Gotthard Nappe (particularly the "Hornblende-garbenschiefer"), whereas Dal Vesco (1964) suggested a link to the Lucomagno Nappe.

A more or less continuous stratigraphy from the polycyclic basement to Upper Paleozoic clastic sediments and the Lower Mesozoic carbonate sequences is preserved not only in the Soja and San Giorgio Units, but also in the Gotthard, Lucomagno, Sambuco and Simano Nappes. For the Simano Nappe, this is the case in its northern frontal region only, i.e. in the so-called Gribbio and Campo Tencia lobes (Grütter and Preiswerk, 1936). Such basement-cover transitions clearly indicate that the crystalline rocks now exposed in these units represent pre-Triassic upper crustal sections.

3.6.4. Upper Paleozoic granitoids in the Sambuco, Simano, Antigorio, Leventina Nappes

Large parts of these nappes consist of substantial volumes of Upper Paleozoic granitoids. Mainly calc-alkaline plutons were emplaced at the end of the Variscan orogeny, during the Upper Carboniferous and Lower Permian. Compositions range from granodioritic to granitic with several leucocratic two-mica granites. Many of these granitoids have been given specific local names; the Mattorello, Verzasca, Antigorio and Leventina gneisses are those most frequently cited in the literature. These gneisses have long been mined in the three main valleys (Leventina, Verzasca and Maggia) and thus have contributed characteristic architectural elements to many historic buildings.

The Mattorello gneiss occupies a large area (only partly covered by the map) in the centre of the Sambuco Unit. This biotite-rich gneiss is granodioritic in composition (Preiswerk, 1918; Günthert, 1954). As shown by isotopic relationships in the Rb/Sr and K/Ar system, the rock has been completely recrystallized during Alpine metamorphism and deformation (Steiner, 1984).

The Antigorio gneiss occurs only in a restricted area on the map; much larger masses outcrop in areas adjacent to the west, where it has been studied repeatedly (Hunziker, 1966; Milnes, 1976a; Niggli et al., 1936). This granoblastic leucocratic two-mica gneiss forms impressive walls in the central portion of the Antigorio valley, where it is more than 1000 m thick. The dominantly granitic to granodioritic biotite-gneiss is cut by a variety of leucocratic dykes. Fabrics range from granoblastic to strongly foliated; coarse-grained augengneiss exists as well as finer-grained varieties. The intrusion age of the Antigorio granitoids has been determined to be Lower Permian from zircon U/Pb data (~290 Ma, Allègre et al., 1974; Köppel et al., 1981).

The Verzasca gneiss represents the typical leucocratic granitic gneiss of the Simano Nappe. It contains both biotite and muscovite; porphyritic augengneiss varieties occur. Isotope studies on monazite and zircon established an Upper Carboniferous intrusive age for the granitic protolith (Allègre et al., 1974; Köppel et al., 1981).

The Leventina gneiss is essentially a leucocratic two-mica granitic gneiss surfacing all along the Leventina valley from Claro to Rodi-Fiesso. Casasopra (1939) described in detail the internal lithological variations and the various types of dykes crosscutting the gneiss. An imprecise Carboniferous intrusive age for the Leventina gneiss has been inferred from zircon U/Pb studies (Allègre et al., 1974; Köppel, 1993). Rütti et al. (2005) addressed the metamorphic and structural evolution of these rocks and discussed the relation between the Leventina gneiss and similar gneiss types of the Simano Nappe.

The Lucomagno Nappe seems to be devoid of Upper Paleozoic metagranitoids. This may suggest a link between Lucomagno and Leventina Nappes, in that the Leventina gneiss may contain the younger granitoid members not represented in the Lucomagno Nappe; this idea was already put forward by Grütter and Preiswerk (1936).

3.6.5. Lower Paleozoic metagranitoids in the Sambuco, Antigorio, Simano and Lucomagno Nappes

Grütter and Preiswerk (1936) distinguished older and younger metagranitoids in the basement of the crystalline nappes. This is based on preserved intrusive relationships and the different style and intensity of deformation; these inferences are shown on the map to the extent possible. These metagranitoids are commonly leucocratic, fine to medium grained quartzo-feldspatic gneisses, locally preserving a granitic texture. Most of them are characterized by biotite and two feldspars; two-mica gneisses are rare. The ages of individual bodies are not known, but a zircon age in one of these metagranitoids in the Simano Nappe indicates a protolith age of ~490 Ma (Allègre et al., 1974). A Lower Paleozoic age has also been suggested to account for the close similarity of these rocks with well-dated Upper Ordovician granitoids in the Gotthard Nappe (Sergeev and Steiger, 1993; see also chapter 3.6.7).

Two complexes outcropping in the Sambuco and Antigorio Nappes show a greater compositional spectrum. The large mass of amphibolite, hornblendite, garnet amphibolite, and meso- to leucocratic banded gneiss of the Alpe Scheggia area (Sambuco Unit; Hasler, 1949) represents the metamorphic equivalent of an intrusive suite with hornblendite, diorite, tonalite, and granodiorite. To account for the predominance of basic rocks, we show this complex as amphibolites on the map. Already Grütter and Preiswerk (1936) had suggested a Lower Proterozoic age for this basic intrusive complex; Steiner (1984) reported an Ordovician whole rock Rb/Sr reference line for these rocks.

Another complex, similar to the Scheggia complex, occurs within the Antigorio Nappe, the Albigia gneiss (Buchmann, 1953; Keller et al., 1980). It consists of a calc-alkaline intrusive suite, showing a weak zonation from gabbroic through tonalitic and granodioritic rocks to more leucocratic granitic members (Keller et al., 1980). The main rock type is a biotite-amphibole-plagioclase gneiss of tonalitic composition with a characteristic strong lineation; gabbroic and granitic types are subordinate. Leucocratic types locally show relic augen-structures (Buchmann, 1953); highly stretched xenoliths and enclaves locally produce a migmatic appearance. Early authors had associated the Albigia gneiss with the Maggia Nappe, based on their structural continuity with the Cocco Unit (Buchmann, 1953). Subsequently, the Albigia gneiss has been connected with the Antigorio Nappe (Keller et al., 1980). We have not distinguished the Albigia gneiss on the map. It outcrops at the northeastern edge of the Antigorio Nappe.

3.6.6. Polycyclic gneiss in the Lucomagno, Sambuco and Simano Nappes

The country rocks of the Lower and Upper Paleozoic granitoid intrusives are high-grade metasedimentary gneisses and amphibolites. The Proterozoic sedimentary and magmatic (for the many amphibolites) protoliths represent the oldest geological activity recognized in the Central Alps. Alpine metamorphism and deformation at amphibolite-facies conditions have obliterated almost all of the relics of Ordovician and Carboniferous orogenic imprints (details described in section 3.6.7). Migmatic structures are an exception: Variscan migmatites are widespread in the Simano Nappe (e.g. Sharma, 1969, Romer et al., 1996). Some of the strongly banded gneisses frequently occurring in the basement may represent Ordovician migmatites, which were deformed multiple times during the Variscan and Alpine orogenies.

Amphibolites and hornblende-rich gneisses are ubiquitous in the polycyclic basement; they are interlayered with metasedimentary and metagranitic gneisses. The thickness of such layers and lenses varies from a few centimeters to several hundred meters. At the scale of the map, amphibolite and amphibole-rich gneisses could be shown only in localities where they represent the dominant rock type. In the Simano Nappe, amphibolitic rocks are irregularly distributed, with large amphibolite bodies concentrated in relatively narrow trails in the northern part of the Verzasca valley. This suggests a possible separation of the Simano Nappe into two members: A northern, frontal one (the "Campo-Tencia Lappen" of Grütter and Preiswerk, 1936) dominated by metasedimentary gneisses, and a southern member with large masses of metagranitoids. A similar architecture also emerges in Val Blenio, in the northeastern part of this nappe.

Meter to decameter size lenses of ultramafic rocks occur within the polycyclic gneiss (Grütter and Preiswerk, 1936; Bossard, 1936; Trommsdorff and Evans, 1974; Pfeifer and Serneels, 1986). Mineral associations change in function of the intensity of Alpine metamorphism and/or reflect local metasomatic reactions with the country rocks (Trommsdorff and Evans, 1974). Schaltegger et al. (2002) obtained a Neoproterozoic age for the protolith of an ultramafic body at the contact between Simano and Leventina Nappe near Loderio in Val Blenio.

3.6.7. The Gotthard Nappe

The Gotthard Nappe represents a well-preserved block of European continental crust, for which the pre-Alpine history of the polycyclic basement has been unravelled (Mercolli et al., 1994 and references therein). This evolution may be regarded as a model for the evolution of the basement in the other crystalline nappes as well. The area was mapped in detail by Steiger (1962). His lithological units have been integrated into the more general lithostratigraphic subdivision of the Gotthard Nappe proposed by Mercolli et al. (1994). We distinguish the following four units:

–Late Variscan granitoids
–Middle Paleozoic metasedimentary rocks
–Late Ordovician metagranitoids
–Proto-Gotthard (pre-Upper Ordovician): Migmatitic gneiss, metasedimentary gneiss and schist, plus metabasalt, metagabbro and ultramafic rocks with an ophiolitic affinity.

Late Variscan granitoids include: (a) the granodioritic gneiss of Acquacalda, which forms an isolated slice within Triassic sediments, and (b) a small wedge of Medel granite west of Lucomagno pass. The latter discordantly cuts the E–W oriented geometry of the other lithostratigraphic units (see Merz, 1989 and petrographic descriptions therein). Early and imprecise age data constrain the emplacement of the protolith of the Acquacalda rocks at 305 to 328±30 Ma (Grünenfelder, 1963) and the Medel Granite at 303±20 Ma (Grünenfelder, 1962).

Steiger (1962) subdivided a suite of metasediments, comprising mica gneiss, hornblende schist, chlorite-mica schist (to phyllite), minor quartzite, calcsilicate, and marble, into different zones: the Pontino Zone, Zone of Sasso Rosso and Nelva Zone. These rocks underwent two stages of metamorphism at very similar conditions (lowermost amphibolite facies), which have been interpreted as a Variscan and an Alpine imprint by Steiger (1962). He thus inferred a Middle Paleozoic age for the sedimentary protoliths. By analogy, Mercolli et al. (1994) assumed such an age also for the garnetiferous micaschist zone ("Granat-Glimmerschieferzone") of the Giubine Serie.

The "Streifengneiss" derives from Late Ordovician granitoids; compositions vary from granite and granodiorite to quartz monzonite. The characteristic leucocratic bands ("Streifen") at mm- to cm-scale resulted from intense deformation of the originally coarse-grained igneous fabric. Locally, this primary fabric is preserved, whereas porphyritic domains have been deformed to augengneiss. The radiometric age of 439±5 Ma (Sergeev and Steiger, 1993) confirms the relative age derived from field relationships, showing that these granitoids intruded older metamorphic units and were subsequently intruded by Variscan granitoids.

The pre-Mid-Ordovician crystalline basement (i.e. the crustal sequence intruded by the protoliths of the "Streifengneis") consists of rocks that underwent at least three major orogenic cycles (Ordovician, Carboniferous, and Tertiary), each with polyphase metamorphic overprints at different conditions. In the area covered by the map, Steiger (1962) distinguished the following units (as summarized by Mercolli et al., 1994) in the pre-Mid-Ordovician crystalline basement:

–The "Schmitzengneise" and the "stromatische Zone" of the "Giubine Series" (i.e. strongly banded and deformed migmatite)
–The "Prato Series" and the "Corandone Zone" (mainly amphibolite and hornblende schist)
–The "Sorescia gneiss" (two-mica - albite/oligoclase gneiss)

Alpine metamorphism at lower amphibolite-facies conditions in this southern part of the Gotthard Nappe has considerably overprinted the previous mineral assemblages, in particular the eclogite and granulite parageneses of the Ordovician cycle (much better preserved in the northern part; Biino et al., 1994). Nunes and Steiger (1974) reported ages ranging from the Permian to the Meso-Proterozoic for different gneiss types of the "Giubine Series", the "Prato Series", and the "Sorescia gneiss". This confirms a pre-Ordovician origin of the sedimentary and magmatic protoliths of these series. More recently, Oberli et al. (1993), Gebauer (1990) and Gebauer et al. (1988) dated the eclogite- to granulite-facies metamorphism in basic rocks similar to the "Prato Series"; these studies show Middle Ordovician ages between 460 and 470 Ma.

3.7. Tertiary intrusive rocks

3.7.1. Bergell intrusive

The Bergell pluton is composed mainly of tonalite and granodiorite, with minor amounts of gabbro, hornblendite, and aplitic granite (Berger et al., 1996; Schmid et al., 1996a; Wenk, 1986). The tonalite predominantly consists of plagioclase, quartz, hornblende, and biotite, with minor epidote and K-feldspar (Reusser, 1987; Schmid et al., 1996a). Magmatic fabrics are preserved in the center of the tonalite pluton (east of the map), but a strong solid-state overprint characterizes the western tail of the intrusive mass (e.g. Berger and Stünitz, 1996; Davidson et al., 1996), which does appear on the map. This part was mapped in detail by Weber (1957) and Fumasoli (1974); it is commonly referred to as the Jorio tonalite. The Bergell intrusives show a typical calc-alkaline evolution, dominated by fractionation and assimilation processes (von Blanckenburg et al., 1991). The age of the Bergell intrusives was discussed by von Blanckenburg (1992) for their eastern parts, whereas Oberli et al. (2004) determined age relationships at their western end. These U–Pb and Th–Pb ages at different levels of the intrusion constrain the presence of melt over a 4 Ma interval; final solidification in the deepest parts of the crust occurred at 28 Ma (Oberli et al., 2004).

3.7.2. Novate granite and related aplites and pegmatites

The Novate granite is a two-mica leucogranite of S-type character (von Blanckenburg et al., 1991; Mottana et al., 1978), showing some variation in grain size. The main bodies are stocks and dykes in Val Mera. However, similar aplites occur over much of the SSB (Romer et al., 1996; Schärer et al., 1996). Chemical and isotopic signatures indicate that the Novate is clearly different from the calc-alkaline Bergell suite (Reusser, 1987; von Blanckenburg et al., 1991). The Novate intrusive was dated at 25 Ma using zircon SHRIMP techniques (Liati et al., 2000). Ages of 29–26 Ma (U–Pb on zircon, monazite and xenotime) have been obtained for leucogranitic dykes in the SSB further west (e.g. Gebauer, 1996; Romer et al., 1996, Schärer et al., 1996). The genetic link between aplites, *in-situ* migmatites, and the somewhat larger Novate intrusive stock has still not been completely established. However, the similarities in chemical composition and structural positions indicate an analogous evolution of these leucogranitic rocks.

4. Pre-Alpine evolution

The main traits of the pre-Alpine evolution of the units reported on the map is similar, even if these belong to different Alpine paleogeographic domains, i.e. Southern Europe, the Briançonnais or Northern Adria (e.g. von Raumer and Neubauer, 1993; Mercolli et al., 1994; Zurbriggen, 1996). Testimony of three orogenic cycles has been found in all of the major tectonic units: the oldest is Middle Ordovician (in the absence of an established paleogeographic framework, we prefer to use this temporal indication instead of the terms "Caledonian" or "Pan African"); the second orogeny (termed "Variscan") is Upper Paleozoic in age, and the latest is Cenozoic ("Alpine"). We use the term "polycyclic gneisses" for rocks of different units having experienced more than one of these orogenic cycles. In the areas shown on the map, the pre-Alpine history is best preserved in the Gotthard Nappe and in the Strona-Ceneri Zone, where the Alpine metamorphism and related deformation are not very intense. Nevertheless, under favourable conditions, some features of the pre-Alpine history have been identified also in units affected by high-grade Alpine overprint.

The major basement units (Gotthard, Lucomagno, Sambuco, Simano, Tambo, Suretta, Maggia, Sesia, Ivrea, Strona-Ceneri, and Val Colla) and the Adula Nappe Complex contain metasedimentary gneisses, the protoliths of which are of Precambrian (mostly Neoproterozoic) age. Some of the amphibolite and metaultramafic rocks in these units are likely to represent Neoproterozoic ophiolites. Clearly preserved relics of Lower Ordovician HP metamorphism, followed by Middle Ordovician HT-metamorphism, have been identified only in the Gotthard Nappe and the Strona-Ceneri Zone so far. These represent the oldest testimony of orogenic activity in the Lower Paleozoic. Metagranitoids of Upper Ordovician age (traditionally called "alte Orthogneisse") have been found in nearly all of the units. These granitic gneisses are strongly foliated and concordant with the country rocks. Locally, discordant compositional banding has been interpreted to indicate intrusive relationships. Middle and Upper Paleozoic sediments are difficult to detect in most areas. Some clastic series in the Gotthard Nappe may be of Silurian/Carboniferous age (Steiger, 1962).

The Variscan orogeny is poorly constrained in units displayed on the map. "Schlingen" structures preserved in the Gotthard Nappe and in the Strona-Ceneri Zone are clearly Variscan, as they fold the Ordovician granitoids and are crosscut by the Late Variscan intrusive bodies. These structures are related to metamorphism at amphibolite-facies conditions, probably of Middle to Upper Mississippian age. Late Variscan magmatism is ubiquitous; almost all of the basement units contain Upper Carboniferous to Permian granitoids. These rocks are slightly foliated, frequently preserving intrusive contact relationships. Coeval acid volcanic rocks are preserved in a few outcrops (e.g. eastern Gotthard Nappe, Southern Alps). Molasse-type clastic sediments of Upper Paleozoic age have been found in some units, topping the polycyclic basement (i.e., Strona-Ceneri, Gotthard, Lucomagno, Soja, San Giorgio, Sambuco, and northern Simano). In all of these units, mono-metamorphic psephitic to psammitic gneisses mark the transition from the crystalline basement to Mesozoic sedimentary sequences. We thus conclude that these units represent upper-crustal sections during the Mesozoic.

5. Alpine tectono-metamorphic evolution

5.1. Overview

The map represents the nappe edifice in the Central Alps (e.g. Schmid et al., 1996b). The formation of the nappe stack outlined above was connected to the development of the main Alpine foliation (see below). Post-nappe folding and faulting have subsequently affected the nappe stack. The frontal part of the nappes developped different fold generations related to the development of the NSB. In addition, the southernmost portion of the nappe stack, as a whole, was bent down sharply along the Insubric Line, thus forming the SSB. Therefore, it is essential to distinguish between post-nappe folding in the southern and the northern Lepontine. In the south, these deformations are well known as D3-deformation, whereas in the north a D3- and a D4-phase have been distinguished (e.g., Grujic and Mancktelow, 1996; Löw, 1987). The structures and the crystallization–deformation relations have been investigated in detail for some localities (e.g. Huber et al., 1980, Steck, 1998). The large-scale significance of these observations is debatable, as deformations vary in space in time (Fig. 7). However, some of the deformation phases mapped can be summarized and correlated with the geodynamic evolution (Fig. 7).

Additional clues to the geodynamic evolution have been inferred from the metamorphic record. The most important types of information available are: (1) relic assemblages (e.g. HP) in weakly deformed bodies; (2) Barrovian assemblages overgrowing the dominant foliation; and (3) local zones of retrogression, notably related to hydrothermal fluid circulation. By combining the information from numerous structural and metamorphic studies, four main Alpine phases of evolution have been distinguished in the Central Alps (bottom of Fig. 7): (1) deformation and metamorphism related to subduction; (2) nappe stacking and Barrovian metamorphism; (3) post-nappe folding, and (4) localized faulting and hydrothermal activity.

5.2. The Periadriatic Lineament

The Periadriatic Lineament is a major tectonic boundary, which has been active from the Cretaceous to the present. The term Periadriatic Lineament is a general term for localized deformation, with different branches and variable kinematics (see Schmid et al., 1989). In the area of the map, the Tonale and Canavese Lines are represented and generally referred to as the Insubric Line. Schmid et al. (1987, 1989) have investigated its kinematic evolution in some detail. Along the western Tonale Line, combined backthrusting and dextral strike-slip have been inferred. The amount of vertical offset changes along the strike of the Tonale Line, and a strike–slip component is evident all along the Tonale Line. The transfer from vertical plus strike–slip movements to mainly strike–slip movements occurs along the eastern contact of the Bergell pluton. The Tonale and Canavese Lines are the locus of backthrusting in the middle crust, but deformation continues into the greenschist facies, with brittle deformation along the Tonale Line. This younger activity is what has been mapped early (e.g. Cornelius and Furlani-Cornelius, 1930; Lardelli, 1981), but the Insubric Line has a protracted history, and the variable distribution of vertical and strike–slip movements over time is still not completely understood (see Handy et al., 2005). Uncertainties exist about the delimitation of the ductile part of the Insubric Line, and different interpretations have been given for this major shear zone (e.g., Nagel et al., 2002b; Handy et al., 2005).

5.3. Metamorphism and deformation during subduction

Low- to medium-T HP rocks are primarily found in the mélange units and in a few of the Bündnerschiefer units. We mainly distinguish a blueschist-facies metamorphism in the metasediments of the

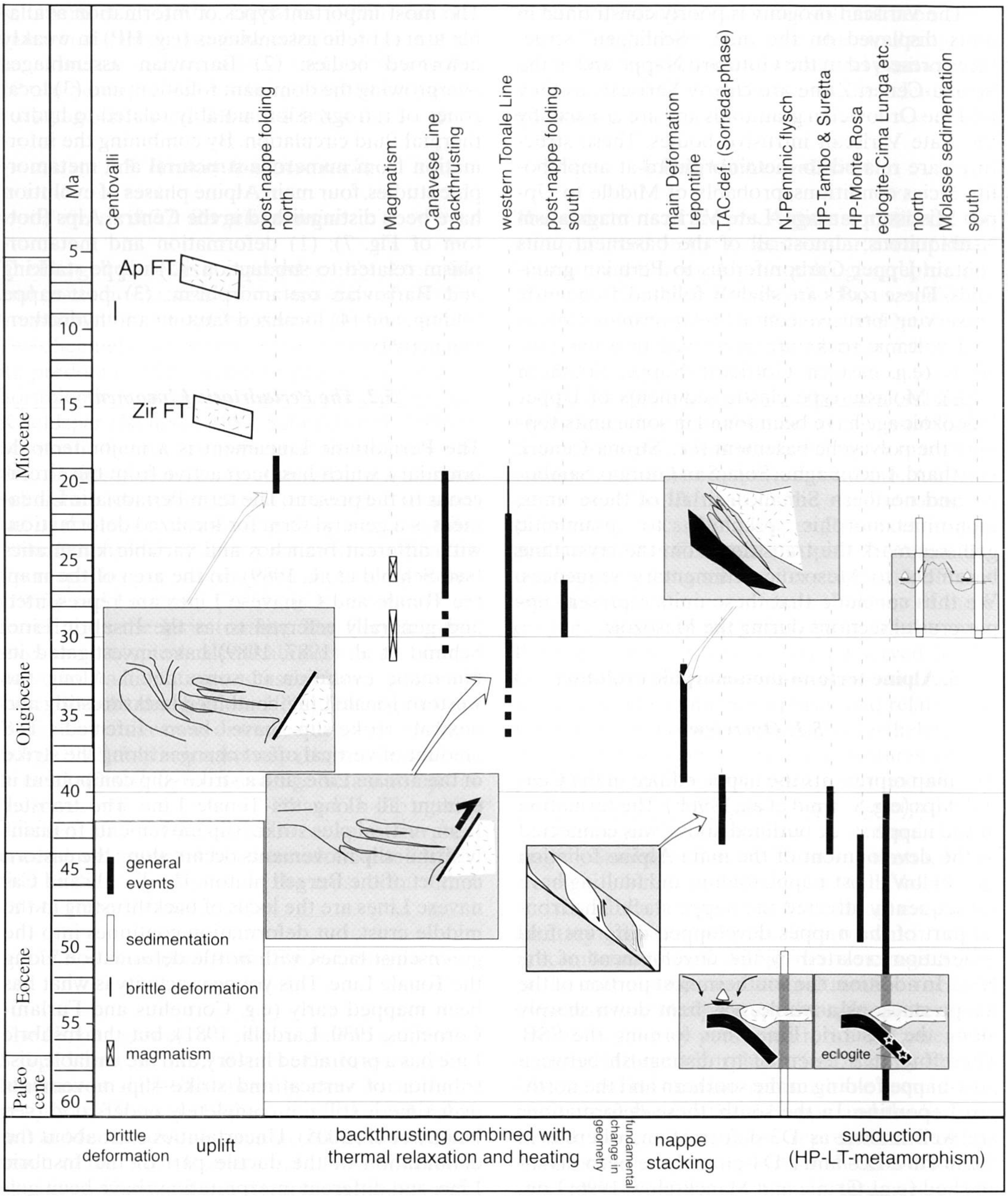

Fig. 7 Timetable of the geodynamic evolution, summarizing the different phases reported in the literature.

Valais Ocean and an eclogite-facies metamorphism in the TAC units (Engi et al., 2004). In the Bündnerschiefer, Fe–Mg-carpholite occurs as relics in quartz-carbonate segregations, whereas chloritoid is rock-forming (Bousquet et al., 2002; Goffé and Oberhänsli, 1992; Oberhänsli et al., 2003). In addition, sodic amphiboles are widespread, but these amphiboles are rich in Mg and Fe^{3+} (Bousquet et al., 1998). Carpholite-bearing rocks indicate conditions in the range of 350°–400°C and 1.1–1.4 GPa (Bousquet et al., 2002). In the deeper crust, the eclogites in the TAC units preserve conditions between ~1 GPa (at 450°C) in the north and 2–2.5 GPa (at 750–800°C) in the south (e.g. Dale and Holland, 2003; Heinrich, 1982). Even higher pressures have been documented for metaperidotites (e.g. Nimis and Trommsdorff, 2001; Pfiffner and Trommsdorff, 1998). Some of these metaperidotites record first an exhumation in an oceanic setting, followed by subduction (HP metamorphism), and renewed exhumation with the entire nappe stack. Other fragments may have flowed up from mantle depth. The eclogites represent oceanic fragments, which were subducted at the beginning of the thermal relaxation (due to decreasing subduction rates) and subsequently extruded (Roselle et al., 2002). The age of the HP stage in the Central Alps is constrained by the beginning of its exhumation between ~70 and 40 Ma (Becker, 1993; Gebauer, 1996; Gebauer, 1999; Brouwer et al., 2005). Two types of deformation structures can be connected with these processes: (1) thrusting of internal Mesozoic sediments into the basement (Sorreda phase of Löw, 1987); and (2) eclogite-facies foliations inside eclogite boudins (Grond et al., 1995; Meyre and Puschnig, 1993; Tóth et al., 2000). Along the suture with down-going and upward flowing fragments, additional deformation is very likely to have occurred (see description of the internal Mesozoic; Jenny et al., 1923). These slices are responsible for the internal structure of the Adula Nappe Complex (see chapter 3.5.5) and may account for isolating various HP remnants of the Cima Lunga Unit and the Zone of Someo, which occur strung out along the contacts between several of the massive crystalline thrust sheets.

5.4. Metamorphism and deformation during nappe stacking

In most areas, the major foliation is a composite foliation, which has been related to one or two deformation phases. D1 is the major deformation producing a first foliation in the units. Any related folds are relics, and not much can be said about their exact geometry. Folds and faults overprint this first foliation. The second deformation shows intense folding in areas of large competence contrast (e.g. near nappe divides), whereas inside granitic gneisses only weak deformations have been reported (Rütti, 2003). However, these deformations are more or less contemporaneous with Barrovian metamorphism, and the relations between geodynamic movement and (re)crystallization/equilibration of minerals during Barrovian metamorphism vary in space and time. The reason may be heat transfer associated with (advective) tectonic movements, local heat sources/sinks (e.g. shear heating, Burg and Gerya, 2005) and the conductive relaxation of isotherms due to decreasing plate convergence rates. The complex interaction of these different factors is most important along plate boundaries involving the TAC units (Engi et al., 2001a; Roselle et al., 2002; Brouwer et al., 2004). In any case, the major deformation in the southern Lepontine is characterized by syn- to post-kinematic Barrovian metamorphism (e.g. sillimanite lineations occur only in the south). In the northern Lepontine, some of the Barrovian mineral growth occurred later than the major penetrative deformation. This diachronism is also evident in monazite equilibration ages documented in the south and the north (e.g. Köppel et al., 1981). The differences between deformation and crystallization relations are related to the spatial-temporal movements of isotherms during thermal relaxation and backthrusting. This relaxation started just prior to collisional extrusion of subducted tectonic masses (at ~40 Ma), producing different P–T paths in TAC units with their deep-seated fragments, in comparison to the frontally accreted wedge (Goffé et al., 2003; Roselle et al., 2002).

5.5. Post-nappe deformation in the southern Lepontine

The youngest phase of the important ductile deformations in the area is the post-nappe folding (see also Berger et al., 1996; Nagel et al., 2002b). It is characterized by open, locally asymmetric folds, which affect the already established nappe stack (Figs. 6, 7; see also Nagel et al., 2002b). Although this folding was of minor influence to the metamorphic history and post-dates the major thrusting, these folds have a remarkable effect on the geometry as seen in map view or in sections (Figs. 2 and 6). Post-nappe folds are large-scale folds changing from open, with N–S striking fold axial planes, to strongly asymmetric, tighter folds with E–W striking axial planes (Fig. 2). In the south, these types of folds developed at amphibolite-facies conditions; they have little impact on the crystallization textures, as no new foliation developed. Best interpretable age relations between post-nappe folds and metamorphic features are due to some of the Tertiary granitic dykes, which are partly folded and partly crosscut these folds. These intrusives have been dated between 28 and 25 Ma (Romer et al., 1996; Schärer et al., 1996). In the area between Bellinzona and Val Onsernone, this type of folding is connected with partial melting (Burri et al., 2005). At a regional scale, some of the major folds are the

Cressim and the Verzasca antiforms in the southern Lepontine, with amplitudes of several hundred meters. Steck (1998) and Maxelon and Mancktelow (2005) discussed post-nappe folds more extensively.

5.6. *Post-nappe folding in the northern Lepontine*

The metasediments of the NSB have been thrusted and folded repeatedly. These deformations affected the Valais units as well as the European nappes. In detail, the geometry of the folded nappe stack changes from east to west (e.g. Frey, 1967). The principal structure responsible for the formation of the NSB is the Chiera synform (e.g. Milnes, 1974, 1976b; Etter, 1987). Various parasitic structures have been reported within frontal parts of the nappes, which are most likely related to the same deformation (e.g. the Carassino phase of Löw, 1987). Similar types of folds developed further west; they are best visible in the Campolungo area, where they are related to deformation in the Sambuco Unit (Bianconi, 1971). The particular lithological variations and the interpretation of the older structures in this area are still being debated (e.g. Bianconi, 1971; Gruijc and Mancktelow, 1996; Steck, 1998; Maxelon and Mancktelow, 2005).

5.7. *Localized low-grade deformation and hydrothermal activity*

The regionally youngest structures are brittle faults at greenschist-facies (and lower) conditions, which clearly overprint the nappe stack. An important late part of exhumation of the Central Alps was accommodated by such brittle structures (e.g. Centovalli Line: Knup, 1958; Surace, 2004, Forcola Line: Meyre et al., 1998). The timing of brittle to semi-brittle fault activity varies (see fission track data by Rahn, 2005; Hurford et al., 1989; Wagner et al., 1977). In several cases, these faults are N–S and ENE–WSW striking. In some areas, the cataclastic faults have been mapped in detail by combining field observations and aerial photographs (e.g., Surace, 2004; Grond et al., 1995; Fumasoli, 1974; Kobe, 1966; Zawadynski, 1952). In other cases cataclastic faults of low local offset have been overlooked. In view of the heterogeneous distribution of observations on these faults and to preserve the readability of the map, only few of these faults (those known to have large offset) are shown for illustration. However, they are of geotechnical importance and are well visible in the field.

During exhumation, brittle deformation in combination with hydrothermal fluid flow has produced fissures and the famed mineralized Alpine clefts. From north to south, open fissures preserve a record of increasing T, and multiple phases of fluid flow produced low-T overgrowths on early cleft minerals (e.g. Mullis et al., 1994). In the south, open fissures occur but on the late retrograde path, whereas fluids at higher grade produced nodules ("Knauer"; Allaz et al., 2005; Kerrick, 1988; Klein, 1976). The distribution of alumosilicate polymorphs within these nodules is regionally not very systematic, but sillimanite-bearing ones are more widespread in the south, whereas kyanite dominates in the north. The occurrence of kyanite and andalusite in the southern part indicates protracted hydrothermal activity with multiple stages. Purdy and Stalder (1973) and Sharp et al. (2005) suggested that hydrothermal cleft minerals in the northern Lepontine formed as early as 17–15 Ma ago and are thus barely younger than the Barrovian peak metamorphism in this region.

6. Controversies and open questions

The geodynamic evolution of the Lepontine Alps is still far from fully understood, and several open questions remain. We single out a few of them, which directly affect the map, and discuss these below.

6.1. *The Sambuco problem and the position of the Maggia Nappe*

The position of the Maggia Nappe in the Alpine nappe stack represents a longstanding controversy (e.g. Kündig, 1936; Fig. 3). Field observations in the north and in the south of the Lepontine Alps – and the relations between them – have been interpreted differently. Most authors assume that the Sambuco Unit is part of the Maggia Nappe (Spicher, 1980). This is owing to the connection between the Triassic metasediments north of Fusio (Mogno metasediments) and the Pertusio Trail. There are two major arguments against connecting these two metasedimentary units: (1) the Mogno metasediments are carbonates, whereas the Pertusio Unit is dominated by quartzites and metaclastic rocks; (2) the Pertusio Unit terminates with a fold around the Cocco Unit of the Maggia Nappe (Keller, 1968; Keller et al., 1980). This steep fold closes in the opposite direction to the fold terminating the Mesozoic sediments at Mogno. Moreover, a few basement rocks have been mapped between the Mogno sediments and the Pertusio Unit. These field observations certainly do not suggest a connection between the Sambuco Unit and the Maggia Nappe *sensu stric-*

to. In our view, the Maggia Nappe *sensu stricto* appears to end in that area, where it is in steep contact with the Variscan basement of the Simano Nappe (as already proposed by Keller et al., 1980).

The position of the Sambuco Unit – notably the Sambuco basement – has several consequences for the interpretation of the nappe stack (see next chapter and Fig. 3). Gruijc and Mancktelow (1994) suggested that the Sambuco Unit must have been located below the Simano Nappe, which is in contrast to earlier constructions (e.g. Heim, 1922; Bianconi, 1971) and the new structural model of Steck (1998). In the south, the position of the Maggia Nappe *sensu stricto* is clear: The Maggia Nappe structurally overlies both the Cima Lunga Unit and the Simano Nappe (Bächlin et al. 1974; Spicher and Wenk, 1981; Leonardi, 2003; Figs. 3, 4).

6.2. The discussion of equivalent tectonic positions

Discussions of the correlation of Alpine nappes are as old as the Alpine geological research (see summary in Kündig, 1936; Staub, 1958, Figs. 3 and 4). It must be kept in mind that most nappes (and other major units) do not show their lateral end. Different nappes thus may have the same tectonostratigraphic position, even if they are not the "same" nappe (cf. Fig. 6). Of major help in lateral reconstructions are former plate boundaries. In part, these former plate boundaries are ophiolitic sequences, elsewhere they are mélange units (TAC). The nappe correlation underlying this contribution is shown in Figure 4.

One of the deepest tectonostratigraphic nappes shown on the map is the Leventina nappe, which is overlain by the Simano nappe. In the southern Verzasca valley, the Cima Lunga Unit separates the Simano Nappe from the overlying Maggia Nappe (see Maxelon and Mancktelow 2005 for an alternative view). The Maggia Nappe is then separated from the structurally deeper Antigorio Nappe by the Zone of Someo. This indicates that the Antigorio Nappe may have the same tectonic position as the Simano Nappe (see Fig. 4). To the east, the Adula Nappe Complex – a tectonic equivalent of the Cima Lunga Unit – overlies the Simano Nappe. The Tambo and Suretta Nappes follow on top of the Adula Nappe Complex. The Avers Nappe is tectonically on top of the Suretta Nappe (e.g., Staub, 1926) and is thought to represent sediments of the Piemont-Liguria Ocean. The Tambo, Suretta, Maggia and Monte Rosa Nappes are situated above the mélange zones and below remnants of the Piemont-Liguria Ocean (Chiavenna Ophiolite Zone and Zone of Zermatt-Saas Fee). This indicates that they belong to the same paleogeographic realm. The portion of the Monte Rosa Nappe visible on the map is in subvertical position, and its tectonic position is not completely clear. However, considering the post-nappe folds of the Central Alps, the Maggia and the Monte Rosa Nappe should occupy the same tectonic position (see also Burri, 2005).

In the frontal part of the nappe stack, some basement fragments (Lucomagno, San Giorgio, Sambuco, and Soja Units) occur almost completely isolated inside their sedimentary cover. These basement units have uncertain tectonic positions and seem to lie in front of the Simano and Antigorio Nappes. This problem is best illustrated by the Lucomagno Nappe: It has an equivalent position as the Leventina Nappe relative to the Simano Nappe, i.e. both are located below the latter, but the Lucomagno Nappe in part overlies the Leventina Nappe. This suggests decoupling between the Leventina and Lucomagno Nappes at some stage. In our view, this is related to early thrusting in the frontal part of the crystalline blocks, which allowed detachment of basement slices and juxtaposition with their own (previously imbricated) Mesozoic sedimentary cover. A similar situation may be suggested for the Simano Nappe as well: Its frontal part (in the Campo Tencia region) may have been overthrusted by the more southern portion, which shows a markedly different lithological composition. We note that earlier authors referred to these units as lobes ("Lappen") of the respective nappes (e.g., Campo Tencia lobe of the Simano Nappe; Grütter und Preiswerk, 1936; Sobrio lobe of the Simano Nappe; Bossard, 1936).

In sedimentary units of the NSB we have distinguished units belonging to the Valais Ocean (Grava-Tomül Nappes) from sediments of the European margin (Gotthard, Piz Terri-Lunschania, San Giorgio, Dangio, Molare, and Lebendun Units). The substratum of the latter sediments remains unclear, as unequivocal stratigraphic basement-cover relationships are rare. The thrust of the Grava Nappe onto sediments of the European margin represents the "Penninic front" (e.g., Frey, 1967). When following this major boundary to the west, the Zone of Sion-Courmayeur represents the sediments of the Valais Ocean, whereas the sediments of the European margin are related to the Gotthard, Lebendun, and Monte Leone Nappes (Steck et al., 1999, 2001).

6.3. The tectonic window near Lostallo

Kündig (1926) mapped the western flanks of the upper and middle part of Val Mesolcina (Misox).

He assigned the gneiss unit surfacing near the valley bottom, around the village of Lostallo, to the Simano Nappe rather than the Adula Nappe Complex, which builds up the upper parts of the surrounding mountains. He used a narrow band of granitic gneiss to separate the metasedimentary gneiss of the Simano Nappe from granitic gneisses of the Adula Nappe Complex. Bellin (1929) mapped the eastern part of the valley in the region of Lostallo and used similar criteria (i.e. a band of granitic "injection gneiss") to separate these tectonic units. These two maps thus isolated the window of Lostallo, with the Simano Nappe in the valley bottom, completely surrounded by the tectonically higher Adula Nappe Complex. Whereas this interpretation was adopted for the first edition of the Tectonic Map of Switzerland (Spicher, 1972), the window of Lostallo no longer appeared in the second edition (Spicher, 1980). Recently, Nagel et al. (2002b) remapped the western side of the window of Lostallo, with special emphasis on structural relationships. Nagel et al. concluded that, at least for the western margin, the interpretation of Kündig (1926) was correct; they did not clarify how the structure continues to the east, but they tentatively suggested that the Simano Nappe might continue into the region of Val Bodengo. Unfortunately, the strongly migmatic gneiss in Val Bodengo does not help much in resolving this question (Hänny, 1972). Hänny, as Bellin (1929) before him, had doubts to assign the rocks between Piz Cressim and Valle della Mera to the Simano Nappe. In view of these controversies, the decision adopted for the present map is based on the classic interpretation of Kündig (1926) and Bellin (1929), i.e. the window of Lostallo has been reintroduced. The limits shown agree entirely with Nagel et al. (2002b) in the NW, whereas they are slightly modified in the SE upon reconsideration of the maps by Bellin (1929) and Bruggmann (1965).

7. Summary of the evolution

The Alps include a Cretaceous and a Tertiary orogeny (e.g. Froitzheim et al., 1994; Stampfli et al., 2002; Schmid et al., 2004). The Cretaceous orogeny is related to the closure of the Meliata-Hallstadt Ocean. During this phase, west-directed thrusting dominated and resulted in a thickened Adriatic crust, which includes oceanic fragments. This orogeny is mainly preserved in the Eastern Alps. In the area of our map, this orogenic lid has been entirely removed by erosion and tectonic unroofing. The Tertiary orogeny is related to subduction of the Piemont-Liguria and Valais Oceans, followed by continent-continent collision. The initially asymmetric shape of these oceans and the lateral termination of the Briançonnais led to a coupled evolution of these lithospheric units during the Tertiary. The Tertiary orogeny resulted from north-directed movements in the Central Alps (i.e. different from the Western Alps). The general setup for the Tertiary evolution can be summarized as three processes:

(1) **Subduction of oceanic crust(s):** detachment of sediments from their substratum, development of blueschist facies in the accretion wedge and internal deformation along the plate boundary, development of mélange units along the plate margin.

(2) **Continent-continent collision:** extrusion of HP fragments to mid-crustal level and incorporation of larger mélange units into the nappe stack.

(3) **Exhumation processes:** localized shear zones related to backthrusting and orogen-parallel normal faulting.

The Piemont-Liguria and Valais Oceans developped passive margins during rifting and show a sedimentary evolution from transgression to deep-sea deposits (chapters 3.4 and 3.6). The subduction history in the Tertiary involved the Piemont-Liguria and the Valais Ocean (relics of basaltic crust and peridotite from both domains have been preserved). One important question is whether the two oceans were subducted in sequence along the same subduction surface, or whether subduction occurred contemporaneously along two subduction zones. In the first case the HP metamorphism should be heterochronous, while in the second it may have a continuous age spectrum. Constraints on the timing of the subduction scenario rest on paleontological observations within the frontal accretionary wedge (Bousquet et al., 2002) and on isotopic ages of eclogites (e.g. Lapen et al., 2003; Brouwer et al., 2005). While the HP ages remain imperfectly constrained, they do not so far indicate a significant temporal difference between fragments attributed to the Piemont-Liguria Ocean and those derived from the Valais Ocean. The timing of subduction is better defined in the Tauern window, where only one ocean existed, and HP ages range between 57–39 Ma (Ratschbacher et al., 2004). This age interval overlaps with the HP data obtained from the Zone of Zermatt-Saas Fee (Piemont-Liguria: Lapen et al., 2003), from the TAC units (Valais and/or Piemont-Liguria: Brouwer et al., 2005), and from the Monte Rosa Nappe (Briançonnais: Lapen et al., 2004).

During subduction, most sediments were stripped off from their substratum, imbricated in front, and accumulated as an accretionary wedge; their relics are now found in front (i.e. north) of the continental basement nappes. Minor remnants derived from the sedimentary cover sequences have been strung out along nappe boundaries of the basement thrust sheets (nappe divides) or deeply subducted and accumulated in the TAC. After closure of the oceans, continent-continent collision led to thickening of the crust in the lower plate, at the same time as slices of the TAC (mélange units) became incorporated in the Lepontine nappe stack. Slab-breakoff has been proposed as a likely mechanism to account for reversal of mass flow along the slab interface and initiation of late-stage plutonism (von Blanckenburg and Davies, 1995; von Blanckenburg et al., 1998).

The processes involved extrusion of HP fragments along the plate boundary, from mantle depths to mid-crustal levels. After development of the main nappe stack, the orogenic domain experienced backthrusting, accompanied by late-stage folding. A substantial change in geometry of the orogen during the Miocene has been deduced from the structural inventory and the foreland-basin sediments (e.g. Pfiffner et al., 2002; Schlunegger, 1999). Simultaneously with the relaxation of the isotherms from their subduction geometry, the continental material accreted along the plate boundary started to add heat to the exhuming nappe stack (Engi et al., 2001a; Roselle et al., 2002), and a brief additional heating spike may have been induced at mantle levels following slab-breakoff (Brouwer et al., 2004).

The principal record of these thermal processes is the Barrovian metamorphic field gradient (Todd and Engi, 1997), which was established diachronously at the scale of the Lepontine Alps (e.g. Engi et al., 1995). Subsequent deformation was localized into faults, with backthrusting along the Insubric Line and a series of normal faults parallel to the orogen.

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New Map:

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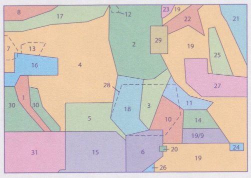
Compiled by:
Alfons Berger and Ivan Mercolli

1:100 000

TOPOGRAPHY: NATIONAL MAP OF SWITZERLAND 1:10

Map sheet **43 Sopra Ceneri**

Maps used for compilation



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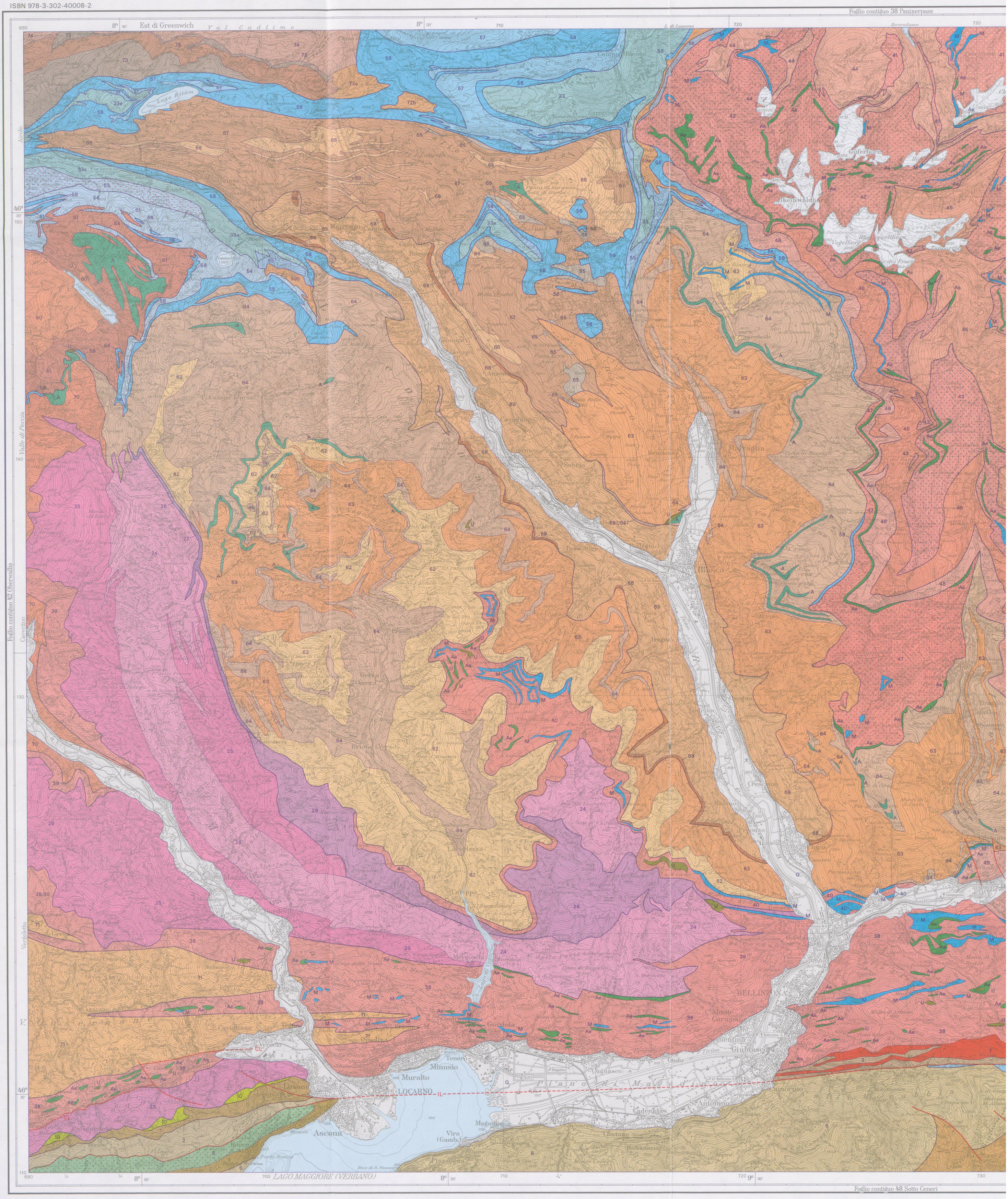

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THE CENTRAL LEPONTINE ALPS

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Adria

Sesia Zone

1	Polycyclic gneisses of various compositions, amphibolite and ultramafic rock

Canavese Zone

2	Gneisses of various compositions and layers of calcareous schist, mainly mylonitic

Tonale Series

3	Mylonite of metasedimentary, mafic and granitic protoliths

Val Colla Zone

4	Mainly dolomite with subordinate calcareous sediment *Triassic*
5	Polycyclic gneisses of various compositions and amphibolite

Strona-Ceneri Zone

6	Polycyclic gneisses of various compositions and amphibolite

Ivrea Zone

7	Polycyclic high-grade gneiss: «Kinzigite» *Paleozoic*
8	Metagabbro and metadiorite: Mafic Complex *Paleozoic*

Piemont-Liguria

Avers Nappe

9	Calcareous micaschist *Jurassic–Cretaceous*

Zone of Zermatt-Saas Fee

10	Metagabbro, ultramafic rock and gneiss

Briançonnais

Schams Nappes

11	Low-grade metamorphic calcareous and siliciclastic sediment, dolomite, evaporite, breccia and flysch *Triassic – Late Cretaceous*

Areua-Bruschghorn Zone

12	Low-grade metamorphic siliciclastic and calcareous sediment, dolomite, evaporite *(Carboniferous–Triassic)* interlayered with gneiss

Knorren Mélange

13	Calcareous micaschist, quartzite, gneiss, marble and greenschist

Suretta Nappe

14	Metacarbonate *Triassic*
15	Quartzite *Triassic*
16	Metapsammitic to metapsephitic gneiss *Permian*
17	Postvariscan granitoid: [17a] Rofna Porphyry *(268 Ma, Marquer et al. 1998)*
18	Polycyclic gneisses of various compositions and amphibolite

Tambo Nappe

19	Quartzite and metacarbonate *Triassic*
20	Metapsammitic to metapsephitic gneiss *Permian*
21	Postvariscan granitoid: [21a] Truzzo Granite *(268 Ma, Marquer et al. 1998)*
22	Polycyclic gneisses of various compositions and amphibolite

Monte Rosa Nappe

23	Two-mica porphyric, granitic gneiss: Monte Rosa Gneiss *(280 Ma, Frey et al. 1976)*

Maggia Nappe

Cocco Unit

24	Mesocratic biotite gneiss with biotite nests: Cocco Gneiss *(275 Ma, Köppel et al. 1980)*. Leucocratic granitic gneiss: Ruscada Gneiss *(240–250 Ma, Köppel et al. 1980)*
25	Polycyclic gneisses of various compositions and amphibolite

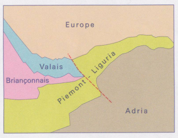
Pertusio Unit

26	Strongly deformed granitic and metasedimentary gneiss: «Pertusio Zug»
27	Banded gneiss

Vogorno Unit

28	Polycyclic gneisses of various compositions and amphibolite: Gaggia Unit. Two-mica granitic gneiss: Vogorno Gneiss

Scetch of the paleogeographic situation in the Early Cretaceous



Valais

Chiavenna Ophiolite Zone

29	Marble
30a	Metabasalt *Jurassic–Cretaceous*
30b	Metagabbro *Jurassic–Cretaceous*
31	Metaperidotite

Tomül Nappe

32	Calcareous micaschist, metapelite and metabasite *Cretaceous*

Grava Nappe

33	Calcareous micaschist, metapelite and metabasite; [33a] Piora, Molare and Leventina units: «Sosto Schiefer» *Cretaceous*

Grava-Tomül Mélange

34	Breccia, quartzite, marble and metabasite: «Gadriolzug» *Jurassic*

Aul Nappe

35	Metasediment, metabasalt (pillow lava) and serpentinite; *Triassic–Jurassic*

Paleogene Tectonic Accretion Channel

Paleogeographically heterogeneous fragments accreted at depth along subduction boundary

Upper Vals Mélange

36	Mainly calcareous micaschist and greenschist *(probably Jurassic)* interlayered with rare dolomitic marble *(Triassic)* and gneiss

Lower Vals Mélange

37	Dolomitic marble, subordinate calcareous micaschist and greenschist *(Triassic–Jurassic)* interlayered with gneiss

Southern Steep Belt

Zones of Bellinzona-Dascio, Arbedo-Mergoscia and Orselina

38	Various gneisses with lenses and layers of eclogite, amphibolite, marble and ultramafic rock

Zone of Someo

39	Various gneisses with lenses and layers of eclogite, amphibolite, marble and ultramafic rock

Cima Lunga Unit

40	Various gneisses with lenses and layers of eclogite, amphibolite, marble and ultramafic rock

Adula Nappe Complex

Fanella Unit

41	Various gneisses with lenses and layers of eclogite, amphibolite, marble and ultramafic rock

Trescolmen Unit

42	Various gneisses with lenses and layers of eclogite, amphibolite, marble and ultramafic rock

Soazza Unit

43	Various gneisses with lenses and layers of eclogite, amphibolite, marble and ultramafic rock

Zervreila Unit

44	Mainly granitic gneiss and banded gneiss (without eclogite boudins)

Gana-Palingera Unit

45	Mainly granitic gneiss and banded gneiss (without eclogite boudins)

Groven Unit

46	Mainly granitic gneiss and banded gneiss (without eclogite boudins)

Claro Unit

47	Gneiss with lenses of amphibolite, marble and ultramafic rock

Argio Unit

48	Granitic gneiss: «Basalgneis»

Bodengo-Gruf Unit

49	Metasedimentary gneiss
50	Gneiss with lenses of eclogite, marble and ultramafic rock
51	Two-mica granite: [51a] Soe Granite, [51b] Garzelli Granite *(Zir: 250 Ma, Mzt: 22 Ma, Hänny et al. 1975)*
52	Migmatite and granitic gneiss: [52a] Val Bodengo area, [52b] Gruf Complex

Europe

Jurassic to Cretaceous metasediments

San Giacomo Unit

53	Calcareous micaschist and quartzite *Jurassic–Cretaceous*

Lebendun Nappe

54	Calcareous micaschist and quartzite *Jurassic–Cretaceous*

San Giorgio, Molare and Dangio Units

55	Calcareous micaschist and quartzite *Jurassic–Cretaceous*

Piz Terri-Lunschania Zone

56	Calcareous micaschist and quartzite *Jurassic*

Gotthard metasedimentary Unit

57	Calcareous micaschist and quartzite *Jurassic*

Triassic metasediments

58	Quartzite, meta-evaporite, dolomitic marble, metapelite, locally metaconglomerate

Soja and San Giorgio Units

59	Metapsammitic to metapsephitic gneiss: [59a] Soja Unit, [59b] San Giorgio Unit

Sambuco Unit

60	Granitic gneiss: Matorello Gneiss *Late Paleozoic*
61	Polycyclic gneisses of various compositions and amphibolite

Simano Nappe

62	Two-mica granitic gneiss: Verzasca Gneiss *(300 Ma, Köppel et al. 1980)*
63	Granitic gneiss *(~490 Ma, Allègre et al. 1974)*
64	Polycyclic gneisses of various compositions and amphibolite

Lucomagno Nappe

65	Metapsammitic to metapsephitic gneiss *Late Paleozoic*
66	Granitic gneiss
67	Polycyclic gneisses of various compositions and amphibolite

Leventina Nappe

68	Metasediment, mainly quartzite
69	Two-mica granitic gneiss: Leventina Gneiss *(300–225 Ma, Allègre et al. 1974)*

Antigorio Nappe

70	Mesocratic granitic-granodioritic gneiss: Antigorio Gneiss *(300–225 Ma, Allègre et al. 1974)*

Zone of Onsernone

71	Migmatite and granitic gneiss with local basic rock

Gotthard Nappe

72	Granitic gneiss: [72a] Cristallina Granite, [72b] Selvasecca Granite *(305/328 Ma, Grünenfelder 1963)*
73	Metasediments: «Tremolaserie» *Middle Paleozoic*
74	Two-mica granitic gneiss: «Streifengneis» *(439 Ma, Sergeev & Steiger 1993)*
75	Polycyclic gneisses of various compositions and amphibolite: «Pratoserie» and «Soresciaserie»

Quaternary

Q	Undifferentiated alluvial and glacial sediments

Tertiary intrusive rocks

N	Two-mica granite: Novate Stock *(25 Ma, Liati et al. 2000)*
G	Bergell Granodiorite *(30 Ma, von Blanckenburg 1992)*
T	Bergell Tonalite *(32–28 Ma, von Blanckenburg 1992, Oberli et al. 2004)*

Layers and lenses of tectonically undifferentiated rocks

M	Marble
U	Ultramafic rock
Ae	Amphibolite-rich layers commonly with eclogitic relics
A	Amphibolite-rich layers in polycyclic basement

Structural elements

──	Limit of tectonic units
── - -	Fault (CL: Centovalli Line; FL: Forcola Line, IL: Insubric Line)

Tectonic overview 1:700000