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Geology of the Monte Rosa massif: historical review and personal comments

by *Giorgio Vittorio Dal Piaz*[1]

Abstract

This paper reviews two centuries of geological work on the Monte Rosa massif, Western Alps, from de SAUSSURE's exploration and systematic mapping by GERLACH and the Italian Geological Service, to BEARTH's fundamental contribution, subsequent developments on surface to subsurface geology, and debated paleostructural restorations. The Monte Rosa massif is modelled within the inner Penninic Monte Rosa nappe and minor ophiolites of the structurally composite overlying Piedmont zone. The Monte Rosa nappe consists of basement rocks and minor cover metasediments. The basement is derived from a Late Carboniferous and/or Permian granitic batholith and roofing high-grade paragneisses which, during the Lower–Middle Eocene, underwent to different extents a subduction-related eclogitic imprint and Late Eocene–Early Oligocene greenschist-amphibolite facies reworking. The Dent Blanche-Piedmont-Monte Rosa nappe stack cooled to nearly 250 °C 33–34 Ma ago and was then transected by post-metamorphic dykes.

The Monte Rosa nappe also includes some narrow tectonic belts called the Furgg zone, characterized by abundant mafic boudins. Its origin and composition are debated. On the northern side of the massif, the Furgg zone (*s.s.*) is sandwiched between the Monte Rosa basement and the Portjengrat-Stockknubel units. It consists of micaschists, leucocratic gneisses and marbles with mafic boudins, and has been referred to as: (i) a Permian–Carboniferous cover of the Monte Rosa basement, with interfingerings of Mesozoic metasediments and boudinaged ophiolites from the Zermatt-Saas and/or Antrona unit; (ii) a Mesozoic volcano-sedimentary cover sequence; (iii) a tectonic mélange between Monte Rosa rocks and Piedmont ophiolites; (iv) an inner tail of the outer Penninic Valais oceanic suture. On the Italian southern side, the Furgg zone occurs at various structural levels, either on top of the polymetamorphic basement or deeply inside it, allowing the Monte Rosa nappe to be subdivided into several subnappes. It consists of eclogitic to retrogressed mafic boudins and minor marbles which are embodied within high-P garnet micaschists and their greenschist-facies derivatives (Alpine imprint), both originating from pre-granitic protoliths (without traces of Mesozoic metasediments). Therefore, the southern Furgg zone is an older lithotectonic complex of the Monte Rosa basement, strongly sheared and metamorphosed during Alpine subduction and exhumation, and in places eventually accreted by minor ophiolitic slices along the contact with the overlying Zermatt-Saas nappe. Recent zircon dating suggests the occurrence of pre-Variscan protoliths also within the northern Furgg zone. Contrasting paleostructural reconstructions are reviewed, and it is concluded that the Monte Rosa continental crust was originally located in the inner sector of the European passive margin, between the Briançonnais domain and the Piedmont ocean.

Keywords: Monte Rosa, Furgg zone, Piedmont ophiolite, Western Alps, isotope dating, paleostructural restoration, geological history.

1. Introduction

This paper is my contribution to the memory of Peter BEARTH (1902–1989) and Martin FREY (1940–2000), as a mark of my gratitude to them and my deep regret at their deaths. I was lucky enough to benefit greatly from BEARTH's teaching and paternal goodwill when I began to study the Italian side of the Monte Rosa massif and the nearby Piedmont ophiolites. Our friendship later developed greatly and was consolidated during stays in Basel and numerous field trips from the Monte Rosa massif to the Monviso and Pelvas ophiolites (BEARTH et al., 1975), across the Mt.

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Fig. 1 Peter Bearth (left) and Martin Frey (right), Jura excursion, May 26–27, 1984. A memorial of their lives is given, respectively, by Streckeisen and Meyer (1990) and Engi et al. (2000).

Emilius klippe (Bearth et al., 1980) and other areas in the Western Alps. The last trip we took together (May 26–27 1984) was in the Jura belt, led by Hans P. Laubscher to celebrate his 60th birthday, and among attending friends and colleagues there was also Martin Frey (Fig. 1). The first time I had met Martin was in 1973, during an excursion of the *Schweizerische Mineralogische und Petrographische Gesellschaft* (September 30–October 3) in the eclogitic Sesia-Lanzo zone in the M. Mucrone and Aosta valley (Dal Piaz et al., 1973), and I later had many opportunities to appreciate his friendliness and scientific skills during the preparation of metamorphic maps of the Alps (Frey et al., 1974, 1999; Niggli et al., 1978).

This paper focuses on the Monte Rosa massif and its geological history. The massif – "the Queen of the Alps" (King, 1858) – is modelled within the crystalline basement of the Monte Rosa nappe, the Italian-Swiss Western Alps, and minor Mesozoic ophiolites which occur at various structural levels in its western (Breithorn) and eastern (Antrona, Anzasca) sides. I refer to the structurally composite Piedmont (Piemontese) zone and Antrona unit which, respectively, are located on the hangingwall and footwall of the Monte Rosa nappe. The Monte Rosa nappe displays the same structural position as the Gran Paradiso and Dora Maira. As a whole, these "internal massifs" constitute the inner and upper continental nappe system of the Penninic zone in the Western Alps and are characterized by a subduction-related eclogitic imprint of Alpine age (Dal Piaz et al., 1972; Compagnoni et al., 1977; Michard et al., 1996, and refs. therein).

2. From the pioneering age to nappe theory

In 1789, H.B. de Saussure devoted one of his famous Alpine journeys (1779–96) to exploring the Monte Rosa massif. His *Voyage autour de Mont Rose* went from the Simplon pass to Macugnaga (Pestarena gold mine and ascent of Pizzo Bianco, from which he measured the altitude of some Monte Rosa peaks), Baranca pass, Carcoforo, Balmuccia, Alagna Valsesia (Cu–Fe mine), Valdobbia pass, Gressoney, Bettaforca (Rothorn climb), St. Jacques, Ayas valley, Cime Bianche pass, Breuil (Cervinia), glacial Theodule pass, Zermatt and Saas valleys. In 1792, de Saussure went back to the Theodule pass and spent three days there, making trigonometric measurements of the Matterhorn's altitude, together with the first description of its geological setting (Dal Piaz, 1996). From the late 1700s to the first half of the 1800s, Kl. Matterhorn (De Saussure) and then the principal summits of the Monte Rosa massif were climbed, whereas the valleys were visited by eminent scientists like Agassiz, Ball, de Beaumont, von Buch, de Dolomieu, Desor, Engelhardt, Escher von der Linth, Sismonda, Studer, von Welden (Puiseux, 1892; Fini, 1979;

DAL PIAZ, 1997; CERRI and OSELLA CREVAROLI, 1998).

In the meantime, the geographic and geological exploration of the Alps was being carried out and enhanced by the brothers Adolf and Hermann SCHLAGINTWEIT (1854). The chapter on the orographic and geological structure of Monte Rosa massif had been anticipated and published, the year before, in German and French (SCHLAGINTWEIT, 1853a, 1853b). The main lithological and structural setting of the massif was carefully described as consisting of dominant feldspar-rich gneisses and micaschists, flanked by serpentinites (regarded as igneous rocks) and concordant *"Graue und Grüne Schiefer"*, limestones and marbles (the future Piedmont zone). The paper is illustrated by a geological map and five cross-sections based on precise measurements of regional bedding, showing the existence of a gigantic central gneiss dome.

In 1851, Bernhard STUDER published his famous *"Geologie der Schweiz"* and related map at 1:380,000 scale, elaborated together with ESCHER.

Modern geological study of the Monte Rosa massif and the Western Alps began in the 19th century, with the amazing fieldwork of Heinrich GERLACH from Mont Blanc to the Bergell area (*Karte der Penninischen Alpen* 1:200,000, 1869), followed by that, equally prominent, of the *Regio Ufficio Geologico d'Italia* (Italian Geological Service). GERLACH's original maps on the Italian side were included in the hand-drawn coloured *Carta Geologica delle Alpi Piemontesi*, scale1:50,000 (BARETTI et al., 1860–79), recently printed thanks to CAMPANINO and POLINO (1999).

The boundary between the Monte Rosa basement and surrounding ophiolites was carefully traced by GERLACH (1869, 1871), providing the first evidence of the Vanzone antiform, together with the structural setting of the Monte Rosa massif along the Gornergrat-Dufour-Col d'Olen transect (profile II, GERLACH, 1883). The occurrence of granitic rocks in the Monte Rosa massif was reported by GERLACH (1883) and then better defined by NOVARESE (1903) and SCHMIDT (1907): the former described the augengneiss body of the Verra glacier (Ayas valley), characterized by decimetric K-feldspar and tourmaline-rich pegmatite veins; the latter described the poorly deformed two-mica granite in the Plattje area (Gorner glacier, Zermatt).

The Geological Map of Italy (1:100,000) was surveyed on a scale of 1:25,000, and regional knowledge on the Western Alps greatly benefited from it. The Monte Rosa massif was mapped by Secondo FRANCHI, Vittorio NOVARESE and Augusto STELLA, and is shown in the sheets Monte Rosa (1912), Domodossola (1913) and Varallo (1917). We can recognize the perfect fit of all lithological units, detailed internal subdivisions and mutual boundaries, although the structural setting had been interpreted according to the then current "fixistic double-fold" views (DAL PIAZ, 1997).

Early in the 1900s, the Monte Rosa massif was involved in the nappe theory, becoming the fifth recumbent fold-nappe of the Penninic zone (LUGEON and ARGAND, 1905; ARGAND, 1909, 1911, 1916, 1934), mantled by Mesozoic covers, locally ophiolite-bearing, and forcedly emplaced between the Grand St. Bernard and Dent Blanche nappes. It was first extended to the Gran Paradiso and Dora-Maira massifs and then correlated to the gneissic core of the Tauern window. The arc of the Western Alps was fully represented by ARGAND's (1911) 1:500,000 tectonic map and detailed cross-sections. As acknowledged by Argand himself, the accuracy of his work greatly benefited from the perfect 1:400,000 geological map of the Western Alps published in 1908 by the *Regio Ufficio Geologico d'Italia*. More information on ARGAND's tectonic, kinematic and paleostructural concepts are reported by COLLET (1927), ESCHER and MASSON (1984), and DAL PIAZ (1997).

In 1924, Rudolf STAUB published his great synthesis of the entire Alpine chain and strengthened the genetic link between paleogeographic zones and tectonic nappes. The attached tectonic map and profiles clearly depict the structural setting of the Monte Rosa nappe and surrounding units.

In 1937, HERMANN printed his 1:200,000 geological map of the North-Western Alps, based on the 1:100,000 sheets of the Geological Map of Italy mentioned above. Opposing ARGAND's belief about stratigraphic links between basement cores and ophiolite-bearing cover metasediments, HERMANN sustained the exotic provenance of the metamorphic ophiolites and related calcschists – namely, the Pietre Verdi-Piemonte nappe – and their independence of the Dent Blanche (Sesia-Lanzo included), Monte Rosa-Arcesa-Gran Paradiso and Gran St. Bernard basement and cover nappes.

STAUB (1937) linked the Monte Rosa and Grand St. Bernard nappes together to form the Mischabel-Decke, and postulated the Lower Austroalpine affinity of the overlying Dent Blanche nappe, presuming its equivalence to the Margna nappe. Gb. DAL PIAZ (1934, 1938, 1939) emphasized correlations among the gneissic granites of Monte Rosa, Gran Paradiso and Hohen Tauern (the first two also described by CORNELIUS, 1937), and the role of the Variscan unconformity.

ARGAND's views long dominated Alpine geology, although his theory of nappe generation by primary folding was criticized, first in the Dent Blanche (*Gleitbrettertektonik*, STUTZ and MASSON, 1938) and then across the Penninic nappe stack (HALL, 1972, in HOBBS et al., 1976; MILNES, 1974).

3. Bearth's contribution

In 1934, Peter BEARTH began his extraordinary fieldwork across the high mountains of the northern, axial and eastern sides of the Monte Rosa massif and surrounding ophiolites, climbing rock and glacial summits mainly unaccompanied. His work led to the splendid 1:25,000 sheets Zermatt (1953), Monte Moro (1954) and Saas (1954) of the *Geologischer Atlas der Schweiz*, some short notes (1939–58) and the conclusive memoir *Geologie und Petrographie des Monte Rosa* (1952). BEARTH also mapped the nearby sheets Randa (1964), Simplon (1972) and St. Niklaus (1978).

Meantime, STELLA (1943) described the Late Alpine gold-quartz lodes of the Monte Rosa district, GÜLLER (1947) studied the northern edge of the Monte Rosa nappe and its relationships with the Mischabel backfold and surrounding ophiolitic units, BLUMENTHAL (1953) worked on the *Antrona Mulde,* and AMSTUTZ (1955) coined the term "subduction" for the overturned root zone in the Ossola valley, re-interpreted as shallow crustal underthrusting to the northwest.

In the tectonic outline of his memoir, BEARTH followed STAUB's (1937) view on the existence of the Mischabel nappe, but clearly pointed out that this Penninic mega-unit encompassed two independent subnappes (Gran St. Bernard and Monte Rosa), characterized by differing tectono-metamorphic features.

In the Monte Rosa basement, two main pre-Alpine protolithic groups were unravelled by BEARTH (1952) below its Alpine overprint, as follows.

1. Pre-granitic metamorphic complex: represented by mid- to coarse-grained high-grade paragneiss rich in concordant to discordant pegmatites. High-grade regional fabrics consist of garnet, biotite, sillimanite, quartz ± andesine, K-feldspar and cordierite, and show local folding prior to the injection of anatectic melts. Traces of a pre-granitic retrogression are locally reported. The gneissic sequence originated from clayey to minor clayey-sandy (banded gneiss) sediments of unknown age.

2. Granitic complex: represented by dominant granitic-granodioritic bodies, often porphyric, and minor sills, younger leucocratic granites in discordant stocks and concordant intrusions, followed by aplitic and pegmatitic dykes, locally still preserving their primary intrusive feature in large low-strain domains (Dufour, Liskamm, Macugnaga easterm wall). The igneous contact did not significantly perturb the high-grade fabric and mineral assemblage of roofing rocks, but only developed very thin zones of massive biotite-rich hornfels (Dufour, Zumstein, Kl. Fillar). The discordant granite was first interpreted as a Late Alpine intrusion (BEARTH, 1945) and then, correctly, referred to the Late Paleozoic magmatism together with the protoliths of larger augengneiss bodies (BEARTH, 1952).

BEARTH's memoirs then concentrate on the post-granitic (Alpine) metamorphism, which was responsible for the partial to complete mineral and structural reworking of high-grade paragneisses into a series of garnet micaschists and albitic schists, as well as of granitoids into various kinds of massive to schistose augengneiss and strongly sheared end-members (quartz-muscovite schists). Alpine mineral assemblages are represented, as a whole, by garnet, albite ± oligoclase rims, quartz, biotite, muscovite-phengite, chlorite, zoisite-epidote ± calcite, together with actinolitic-hornblende in some mafic boudins of supposed sedimentary origin, scattered inside paraschists south of the Furgg zone. In addition, BEARTH described the stable association of chloritoid and kyanite in both complexes, supposedly derived from biotite-rich and alkali-depleted protoliths, respectively.

To sum up, a single Alpine metamorphic cycle was recognized in the Monte Rosa nappe. It mainly developed with synkinematic mid- to low-grade (meso-epizone) features and lasted to the late growth of porphyroblastic albite, biotite and chlorite. No trace of eclogitic metamorphism like that in the overlying Zermatt-Saas ophiolite was revealed. Further regional study allowed BEARTH (1958) to demonstrate that the Alpine metamorphism grades from greenschist to amphibolite facies conditions, and to trace the albite-oligoclase isograd along the domed axial plane of the Monte Rosa recumbent fold-nappe (Fig. 2). Furthermore, BEARTH (1952, 1954, 1957a, 1964, 1967) coined the terms *Stelli zone* and *Furgg zone*.

The Stelli (Stellihorn) zone is a large, strongly sheared and mylonitic belt inside the crystalline basement, obliquely extending across the Monte Rosa nappe from its north-eastern margin to the upper Macugnaga and Quarazza valleys. It mainly developed on granitic and leucocratic protoliths, is free of Mesozoic components, and is regionally characterized by the late-kinematic growth of albite. It is truncated by the Furgg zone in the Cam-

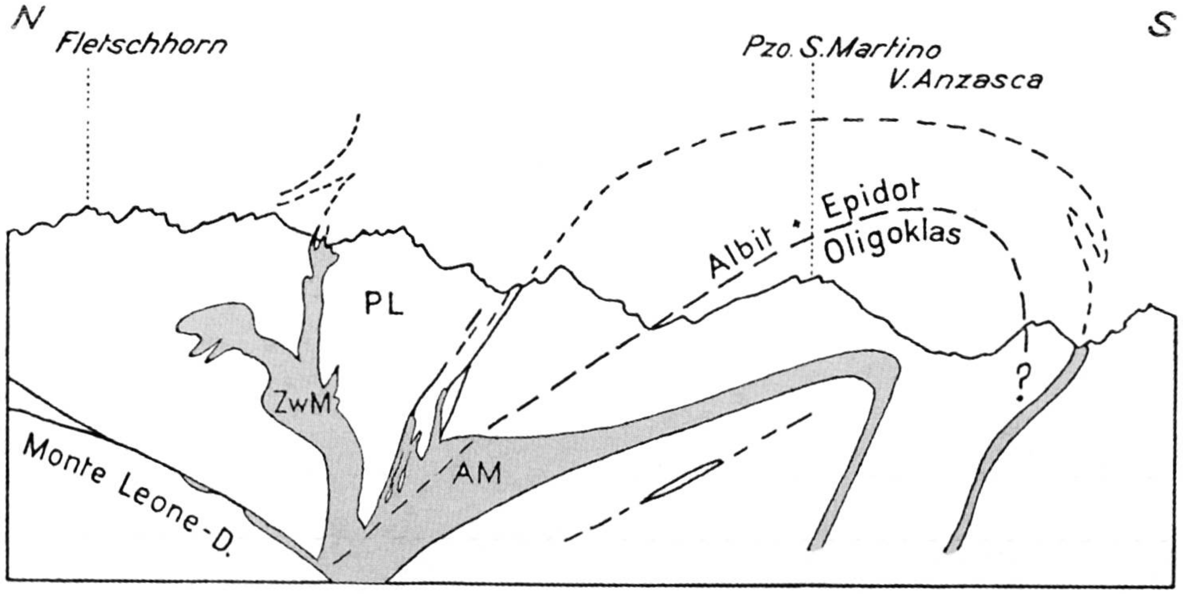

Fig. 2 Albite + epidote/oligoclase isograd across Monte Rosa and other Penninic nappes (BEARTH, 1958). AM-ZwM: Antrona and Zwischenbergen synforms; PL: Portjengrat unit.

posecco-Bottarello area (uppermost Antrona valley). The Stelli zone allows the Monte Rosa basement to be subdivided into two huge slices, i.e., an upper element (Oberbau), encompassing the Monte Rosa gneissic granite and roofing paraschists with numerous sills, and a lower element (Unterbau), dominated by the Macugnaga augengneiss.

The Furgg zone *(*ARGAND*'s synclinal de Furggen,* Mesozoic, 1911) was depicted in the 1:150.000 tectonic inset of the Saas geological map (BEARTH, 1954) as a narrow, sheared northern belt along the Monte Rosa-Portjengrat contact and, to the west, in the Stockknubel area, south of the Stockhorn basement and Gornergrat cover. It consists of micaschists, albitic schists and leucocratic gneisses (Permian–Carboniferous?) with abundant greenschist-facies mafic boudins and multiple upward interfingerings of Mesozoic metasediments and ophiolites from the underlying Antrona unit (BEARTH, 1957a, 1964b). This interpretation was confirmed and developed by WETZEL (1972).

A ribbon of Permian-Jurassic clastic to carbonate metasediments (Gornergrat zone), discontinuously exposed along the northern border of the basement, is clearly shown in the Zermatt and Saas sheets and related tectonic insets (BEARTH, 1953, 1954, 1957a, 1967a). BEARTH interpreted this metasedimentary sequence as a detached remnant of the Monte Rosa cover (alternative views are discussed in the following). The underlying Stockhorn basement mainly displays garnet micaschists, locally kyanite-chloritoid-bearing, and albitic schists. It is separated from the main Monte Rosa nappe by the Stockknubel Schuppenzone, consisting of serpentinitic slices, talc- and chlorite-schists, epidote amphibolites and calcschists which, to the south, disappear below the Gorner glacier (BEARTH, 1953, 1967a; AUBERT et al., 1980).

BEARTH (1956a, 1956b, 1957b) also studied the Simplon fault, the Vanzone antiform (ARGAND's *vôute de Vanzone*, 1911) and related rocks.

When his field and laboratory work on the Monte Rosa was successfully concluded, BEARTH's interest concentrated on his beloved ophiolites. The lithostratigraphic, metamorphic and tectonic features of the ophiolitic sequences were thoroughly described in the Saas and Zermatt mapped areas, and then along the Western Alpine arc as far as Monviso (BEARTH, 1959, 1967b, 1970, 1973, 1974).

From top to bottom, the Piedmont sequences on the Swiss side were subdivided into the *Obere Zermatter Schuppenzone, Theodul-Rothornzone* and *Ophiolithzone of Zermatt-Saas Fee* (later shortened to Zermatt-Saas by BEARTH himself, 1973) (Fig. 3A). The first two units constitute the laminated footwall of the Dent Blanche nappe and correspond to ARGAND's Combin zone, if we exclude the Briançonnais cover units cleverly recognized by ELLENBERGER (1953; see also MARTHALER, 1984, and SARTORI, 1987). They consist of calcschists and interbedded greenschist-facies meta-ophiolites and are separated by a Triassic band which essentially vanishes south of the Swiss-Italian border.

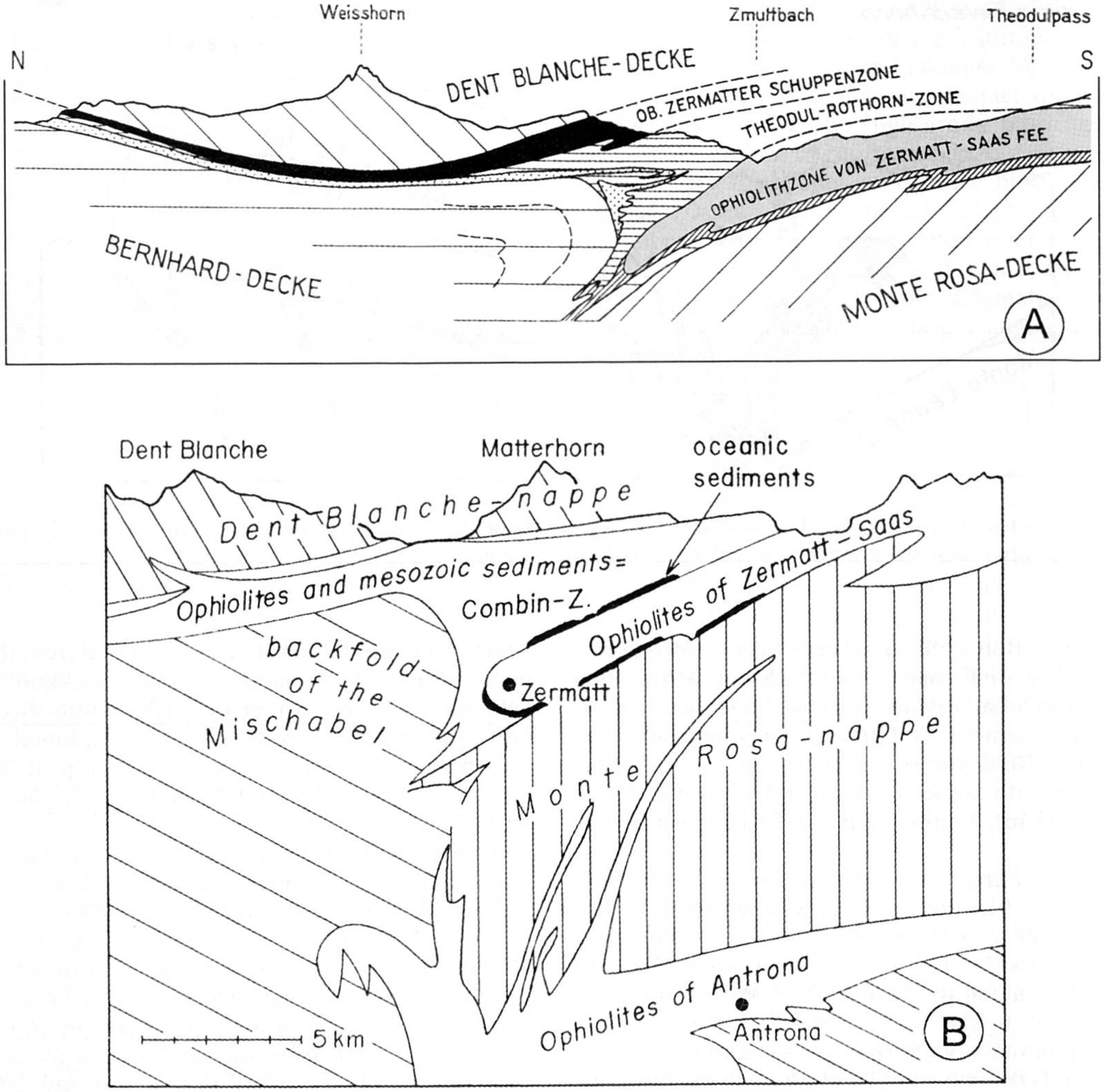

Fig. 3 Ophiolitic units and nappe stack in the Zermatt area (A: Bearth, 1967a; B: Bearth and Schwander, 1981).

The underlying Zermatt-Saas zone mantles the Monte Rosa carapace and disappears below the Mischabel backfold (Fig. 3A–B). It is dominated by a classic ophiolitic sequence (capping diabase-basalt, intermediate gabbro, basal peridotite-serpentinite), supposedly derived from a mega-effusion like those envisaged by Dubertret and Brunn (in Bearth, 1952) in the eastern Mediterranean – Argand's (1934) concept of geosyncline and ensialic emplacement of ophiolitic magmas were still popular (Dal Piaz, 1997). The lower Piedmont nappe also has a pervasive tectono-metamorphic overprint and occurrences of eclogite.

Bearth's classic memoir (1967b) and other notes focused on the Zermatt-Saas nappe and its Alpine metamorphism. Major advances dealt with: (i) the discovery of flattened eclogite-glaucophanite pillow lavas in the Täsch valley, east of Zermatt (Bearth, 1959, 1973); (ii) Allalingabbro and its metamorphic imprint, characterized by coronitic to pseudomorph eclogitic assemblages (garnet, sodic pyroxene, zoisite, rutile, talc, glaucophane, Mg-chloritoid, kyanite, white micas) from primary olivine, pyroxene and plagioclase (see Chinner and Dixon, 1973, for detailed descriptions and P-T estimates of high-P mineral assemblages in the Allalin metagabbro); (iii) whole rock and mineral composition (see also BEARTH and STERN, 1971, 1979); (iv) manganiferous quartzite of Cignana (later famous for the discovery of coesite; REINECKE, 1991; VAN DER KLAUWE et al., 1997) and other oceanic cover sequences in the Zermatt-Saas area (BEARTH and SCHWANDER, 1981, Fig. 3b); (v) post-eclogitic evolution and development of albite-rich (prasinitic) assemblages in mafic rocks, confirming previous observations in similar western Alpine occurrences (e.g., FRANCHI, 1902; Gb. DAL PIAZ, 1928).

Lastly, the metamorphic features of the ophiolites, characterized by concurrent eclogites, glaucophane schists and prasinites, were compared with those in the Western and Central Alps. Four groups of mineral assemblages and related rocks were distinguished: blueschist, prasinite, eclogite plus prasinite, and amphibolite facies.

4. The southern side

In the late 1950s, I began to map the Italian side of the Monte Rosa massif, long neglected after the 1:100,000 geological sheet had been printed by the Italian Geological Service (1912). My work began at the head of the Sesia valley (DAL PIAZ, 1960), together with my friend Giuseppe "Bepi" GATTO (1961), and then extended (1960s–early 1970s) to the Gressoney and Ayas valleys, involving the Monte Rosa basement and Piedmont ophiolites. These maps (1:10,000) are still unpublished, except that for the Pillonet klippe and underlying Combin zone along the Ayas/Valtournanche divide (DAL PIAZ, 1976).

Original results on the Monte Rosa nappe were (DAL PIAZ, 1964, 1966, 1971a; GOSSO et al., 1979): (i) recognition of Alpine low-strain domains (Sesia valley, Lyskamm, Castor massif) which preserve to different extents the sharp intrusive contact of granitoids into the high-grade metamorphic complex; reconstruction of the pre-Alpine crust and regional comparisons (BORIANI et al., 1976; DAL PIAZ, 1993); (ii) partial to complete transformation of pre-granitic paragneisses and anatectic migmatites to Alpine high-P micaschists (garnet, phengite ± kyanite, chloritoid, Mg-chlorite) in nearby high-strain domains, in turn evolving to greenschist-facies albite-rich schists; similarly, increasing strain in igneous protoliths is revealed by the sequence: porphyric metagranite –> augengneiss –> micro–augengneiss –> mylonitic schists, and progressive transposition of leucocratic dykes parallel to the Alpine schistosity; (iii) discovery of a relict high-P imprint of Alpine age (DAL PIAZ, 1971a), recorded by the pseudomorphic replacement of pre-Alpine porphyroblastic sillimanite and cordierite by fine aggregates of kyanite and kyanite + garnet, respectively, as well as by white-schist mylonites in felsic rocks and typical eclogitic assemblages in mafic boudins embodied within the post-Variscan metagranitoids (sources of Sesia river; DAL PIAZ and GATTO, 1963) and dominant polymetamorphic paraschists (Sesia-Gressoney divide, Indren glacier, Rifugio Gnifetti, Ayas valley, DAL PIAZ, 1964, 1966; Fig. 4); garnet-clinopyroxene geothermometry and eclogite phase compatibilities were later reported by DAL PIAZ and LOMBARDO (1986); (iv) occurrence of the Furgg zone at various structural levels, defined by the association of mafic boudins and minor marbles, either on top of the polymetamorphic basement (as described by BEARTH for the northern margin, but without conclusive evidence of Permian–Mesozoic metasediments) or deeply inside it (to the east), allowing the Monte Rosa nappe to be subdivided into three subnappes (DAL PIAZ, 1966), later corroborated by WETZEL (1972) and MILNES (1974); note that some mafic boudins had previously been reported by FRANCHI (1903, Sesia valley), and marbles by STELLA (1905, Pizzo Bianco-Macugnaga) and CORNELIUS (1937, Quintino Sella crest); (v) multiple recumbent backfoldings of the Monte Rosa/Zermatt-Saas contact in the Gressoney and Sesia valleys, not involving the overlying Combin zone (GOSSO et al., 1979); (vi) dating of calc-alkaline to ultrapotassic dykes (Oligocene, 31–32 Ma; previously thought to be of Permian age; COMPAGNONI et al., 1977, and refs. therein) which transect the Arcesa-Brusson (Monte Rosa)-Piedmont-Austroalpine nappe stack, Barrovian regional schistosity and post-nappe foldings (DAL PIAZ et al., 1979a; VENTURELLI et al., 1984; see also DIAMOND and WIEDENBECK, 1986).

As regards the structurally composite ophiolitic Piedmont zone (DAL PIAZ, 1965): (i) its allochthony with respect to the Monte Rosa basement; (ii) southward extension of BEARTH's tectonic subdivisions (Fig. 5); (iii) rodingitic gabbro dykes inside the huge Verra slice of mantle serpentinite, Zermatt-Saas nappe, in places so abundant to form a sort of intra-mantle sheeted complex, and rodingitic reaction zones between serpentinites and surrounding metasediments, that now I believe to be in primary contact (DAL PIAZ, 1969 a; DAL PIAZ and ERNST, 1978); (iv) new occurrences and mineral composition of supra-ophiolitic magnaniferous quartzites (DAL PIAZ et al. 1979 b), also locally resting over serpentinites (DAL PIAZ, 1969 b); (v) contrasting metamorphic features in the upper (Combin, eclogite-free) and lower (Zermatt-Saas, eclogitic) Piedmont units before their mutual greenschist-facies overprint

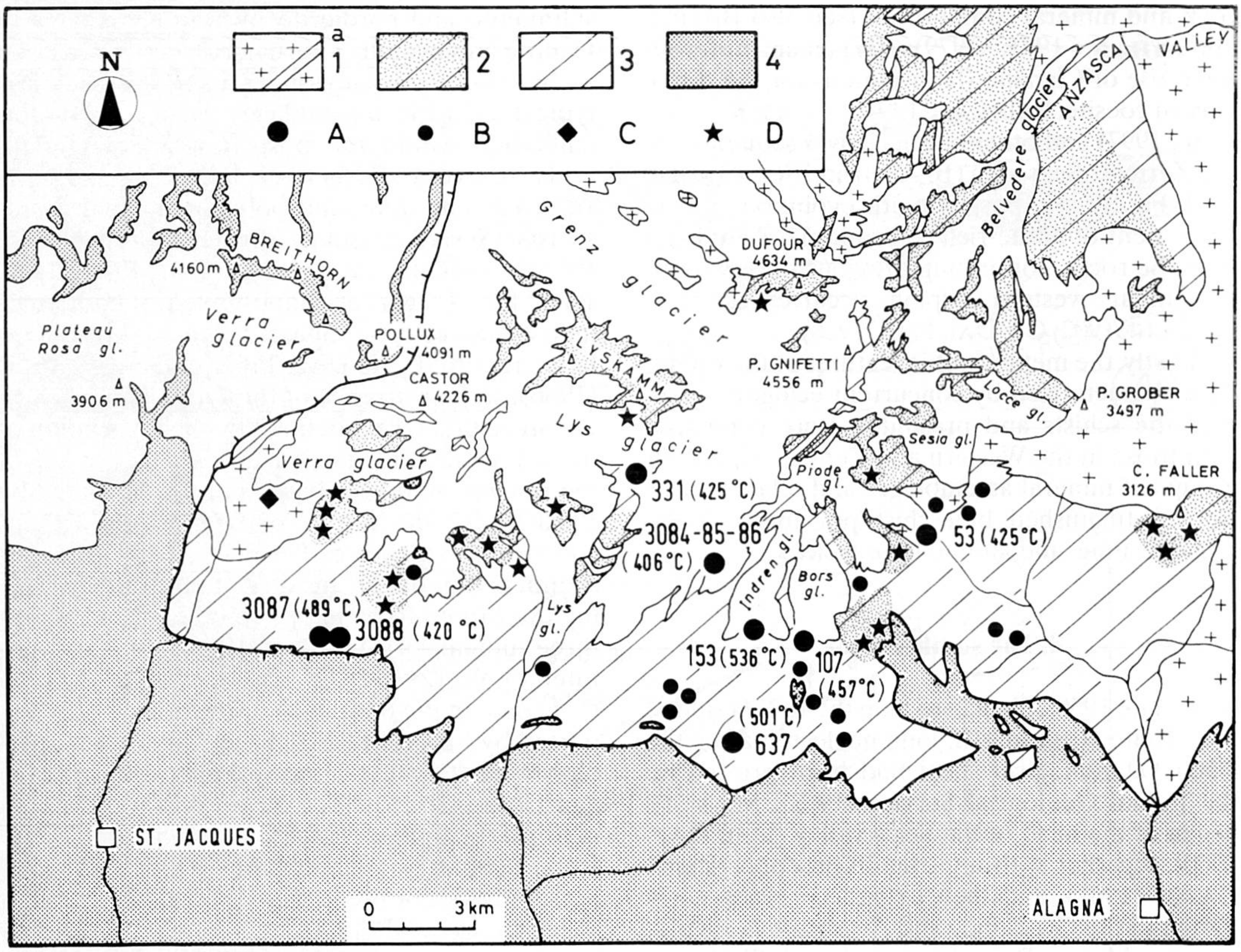

Fig. 4 Generalized map of southern Monte Rosa nappe and distribution of high-P occurrences (Dal Piaz and Lombardo, 1986). Monte Rosa basement: (1) Augengneisses, metagranites and (a) large dykes from Late Paleozoic intrusives; (2) Pre-granitic high-grade metapelites weakly overprinted by Alpine metamorphism; (3) High-grade metapelites with partial to complete Alpine tectono-metamorphic reworking, including the southern Furgg zone (undifferentiated); (4) Composite Piedmont zone (Zermatt-Saas and Combin units); (A) Location of analysed mafic eclogites and temperatures estimated for garnet-omphacite pairs, assuming a nominal pressure of 10 kbar; (B) other occurrences of mafic eclogites inside the basement; (C) phengite-chloritoid-Mg-chlorite-kyanite assemblages in mylonitic granites; (D) kyanite pseudomorph after sillimanite and kyanite-phengite-garnet assemblages in metapelites.

(Kienast, 1973; Dal Piaz, 1974, 1976, and related metamorphic map); (vi) petrological estimates on eclogitic and blueschist to greenschist-facies Alpine metamorphism in the St. Jacques-Breuil area (Dal Piaz and Ernst, 1978; Ernst and Dal Piaz, 1978); (vii) whole-rock composition of Combin and Zermatt-Saas metabasalts, showing the transitional to normal-MORB affinity of the protoliths (Dal Piaz et al., 1981; Beccaluva et al., 1984; see also Pfeifer et al., 1989).

5. Further advances

In the meantime, the Monte Rosa tail in the Ossola valley and the petrographic features of the Furgg Zone were studied by Reinhard (1966) and Wetzel (1972), both Bearth's students. Reinhard (1966) described the "root zone" of the nappe pile to the east of the Ossola valley. Wetzel (1972) focused on the lithological and tectonic complexity of the northern Furgg Zone, from the Stockknubel to the Bognanco valley (named Furgg zone s.s.), confirming Bearth's view that it belonged to the Monte Rosa nappe. This narrow belt was depicted as a strongly deformed association of albitic schists, garnet micaschists, granitic gneisses, mafic boudins (with eclogitic to prasinitic mineral assemblages), thin micaceous quartzite (± garnet, carbonate, albite-oligoclase) and dolomitic marble of pre-Mesozoic (Paleozoic?) age, variously including or mantled by tectonic slices

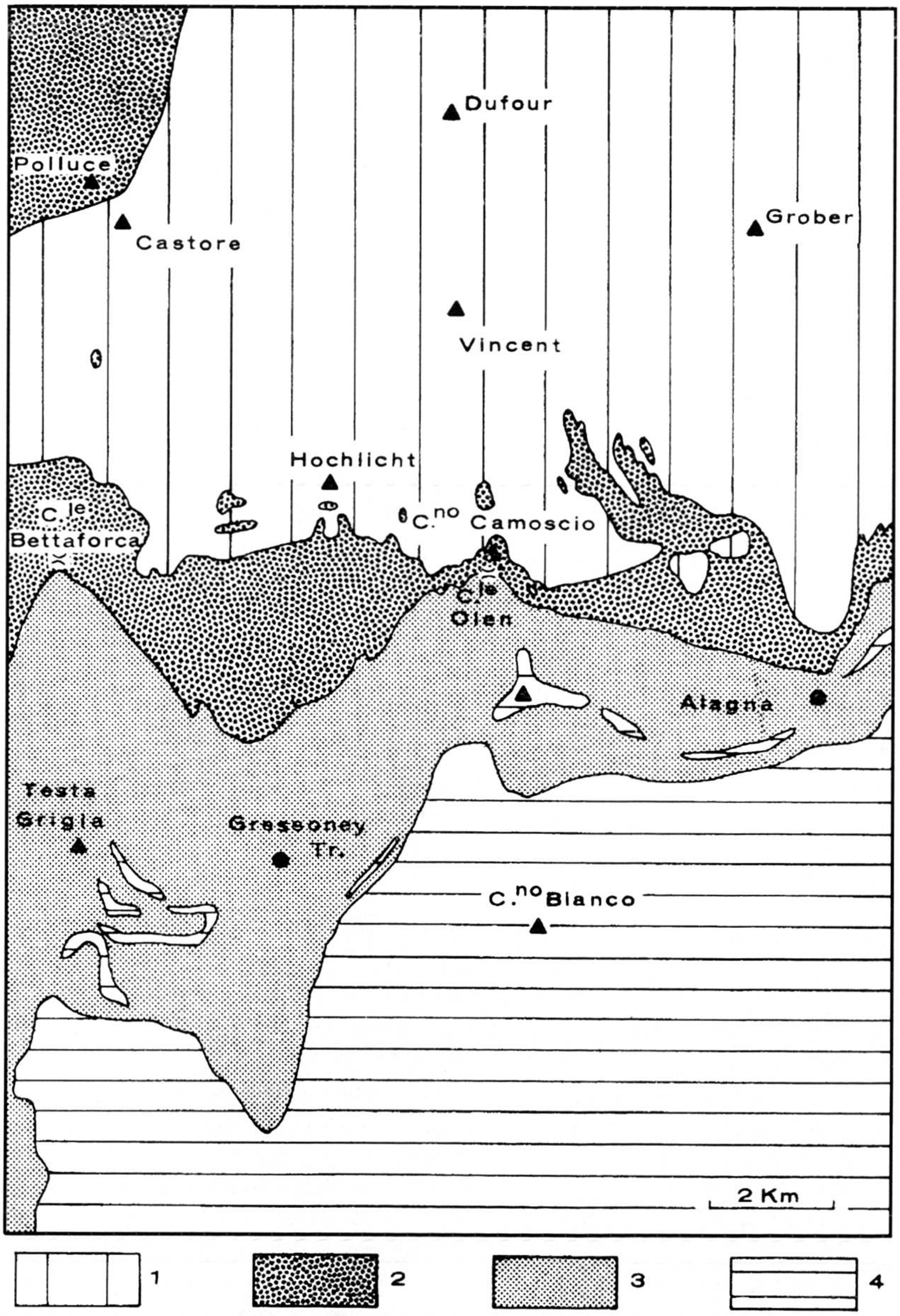

Fig. 5 Tectonic subdivision of the ophiolitic Piedmont zone in the southern Monte Rosa massif (Dal Piaz, 1965). (1) Monte Rosa nappe; (2) Corno Camoscio-Breithorn unit (= Zermatt-Saas nappe); (3) Gressoney-Gran Tournalin unit (= Theodul-Rothorn zone, Combin zone); (4) Sesia-Lanzo zone.

of Mesozoic rocks (see also Blumenthal, 1953), mainly represented by tabular quartzite, dolostone, carnieul, calcschists, amphibolite and serpentinite, locally titanclinohumite-bearing.

Tertiary Rb–Sr ages were obtained on biotite and white micas from the Monte Rosa and other Penninic nappes, pointing to a Lepontine metamorphic climax at 38 ± 2 Ma (Hunziker, 1970; Hunziker and Bearth, 1969). Late Carboniferous and Permian intrusion ages (310 Ma, 260 Ma) and high initial Sr ratio of Monte Rosa granite were established by Hunziker (1970) and Frey et al. (1976). Moreover, some sheared and albitised granitic gneisses and schists provided a Rb–

Sr whole rock isochron of 125 ± 20 Ma (HUNZIKER, 1970). HUNZIKER and BEARTH (1969) documented the differential uplift across the Simplon-Centovalli fault by the existence of a chronological gap.

Polyphase post-nappe folding was reconstructed in central Pennine zone of the central Alps (MILNES, 1974), significant areas between the Mischabel backfold and Vanzone antiform (KLEIN, 1978; MILNES et al., 1981; MÜLLER, 1983), as well as along north-south cross-sections in the Sesia, Gressoney and Ayas valleys, from the Monte Rosa southern side to the frontal Sesia-Lanzo zone (GOSSO et al., 1979, Fig. 6).

The breakthrough for regional tectonics and deformation mode was the demonstration

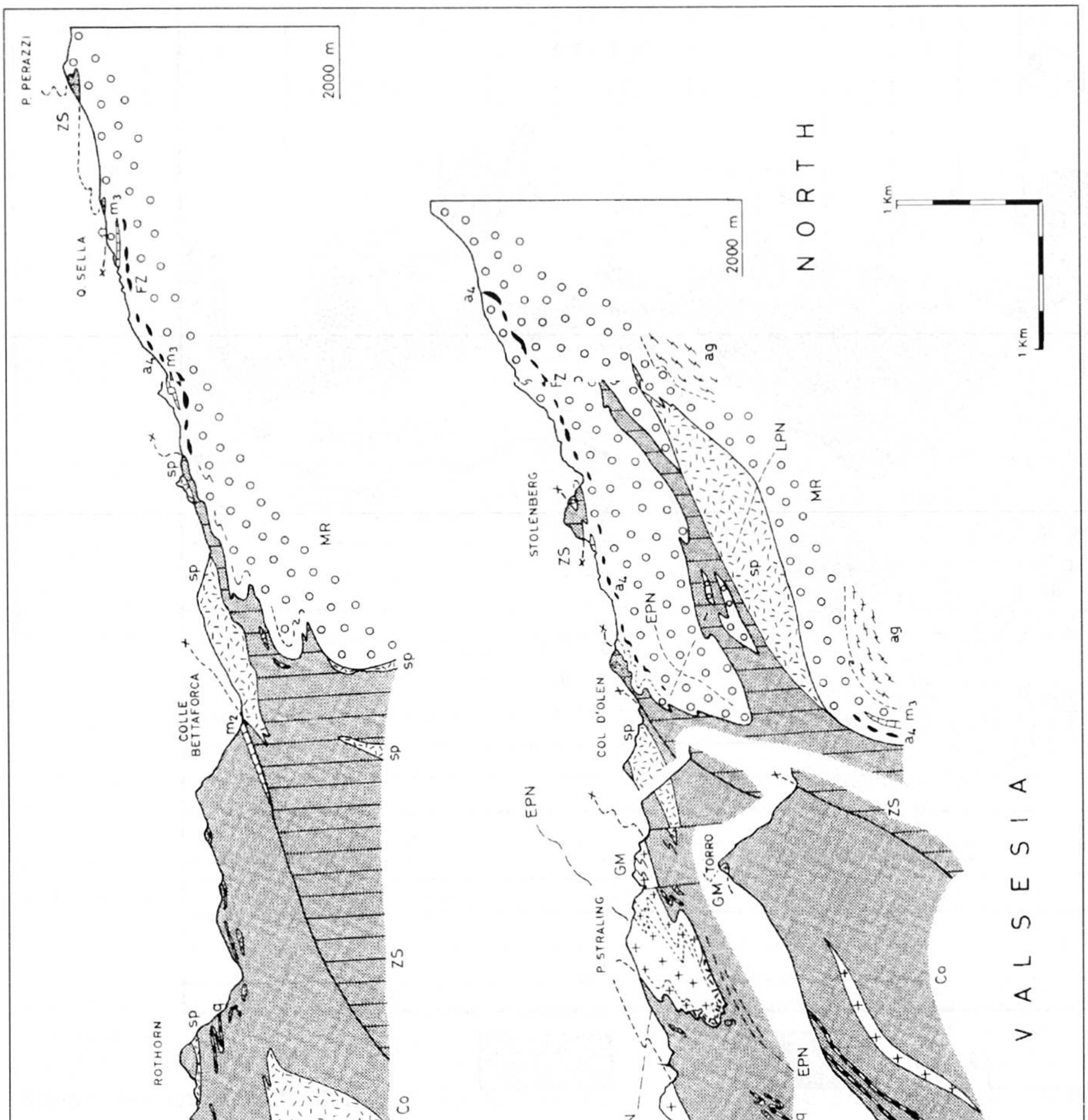

Fig. 6 Cross-section of southern Monte Rosa massif along Gressoney-Valsesia divide (GOSSO et al., 1979, northern part of Plate 1). (1) Frontal Sesia-Lanzo zone, Gneiss Minuti complex (GM): granitic gneisses including metagabbro (g) from Permian protoliths, amphibolites (a3), impure marbles (m1, Mesozoic?). (2) Piedmont zone: upper unit (Combin: Co) and lower unit (Zermatt-Saas: ZS), including impure quartzites (± Mn), serpentinite slices (sp), Triassic exotic unit (m2: Bettaforca). (3) Monte Rosa nappe (MR): polymetamorphic paraschists, major augengneisses (ag) and Furgg zone (FZ; pre-Triassic mafic boudins: a4, minor marbles: m3). EPN-LPN: early and late post-nappe foldings.

(MILNES, 1974, MILNES et al., 1981) that ARGAND's root zone is a steep belt not genetically related to the development of the nappe structures. In other words, the Monte Rosa recumbent fold is not a primary feature but an antiformal structure which deformed previously imbricated thrust sheets. This antiform (Ragno fold) is well exposed along the eastern side of the Ossola valley (REINHARDT, 1966).

MÜLLER (1983) improved the structural interpretation given by MILNES et al. (1981), showing that the Mischabel backfolding was generated at the end of the Lepontine metamorphism and, except for the Zermatt area, mainly developed as large shear zones which include rigid bodies of polymetamorphic basement. His general profile of the Monte Rosa nappe describes the Furgg zone along the Monte Rosa-Portjengrat boundary.

The main lithologies of the Monte Rosa basement in the Vanzone antiform and Antrona synform, Anzasca valley, were described by LADURON and MERLIN (1974) and LADURON (1976), together with mafic rocks including cores of pre-eclogitic brown hornblende.

In the early 1970s, the paleostructural setting and orogenic evolution of Monte Rosa and other Penninic nappes were re-interpreted in accordance with plate tectonic concepts, becoming representative of large and coherent fragments of the European passive margin, dragged into the subduction zone to the eclogitic climax (together with Austroalpine slices) and then exhumed and thermally re-equilibrated (DAL PIAZ, 1971b, DAL PIAZ et al., 1972; ERNST, 1973; FREY et al., 1974). This was against current geophysical tenets about the light continental crust, which supposedly could not be subducted.

An Eoalpine age was hypothesized for the eclogitic metamorphism of the Monte Rosa and other inner Penninic nappes (DAL PIAZ et al., 1972) by extrapolation of Cretaceous–Paleocene K–Ar ages regionally obtained in the high-P Sesia-Lanzo zone (HUNZIKER, 1974) and Piedmont units (BOCQUET et al., 1974). Later, this hypothesis was corroborated by Cretaceous ^{40}Ar–^{39}Ar dating, systematically obtained on high-P micas from the Gran Paradiso (CHOPIN and MALUSKI, 1978, 1980), Monte Rosa (110 ± 3 Ma, CHOPIN and MONIÉ, 1984) and Dora-Maira (MONIÉ and CHOPIN, 1991) nappes, predating the Mesoalpine greenschist-facies overprint (HUNZIKER, 1970, 1974; MONIÉ, 1985).

Lastly, one high-P quartz-rich "metapelite" from the Monte Rosa massif and one coesite-pyrope quartzite from the Dora Maira massif (CHOPIN, 1984) were analysed by U–Pb zircon, Rb–Sr on whole rock, apatite and phengite, and Sm–Nd whole rock methods (PAQUETTE et al., 1989). The Monte Rosa "metapelite" (the same sample studied by CHOPIN and MONIÉ, 1984) was collected in the Verra moraine, Ayas valley. Its mineral assemblage, consisting of Mg-chloritoid, talc, kyanite, clinochlore and phengite, indicates formation conditions of about 500 °C and 1.6 GPa (CHOPIN and MONIÉ, 1984; see also BORGHI et al., 1996, for inferred P-T paths). REE patterns show HREE fractionation and contents similar to those of the eclogitic Monte Mucrone granite (Sesia-Lanzo, COMPAGNONI et al., 1977), suggesting that the analysed morainic boulder probably derived from the high-P silvery mylonite (metasomatized) which transects the Monte Rosa metagranite at the base of the Piccolo Ghiacciaio di Verra (DAL PIAZ, 1971; DAL PIAZ and LOMBARDO, 1986), although similar whiteschists also originated from the roofing polymetamorphic paraschists which include a few Mg-marbles. A U–Pb zircon lower intercept of 192 ± 2 Ma and a 2.1 Ga Nd model age have been obtained, both geologically meaningless. In contrast, a Rb–Sr whole rock-apatite pair and a phengite-apatite pair provided precise ages of 102 ± 2 and 91 ± 2 Ma, respectively (PAQUETTE et al., 1989): the former is consistent with the ^{40}Ar–^{39}Ar plateau age (110 ± 3 Ma) measured on the same sample by CHOPIN and MONIÉ (1984); the latter is interpreted as a cooling age. The Dora Maira coesite-pyrope quartzite yielded a lower intercept of 121 ± 12–29 Ma and a Rb–Sr whole rock-phengite age of 96 ± 4 Ma.

In conclusion, disregarding the problem of argon excess, the existence of a subduction metamorphism of Eoalpine age wholly across the Europe/Adria collisional zone appeared to be ultimately confirmed at the end of the 1980s (see HUNZIKER et al., 1992, for an extended review of thirty-two years of geochronological work in the Western Alps). As discussed later, in the following decade this chronological belief was criticized on the basis of new dating on retentive systems and lessened.

The post-Lepontine cooling and uplift history of the Penninic nappe pile in the Ossola-Tessin window was reconstructed by WAGNER et al. (1977), showing that this process accelerated from 0.3 to 0.7 mm/y about 6 Ma ago in the Monte Rosa massif and from 0.7 to 1.1 mm/y 3 Ma ago in the underlying Lepontine dome.

Fission-track dating rapidly developed, allowing new temporal constraints on the activity of post-nappe faults and related differential uplift. Zircon and/or apatite fission-track ages were provided by HURFORD et al. (1991) for various localities in the Monte Rosa nappe (Mezzalama and

Arcesa, Ayas valley; Alagna Valsesia; Monte Moro pass, Macugnaga) and other units in the North-Western Alps. In the Ayas valley, zircon from the top of the Monte Rosa nappe and Arcesa-Brusson unit yielded fission-track ages of 34.4 ± 0.3 and 33.3 ± 1.8 Ma, respectively, similar to those sampled in the Valpelline (33.5 ± 1.9: Prarayer; 30.2 ± 1.9 Ma: Oyace) and Arolla series (33.3 ± 2.4 Ma: Matterhorn) of the Dent Blanche nappe. The fundamental regional inference was that Alpine metamorphic rocks from the Monte Rosa-Gran Paradiso nappes and Dent Blanche-Sesia system, which are now at the surface, cooled to similar temperatures of ca. 225 °C during the Oligocene (overall mean of 33 Ma). This interpretation may be extended to the ophiolitic Piedmont units which, in that time, had been already sandwiched between the Austroalpine and Monte Rosa-Gran Paradiso nappes.

Since the beginning, the exhumation mode of Monte Rosa and other high-P units became a critical problem, much more difficult to explain univocally than subduction (see MICHARD et al., 1996, for a careful review of various tectonic reconstructions). The breakthrough was extension of wedge suprastructure coupled with accretion at depth and active plate convergence, cleverly applied to the North-Western Alps by PLATT (1986) and also sustained by POLINO et al. (1990).

Meanwhile, BALLÈVRE et al. (1986) innovated the structural setting and inferred exhumation in the upper part of the orogenic wedge, represented by the Austroalpine outliers (Dent Blanche nappe *s.l.*) and their ophiolitic footwall in the Aosta valley and southern Valais. Two overlapping pairs of continental-oceanic nappes were distinguished: (i) the upper Austroalpine Dent Blanche-Mt. Mary-Pillonet outliers plus the Combin zone, non-eclogitic; (ii) the underlying Mt. Emilius (DAL PIAZ et al., 1983; PENNACCHIONI, 1996), Glacier-Rafray (DAL PIAZ and NERVO, 1971), Etirol-Levaz (BALLÈVRE et al., 1986) and other lower Austroalpine outliers, plus the Zermatt-Saas nappe, all eclogitic (like the underlying Monte Rosa-Gran Paradiso nappes). Contrasting P-T-paths and differential exhumation are recorded in these nappe pairs, which are separated by a pressure gap of at least 0.5 GPa (later also supported by a temporal break of 20–25 Ma; DAL PIAZ, 1999; DAL PIAZ et al., 2001) – therefore by a first-rank tectonic contact. The metamorphic gap was explained by large-scale top-SE extension along the contact (Combin fault) of supposed Late Cretaceous age, later reactivated as an Eocene thrust fault (BALLÈVRE and MERLE, 1993). This extensional exhumation model was corroborated by REDDY et al. (1999) and referred to Eocene times on the basis of white mica Rb–Sr ages from the Combin zone in the Gressoney valley. A top-SE detachment was also envisaged between the exhuming Austroalpine Sesia-Lanzo inlier and underlying Combin zone in the Ayas valley, north of the Aosta-Ranzola fault (WHEELER and BUTLER, 1993). However, its importance is lessened by the absence in that area of a metamorphic break between the non-eclogitic Sesia-Lanzo "Gneiss minuti" complex, Pillonet klippe and their Combin footwall (CORTIANA et al., 1998), and therefore the relative displacement between them was clearly not of the same order as that of the Combin fault (BALLÈVRE and MERLE, 1993).

From the 1980s onwards, after the pioneering work by DAL PIAZ and SACCHI (1969) on the Pillonet klippe and those already mentioned by MILNES (1974) and MILNES et al. (1981), modern structural study began to develop in some areas of the Monte Rosa nappe and ophiolitic Piedmont units across the Swiss-Italian boundary, using mineral stretching lineations and metamorphic fabrics to reconstruct transport directions and kinematic evolution at different times and structural levels (LACASSIN, 1983, 1987; LACASSIN and MATTAUER, 1985; BAIRD and DEWEY, 1986; BALLÈVRE at al., 1986; ELLIS et al., 1989; STECK, 1990; RING and MERLE, 1992; WHEELER and BUTLER, 1993; RING, 1995). Evidence of early top-W thrusting was locally recognized in high-P units (first in the Late Cretaceous blueschist-facies Pillonet klippe; DAL PIAZ and SACCHI, 1969). Dominant greenschist lineations indicated tectonic transport NNW or NW, followed by SE-vergent regional backfolding, generally referred to as Late Oligocene and/or Miocene.

In addition, VAN DER KLAUW et al. (1997) reconstructed in great detail the metamorphic and deformational history recorded in the Zermatt-Saas nappe by the slice of coesite-bearing eclogitic metabasalt, metasediments and related veins of the Cignana lake (REINECKE, 1991), nearly over the buried front of the Monte Rosa nappe, which was exhumed along a decompression and cooling path from a depth of more than 80 km. Among other interesting results are the absence or deletion of the structural record over the first 40 km of the exhuming path.

The Neogene (Neoalpine) evolution of the Monte Rosa nappe (RING and MERLE, 1992) was related to the activity of the Southalpine indenter (SCHMID et al., 1989) and Simplon low-angle normal fault (MILNES et al., 1981; STECK, 1984, 1990; MANCKTELOW, 1985, 1992), allowing the ultimate vertical extrusion of the orogenic wedge, steepening and backthrusting of its inner part, tectonic denudation of the Simplon dome, and lateral SW escape of the hanging Pennine-Graian Alps block of nappes, internally bounded by the 70 km-long sinistral Ospizio Sottile fault zone (BISTACCHI and MASSIRONI, 2000; BISTACCHI et al., 2001).

Important progress was also made on the behaviour of fluids and related brittle tectonics across the collisional nappe stack. I refer to the listvenitic fault breccias in the Zermatt-Saas serpentinites (DAL PIAZ and OMENETTO, 1978) and gold-quartz lodes in the Arcesa-Brusson window (Ayas valley) and Monte Rosa nappe (RICHARD, 1981; DIAMOND and WIEDENBECK, 1986; DIAMOND, 1990), showing that postnappe hydrothermal activity initiated during the Oligocene in the Arcesa-Brusson area, concurrently with the development of the Aosta-Ranzola normal fault and calc-alkaline to ultrapotassic dykes (DAL PIAZ et al., 1979a; BISTACCHI and MASSIRONI, 2000; BISTACCHI et al., 2001), and then shifted towards the Simplon dome, becoming progressively younger (PETTKE et al., 1999a, 1999b). In conclusion, the supposed structural connection between the Monte Rosa and Gran Paradiso nappes through the Arcesa-Brusson unit was noticeably perturbed, together with the overlying Piedmont and Austroalpine units, by the Oligocene (normal) and Neogene (transcurrent) fault systems. Only a single vertical fault (Aosta-Ranzola) was reported in previous tectonic maps (e.g., SPICHER, 1980; BIGI et al., 1990).

5.1. REGIONAL TECTONICS AND SUBSURFACE INTERPRETATION

The elegant profiles by ESCHER et al. (1987, 1993) gave a detailed structural reconstruction of the Pennine-Lepontine nappe stack from the Simplon-Tessin core to the Dent Blanche structural low. Major innovations in the Penninic zone were: (i) new internal subdivision of Grand St. Bernard nappe system (ESCHER, 1988); (ii) linkage of its upper unit (Mont Fort nappe, Permian–Mesozoic) to the Monte Rosa domain (Stockhorn), through thin, semi-continuous, décollement sheets of ophiolite-free Permian–Mesozoic metasediments inside and at the base of the Combin (Tsaté) nappe (MARTHALER, 1984; SARTORI, 1987). In this view, the Stockhorn unit became independent of the Monte Rosa metagranitoids and polymetamorphic basement, with the Stockknubel serpentinitic slice between them. In my opinion, the Mont Fort-Stockhorn correlation needs more investigation: it would be confirmed or discarded by the occurrence in the latter sequences of a relict blueschist-facies (as in the Mont Fort unit) or an eclogitic imprint (as in the Monte Rosa basement). The first solution appears to be favoured by the mineral assemblage (non-eclogitic) of the Gornergrat quartzite dated by RUBATTO and GEBAUER (1999), consisting of phengite (Si: 3.35), albite, quartz, minor epidote and titanite. The metamorphic similarity claimed by these authors between the Gornergrat zone and the eclogitic Monte Rosa basement is not supported by reported metamorphic data and is, in any case, contrasted by the zircon age (35 Ma) which cannot date the Monte Rosa high-P metamorphism (see later).

In the 1980s, the CROP-ECORS deep seismic experiment allowed the buried Alpine belt to be reconstructed along the transect Ivrea zone-Belledonne massif, through the Gran Paradiso nappe, some tens of kilometres south of the Monte Rosa massif. Its major result was the first identification in the Alps of two Moho discontinuities (instead of the classic one), supporting the roles of Europe and Adria as colliding lower and upper plates respectively, and the Austroalpine-Penninic wedge between them, floating over the former lithospheric plate and indented by the latter (NICOLAS et al., 1990; POLINO et al., 1990; DAL PIAZ, 1999). A new general profile of the CROP traverse (in progress) is based on the geological and structural survey at 1:10,000 scale recently accomplished by the Regione Valle d'Aosta for the 1:50,000 Geological Map of Italy, sheets Courmayeur (Torino University), Aosta (Torino CNR) and Chatillon (Padova University). It is at odds with various points of the profile compiled by SCHMID and KISSLING (2000) along the same transect.

The deep crustal structure of the Swiss Alps was systematically investigated (NRP 20, 1986–1995) by integration of geophysical and geological projects (PFIFFNER et al., 1997). Seismic profiles W2 (Anniviers valley), W3 (Zermatt valley) and W4 (Findelen-Zermatt-Zmutt) were the bases for detailed reconstructions of the Penninic nappe stack in the Valais area (STECK et al., 1997). In particular, the W3 and W4 images are rich in information about the tip of the Adriatic mantle, Penninic wedge basal boundary and its overturned inner sector (to ca. 35 km), inverted limb of the Mischabel backfold, and flat to gently folded Monte Rosa-Antrona contact. Accordingly, the structural setting of the Western Swiss-Italian Alps was revisited and synthetized in a global profile (ESCHER et al., 1997) which extends the surface interpretation of previous cross-sections (ESCHER et al., 1987) to depths of 30–70 km.

Focusing on the Monte Rosa nappe, it is depicted as a huge NW-vergent isoclinal recumbent anticline (ARGAND's fold-nappe), strongly refold-

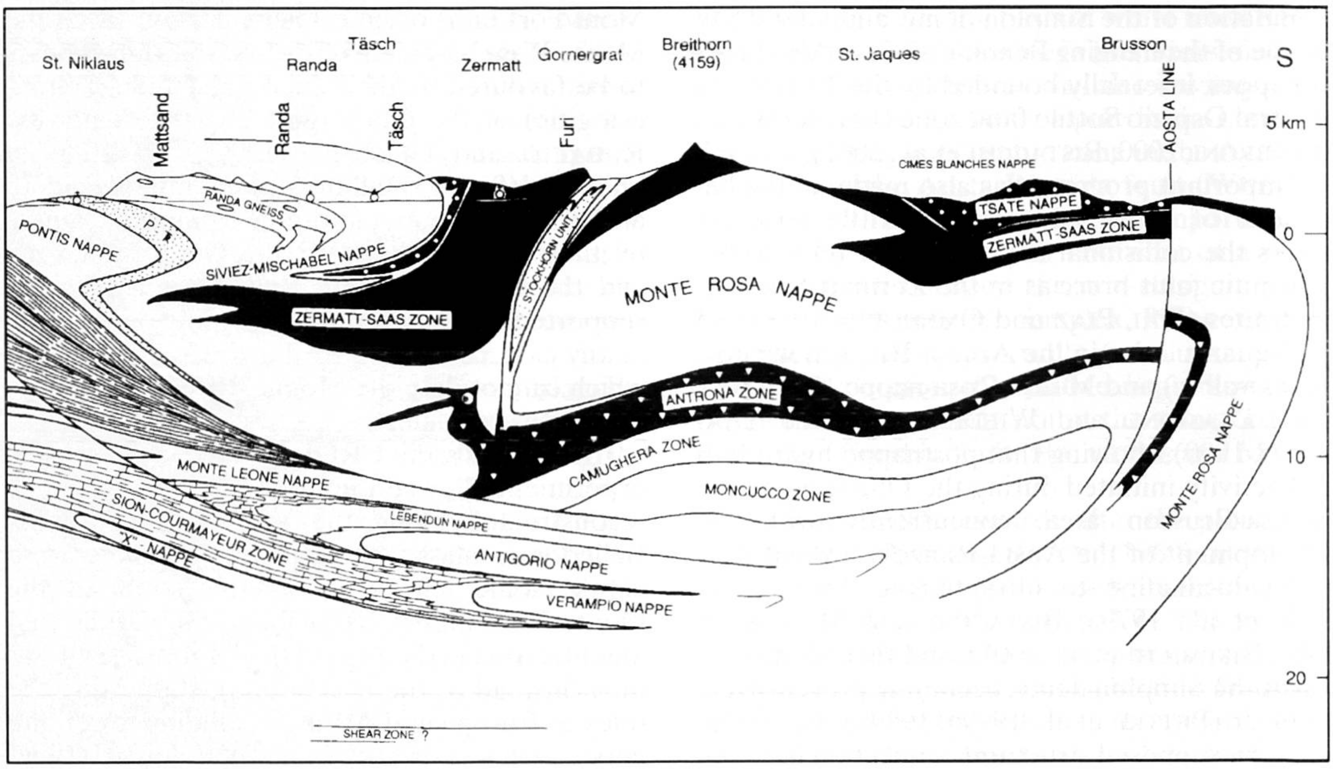

Fig. 7 Geological interpretation of the W3 seismic profile (N–S) Visp-Zermatt-Brusson (STECK et al., 1997). Its northern segment (Visp-Stalden) is omitted. In fact, south of Brusson and the related Oligocene extensional fault, the upper-inner Penninic basement nappe reappears in the Arcesa-Brusson window and then gently merges south, towards the Gran Paradiso dome (GOSSO et al., 1979; BISTACCHI et al., 2001).

ed by S-vergent backfolds of supposed Oligocene age (STECK et al., 1997; ESCHER et al., 1997; Fig. 7). It may be noted, however, that backfolding in the inner side of the nappe stack (Gressoney and Ayas valleys) predates the ultrapotassic dykes, quartz lodes and Aosta-Ranzola fault system, all of Oligocene age (GOSSO et al., 1979; BISTACCHI et al., 2001, and refs. therein). According to previous literature, the nappe core is described by ESCHER et al. (1997) as built up of high-grade paragneisses and minor basic rocks intruded by Late Paleozoic granitoids and mantled by an envelope of the same paragneisses with some Permian–Carboniferous schists and conglomerates. The polyphase Alpine metamorphism is still referred to as Cretaceous (high-P) and Tertiary (greenschist-amphibolite facies). The Stockhorn basement (garnet micaschists and albitic schists) and overlying Gornergrat Permian–Mesozoic cover (BEARTH, 1953, 1967; AUBERT et al., 1980) is interpreted as an inner extension of the Mont Fort nappe (ESCHER, 1988), whereas the Mesozoic cover sequences actually belonging to the Monte Rosa nappe should be restricted only to its frontal part, forming the Furgg zone *s.s.*

Lastly, ESCHER et al. (1997) emphasize in the buried part of their general profile the cylindristic reconstruction of the so called root zone and inner extension of the European lower crust, without any seismic evidence. I cannot agree, and also dislike the backfolded "roots" of the Monte Rosa nappe described south of the Aosta-Ranzola fault (Fig. 7), where the Monte Rosa and Gran Paradiso nappes are expected to be gently connected along the same structural level below the tectonic low of the Aosta valley, and deformed by the Oligocene normal fault system (Fig. 3, G–G' in BISTACCHI et al., 2001).

5.2. RECENT ISOTOPE CHRONOLOGY AND STRUCTURAL INFERENCES

In the last decade, the generalized Eoalpine age long attributed to subduction metamorphism as a whole (HUNZIKER et al., 1992, and refs. therein) has been criticized, thanks to Tertiary datings on retentive systems and recognition of argon excess in the inner Western Alps: first in the coesite-bearing unit of the Dora-Maira nappe (see GEBAUER, 1999, for a review) and Zermatt-Saas eclogites (BOWTELL et al., 1994; RUBATTO et al., 1998; AMATO et al., 1999; MAYER et al., 1999; DAL PIAZ et al., 2001) on both sides of the Aosta-Ranzola normal fault system, and then in the Gornergrat zone (assumed as a remnant of the Monte Rosa cover; RUBATTO and GEBAUER, 1999) and lower Austroalpine outliers (DAL PIAZ et al., 2001). In conclusion, we now know that subduction metamorphism developed in the Late Cretaceous (75–69 Ma) only in the eclogitic Sesia-Lanzo zone (GEBAUER, 1999, and refs. therein), blueschist-facies Pillonet klippe (CORTIANA et al., 1998) and probably the entire upper Austroalpine Dent Blanche-Mt. Mary-Pillonet thrust system (DAL PIAZ, 1999). In contrast, the eclogitic imprint in the Mt. Emilius, Glacier-Rafray, Etirol-Levaz and other lower Austroalpine outliers and Zermatt-Saas ophiolite is of Early–Middle Eocene age (50–42 Ma; DAL PIAZ et al., 2001). The occurrence of a temporal gap (20–25 Ma) in these subducted units, instead of an outward rejuvenating sequence of isotopic ages, may reflect discontinuous exhumation processes and/or loss at depth of oceanic material (DAL PIAZ, 1999).

In this view, it may be noted that the ophiolitic Piedmont zone is a complex tectonic multilayer which also includes the Combin zone (composite nappe), oddly neglected in recent reviews on subduction metamorphism and its timing (dealing only with the Zermatt-Saas nappe), and inferred restoration of the western Alpine Tethyan ocean (e.g., FROITZHEIM et al., 1996; RUBATTO et al., 1998; GEBAUER, 1999). Indeed, the relict blueschist minerals from the greenschist-facies Combin zone are not yet dated and may yield an age (Latest Cretaceous and/or Paleocene, > 50 Ma ?) intermediate between those obtained in the overlying Pillonet klippe and underlying Zermatt-Saas nappe (DAL PIAZ, 1999). In addition, without robust dating, it is still difficult to establish whether the present sequence of nappes is really and fully consistent with their original location in Western Alpine Tethys, i.e., with the order in which these units entered the subduction zone. If so, the temporal gap between the Sesia-Lanzo and Pillonet high-P climax and that in the underlying oceanic and continental units could be partly or completely filled by the interposed Combin zone, accreted below the exhuming upper Austroalpine outliers (MARTHALER and STAMPFLI, 1989; DAL PIAZ, 1999; DAL PIAZ et al., 2001). This hypothesis fits the steady-state low thermal regime by continuing subduction of cool oceanic lithosphere, inferred from petrological and other constraints (SPALLA et al., 1996).

Focusing on the debated age of the high-P metamorphism in the Monte Rosa and Gran Paradiso nappes, its Eocene development may be reasonably assumed (FROITZHEIM et al., 1996; DAL PIAZ, 1999; GEBAUER, 1999) on the basis of various arguments, i.e.: (i) correlation with recent dating in the Dora Maira coesite-bearing eclogitic crust; (ii) evidence of argon excess in high-P micas from mafic and felsic systems; (iii) Lower–Middle Eocene ages in the overlying eclogitic Zermatt-Saas nappe and lower Austroalpine outliers; (iv) Tertiary age (post-Lutethian, <43 Ma) of the blueschist-facies imprint in the Briançonnais cover and basement units (MICHARD et al., 1996, and refs. therein).

In the Monte Rosa case, however, this interpretation is apparently contradicted by the previously mentioned Cretaceous Rb–Sr age obtained by PAQUETTE et al. (1989) on white micas from the felsic high-P schists. In my opinion, the Rb–Sr age from the Verra cirque (Ayas valley) is geologically meaningless, and is probably due to disequilibrium by inherited pre-eclogitic components and water-deficient conditions, like those recognized in pre-Alpine mylonites of the upper Austroalpine Mt. Mary outlier (PENNACCHIONI and CESARE, 1997). Further investigations are needed for ultimately tackling the problem of the eclogitic metamorphism in the Monte Rosa nappe and related paleostructural inferences.

Whatever the age may be, the subduction thermal regime had already changed in the Late Eocene, when "Mesoalpine" greenschist- to amphibolite-facies metamorphism (thermal relaxation and heating) developed in the collisional nappe stack, including Monte Rosa (peak at 38–40 Ma; HUNZIKER, 1970; HUNZIKER et al., 1992; ESCHER et al., 1997; REDDY et al., 1999). This temporal estimate is confirmed by consistent ages (around 35 Ma) of late-metamorphic back-thrusting and folding on the already shallower Penninic wedge from the Aosta valley (Grand Nomenon-Entrelor: FREEMAN et al., 1995) to southern Valais (Mischabel: BARNICOAT et al., 1995; MARKLEY et al., 1998), previously thought to be noticeably younger.

This means that the U–Pb age (35 Ma) obtained by RUBATTO and GEBAUER (1999) on the Gornergrat zone represents only the post-eclogitic evolution if this metasedimentary cover is referred to the Monte Rosa nappe; alternatively, it dates a blueschist-facies climax similar to that in the Grand St. Bernard system – additional proof that the Gornergrat zone may be correlated with the blueschist Mont Fort nappe (ESCHER et al., 1987, 1997).

5.3. PALEOSTRUCTURAL RESTORATION

The European passive margin was regarded as the birthplace of the Penninic continental nappes in classic and most modern reconstructions of western Alpine Tethys, based on facies analysis of sedimentary cover, present superposition order of nappes and direction of tectonic transport, later integrated by the distribution of subduction metamorphism and its debated age (see MICHARD et al., 1996, for a review). In particular, the Penninic internal massifs (Monte Rosa, Gran Paradiso and Dora Maira) were restored along the greatly thinned ocean-facing border zone (pre-Piedmont; ELTER, 1972, and refs. therein) of the middle Penninic Briançonnais domain, north-west of the Piedmont ocean (e.g., DAL PIAZ et al., 1972; ELTER, 1972; DAL PIAZ, 1974, 1999; BECCALUVA et al., 1984; COMPAGNONI et al., 1977; CABY et al., 1978; TRÜMPY, 1980; BALLÈVRE et al., 1986; BALLÈVRE and MERLE, 1993; MICHARD et al., 1996; ESCHER et al., 1997).

Alternative reconstructions envisaged the original position of the Monte Rosa continental crust inside the ocean, as a microcontinent (PLATT, 1986), along the Adriatic margin (HUNZIKER et al., 1989; POLINO et al., 1990; STAMPFLI et al., 1998) or once again on the European side, but beyond the Briançonnais and Valais domains, i.e., far from the continent-ocean transition (MILNES et al., 1981; FROITZHEIM, 1997, 2001). The Monte Rosa and Gran Paradiso nappes may even be regarded as derived from an extensional allochthon (DAL PIAZ and GOSSO, 1994) like those envisaged for the original source of the Sesia-Lanzo zone (FROITZHEIM and MANATSCHAL, 1996) and/or the eclogitic lower Austroalpine outliers (DAL PIAZ, 1999).

The restoration of the inner Penninic nappes on the Adriatic margin (future upper plate) was inferred from the supposed Cretaceous age of the eclogitic imprint, presuming that the present sequence of nappes does not reflect their original position, strongly perturbed during ductile accretion at depth and/or exhumation (HUNZIKER et al., 1989; POLINO et al., 1990).

More recently, the paleogeographic inferences envisaged by MILNES et al. (1981) from the stepwise restoration of post-nappe folds in the Gran St. Bernard-Monte Rosa-Piedmont nappe stack have been reappraised by FROITZHEIM (1997, 2001), dealing with the sequence of middle to inner Penninic nappes represented, from bottom to top, by the Gran St. Bernard, Antrona, Monte Rosa, Zermatt-Saas and Combin units. FROITZHEIM confirmed a more external (north-west) origin for the Monte Rosa continental crust than the Grand St. Bernard nappe system. In particular: (i) the Monte Rosa was allocated beyond the Valais basin, becoming part of the inner Helvetic-Subpenninic domain; (ii) the Monte Rosa nappe was overlain by the Valais (North-Penninic) oceanic suture, supposedly represented (from south to north) by the Furgg zone, Antrona ophiolite and Sion-Courmayeur flysch zone, and in turn capped by the south-eastward wedging and originally internal Gran St. Bernard system; (iii) these continental nappes and the intervening Valais suture (Furgg zone) were overlain by the Zermatt-Saas and Combin ophiolitic units (Piedmont-Ligurian ocean); (iv) the Monte Rosa and Gran Paradiso nappes were subducted during a late collisional stage, in Eocene to very early Oligocene times, based on zircon dating by RUBATTO and GEBAUER (1999) on the Gornergrat zone.

Two principal points against this hypothesis may be pointed out. First, in spite of the correct retrodeformation, this approach only concerns the latest steps of a long accretion-exhumation history. Indeed, in terms of paleostructural reconstruction, one cannot discern what happened during the large-scale transpositions and mylonitic flows which developed inside the subduction complex during the so-called F1 group of high-P deformations, before the ultimate juxtaposition of the nappes concerned (e.g.,GOSSO et al., 1979; POLINO et al., 1990; VAN DER KLAUW et al., 1997). Therefore, different paleostructural settings cannot be excluded.

Second, FROITZHEIM's reconstruction implies that the Monte Rosa continental crust entered the subduction zone after the Briançonnais and Valais domains. As previously discussed, this possibility is contradicted by the Barrovian reequilibration (38–40 Ma) which postdates the eclogitic imprint and makes the zircon age (35 Ma) of the Gornergrat zone unreliable (RUBATTO and GEBAUER, 1999) if it is also used to date the eclogitic climax in the Monte Rosa nappe. Zircon fission-track dating ultimately demonstrates that, around 33–35 Ma, the Austroalpine-Piedmont-Monte Rosa nappe stack in the Aosta valley area was essentially exhumed and cooled to ca. 225 °C (HURFORD et al., 1991). Therefore, there is no conclusive evidence for displacing the birthplace of the Monte Rosa continental crust from its classic pre-Piedmont position.

5.4. RECENT WORK

In the last few years, field and laboratory work on the Monte Rosa nappe, Furgg zone and surrounding Antrona and Zermatt-Saas ophiolites has been reappraised by the Basel, Bern, Lausanne and Mainz teams.

JABOYEDOFF et al. (1996) studied the Furgg zone in the Monte della Preja area, Antrona valley, along the contact between the frontal part of the Monte Rosa basement and the Portjengrat unit, strongly affected by backfolding. The Furgg zone was subdivided into three units: (i) lower Furgg zone, consisting of garnet paragneiss and micaschists with some mafic boudins; (ii) middle Furgg zone, consisting of basal dolostones with minor thin interbeddings of quartzites, bluish marble and capping arenaceous calcscists, cut by some metabasalt dykes; (iii) upper Furgg zone, consisting of garnet paragneiss and gneissic aplites (interpreted, without conclusive evidence, as leucocratic metasediments) which include abundant mafic boudins. As a whole, these three units are thought to represent a post-Variscan sedimentary cover of the Monte Rosa basement, extending respectively from the Permian–Carboniferous, through the Triassic–Liassic, to the Middle Jurassic (Cretaceous, according to STECK et al. 1999). Lastly, this sequence has been subdivided into the Cavalli series (post-Variscan Paleozoic), corresponding to BEARTH's Furgg zone, and the Preja series, extending from the Lower Triassic to the Middle (Upper?) Jurassic, and both transected by tholeiitic basalt dykes (STECK et al., 2001).

The points of view of JABOYEDOFF et al. (1996) and ESCHER et al. (1997) are figured and developed in the 1:100,000 tectonic map of the Western Swiss Alps (STECK et al., 1999), as follows: (i) BEARTHS's Gornergrat zone is eliminated and substituted by the Mesozoic cover of the Stockhorn unit (Mont Fort nappe, Paleozoic) and the Permian–Cretaceous metasediments of the overlying Cimes Blanches nappe; (ii) the latter nappe extends to the Saas valley, between the Zermatt-Saas ophiolites and the underlying Monte Rosa and Siviez-Mischabel basements (including Portjengrat), and inside the latter; (iii) the northern Furgg zone is re-interpreted as the Triassic–Cretaceous cover of the Monte Rosa nappe and named *"marbres et flysch à blocs"*; it is subdivided into two segments: the former is limited to the Stokknubel zone and does not include the serpentinitic slices; the latter mantles the northern (frontal) and eastern (lower) margins of the Monte Rosa basement, continuously extending from the Saas valley to the Antrona-Anzasca divide, in tectonic contact with the Antrona ophiolites; (iv) the southern Furgg zone is not depicted.

Other preliminary results were presented at the 17th Swiss Tectonic Studies Group Meeting and Monte Rosa 2000. Among them are the U–Pb SHRIMP dating of zircon (270 ± 4 Ma) and monazite (268 ± 2 Ma) from the Monte Rosa granite in the upper Ayas valley (LANGE et al., 2000), new petrological estimates on high-P shear zones inside metagranites ($P \geq 1.7$ GPa, $T < 600$ °C, LANGE et al., 2000; see also CHOPIN and MONIÉ, 1984, DAL PIAZ and LOMBARDO, 1986), and the hypothesis that the Furgg zone is a tectonic mélange which developed as a shear zone between Piedmont ophiolites (Zermatt-Saas and Antrona), Monte Rosa and Portjengrat units (KRAMER, 2000), according to previous suggestions by BEARTH and MILNES. KRAMER also confirmed the link between the Stockhorn and Portjengrat elements, originally thought to be a continuous unit belonging to the Siviez-Mischabel unit (Gran St. Bernard nappe).

In the upper Ayas valley, PAWLIG et al. (2001) also attempted to date by ^{40}Ar–^{39}Ar UV-laser ablation relict muscovites, phengites and greenschist-facies white micas from talc-kyanite-chloritoid mylonitic schists occurring inside metagranites (DAL PIAZ, 1971; DAL PIAZ and LOMBARDO, 1986), previously dated by CHOPIN and MONIÉ (1984; ^{40}Ar–^{39}Ar: 110 Ma) and PAQUETTE et al. (1989; Rb–Sr: 102 and 91 Ma) and supposedly developed in "dry and static high-P conditions". The obtained results display a broad distribution of ages from 290 to 140 Ma, with geologically meaningless modes (in my opinion) around 250 and 190 Ma, in spite of the undoubted Alpine age of these high-P shear zones (even if rifting forerunners are presumed).

KELLER and SCHMID (2001) studied the contacts between the Monte Rosa nappe, Furgg zone, Portjengrat unit and Antrona ophiolite in the Loranco valley (eastern Monte Rosa), concluding that this Furgg zone segment is derived from basement and cover rocks of the Portjengrat unit, intruded by post-Triassic mafic dykes (JABOYEDOFF et al., 1996), and that it does not represent an ophiolitic mélange. Moreover, the nappe stack before D3 straining turns out to consist, from bottom to top, of Antrona ophiolite (Valais ocean), Monte Rosa-Furgg zone-Portjengrat continental fragment (eclogite facies part of the Briançonnais) and Zermatt-Saas ophiolite (Piedmont-Ligurian ocean).

Zircons from two rocks of the northern Furgg zone (BEARTH, 1954) were dated by LIATI et al. (2001a, 2001b) using the U–Pb SHRIMP technique: (i) a large eclogitic boudin re-equilibrated in amphibolite facies conditions occurring in the Andolla area, upper Loranco valley, inside marbles of probably Triassic age which may be representative of the Furgg zone (JABOYEDOFF et al., 1996; STECK et al., 1999) or the Monte Rosa sedimentary cover (KELLER and SCHMID, 2001); (ii) the leucocratic gneissic matrix enveloping, together with Permian–Early Triassic metaconglomerates and schists, abundant mafic boudins, north-west of Mattmark dam, upper Saas valley. Zircon magmatic domains from the former sample yielded a weighted mean Cambrian age (510 ± 5 Ma) which was interpreted as the time of crystallization of the gabbroid protolith. This is the first isotopic proof of the existence of old protoliths among the Monte Rosa mafic rocks, as previously documented from field evidence in the polymetamorphic southern side of the massif (Dal Piaz, 1964; 1966). Nevertheless, still unsolved is the question of why the polyphase and pervasive Alpine metamorphism only left faint traces in the zircons and no evidence of the anatectic event, granulitic imprint and possible older metamorphic pulses which developed regionally before, during and after the Variscan orogeny in the Western Alps. Co-magmatic domains of zircons from the Mattmark leucocratic orthogneiss yielded a weighted mean age of 272 ± 4 Ma, which was interpreted as the time of crystallization of the igneous protolith.

This result is consistent with other recent datings on the Monte Rosa granite in the Verra cirque (Lange et al., 2000) and slightly younger than igneous zircons from some Austroalpine granitoid and gabbroid protoliths (Paquette et al., 1989; Bussy et al., 1998).

Chemical Th–U–Pb dating (EMPA) of single monazite grains selected from numerous pre-granitic metapelites of the Monte Rosa nappe (Anzasca and Antrona valleys) and its eastern tail has been provided by Engi et al. (2001b) and integrated by P-T calculations on the polymetamorphic evolution of host rocks. Essential results are: (i) monazite included in old garnet from two samples records ages of 330 Ma, supposedly corresponding to the intrusion of the main Monte Rosa granodiorite pluton; (ii) some high-grade metapelites retain monazite grains which formed some 260 Ma ago in supposed response to the intrusion of minor granitic bodies; (iii) the same stage of low to medium pressure is regionally recorded by monazite inclusions inside garnets from metapelites and migmatitic restites; it may represent a regional event at a depth of 10–20 km, associated with abundant leucocratic dykes and small stocks, or widespread contact metamorphism; (iv) there is no evidence of high-P metamorphism of Cretaceous age; (v) petrological estimates on kyanite-garnet-phengite ± staurolite mineral assemblages (P: from 0.92 ± 0.18 to 1.2 ± 0.15 GPa; T: from 595 ± 25 to 755 ± 65 °C) give median conditions of 1.0 ± 0.12 GPa and 625 ± 41 °C, with no significant regional gradient; (vi) monazite dating of this stage ranges from 46 to 31 Ma, with most ages between 38 and 32 Ma, probably representing partial re-equilibration upon decompression; vii) the very few younger monazite ages (< 30 Ma) may represent the late Alpine thermal overprint.

The existence of a narrow tectonic accretion channel has been envisaged at the subducting plate boundary in the southern steep belt of the Central Alps, and has been tested by numerical models (Engi et al. 2001a). Simulations indicate that accretion of felsic crust enriched in radioactive elements to mantle depth would be a suitable mechanism to generate the P-T-t paths recorded by natural rocks, as well as the late-orogenic magmatism. This model also has good chances of suiting the inner part of the western Alpine accretionary wedge.

6. Concluding remarks

After the fundamental work and systematic mapping of Peter Bearth, knowledge on the Alpine and pre-Alpine history of the Monte Rosa nappe noticeably advanced through a growing body of field and modern laboratory data. Nevertheless, recent progress has also given rise to contrasting interpretations, mainly on the composition, age and origin of some units. Indeed, some recostructions reflect attempts at regionally extrapolating local or unilateral observations; others are based on uncertain or scanty data, or underevaluate essential constraints. This mainly concerns the large data-base of isotopic data which, in some instances, would have gained by more discussion on their geological and petrological meaning prior to their use in geodynamic reconstructions. In addition, some crucial questions are still open.

In this view, I hope that a tentative synthesis of generally accepted points, debated interpretations and open questions would be welcome as a conclusion to this geological journey across the "Queen of the Alps".

In my opinion, nowadays there is no essential uncertainty about the main lithology, igneous and tectono-metamorphic evolution of the Monte Rosa basement, whereas there are contrasting views on its post-Variscan cover, lithological composition and meaning of the Furgg zone, and the original position of the Monte Rosa domain before the Alpine orogeny.

6.1. PRE-ALPINE FEATURES

The Monte Rosa basement is a fragment of continental crust consisting of a composite batholith (mainly granitic-granodioritic) of Late Paleozoic age and roofing paragneisses which were transposed and reworked to different extents by the

Alpine tectono-metamorphic overprint from subduction to continental collision. The pre-granitic metamorphic complex includes some horizons very rich in boudinaged mafic bodies and minor marbles which are particularly abundant on the Italian southern side of the massif, constituting the main marker of the southern Furgg zone (DAL PIAZ, 1964, 1966). Similar basement protoliths and mafic enclaves may also be seen in the Arcesa-Brusson window, south of the Aosta-Ranzola fault, and in the Gran Paradiso massif (DAL PIAZ and LOMBARDO, 1986, and refs. therein).

Disregarding the Alpine overprint, the pre-granitic gneissic complex is dominated by high-grade metapelites, characterized by garnet-biotite-sillimanite mineral assemblages and the late development of cordierite-rich anatectic melts (*in situ* to mobilized) which clearly predate the sharp granitic intrusion, as it is documented by overprinting patterns in Alpine low strain domains. Temperature estimates and mineral compatibilities are similar to those of the Austroalpine kinzigites, equally rich in migmatites. The absence of exhaustive radiometric data and the isotope resetting of pre-Alpine relics prevent the high-grade gneissic imprint from being precisely dated. Nevertheless, the regional fabric may probably be referred to the Variscan orogeny (by regional comparisons), as well as its depressuring evolution (post-thickening collapse) if the main granite-granodiorite intrusion is Late Carboniferous in age (HUNZIKER, 1970; FREY et al., 1976; ENGI et al., 2001b). Conversely, if the Monte Rosa intrusions are wholly or mostly Late Permian in age (LANGE et al., 2000), it is likely that the anatectic activity and subsequent discordant emplacement of the Monte Rosa igneous suite represent the incoming lithospheric extension (post-Variscan) and related thermal perturbation which, extensively recorded in the Southalpine basement and elsewhere in the Alps, anticipated the opening of the Tethyan basin (LARDEAUX and SPALLA, 1991; DAL PIAZ, 1993, DAL PIAZ and MARTIN, 1998, and refs. therein).

The Verra pluton, dated as Late Permian by LANGE et al. (2000) and probably linked to BEARTH's Monte Rosa (Gorner-Grenz) body, and the main intrusion of supposed Late Carboniferous age (ENGI et al., 2001b) which dominates the eastern side of the massif, occur at different structural levels inside different subnappes (DAL PIAZ, 1966; WETZEL, 1972; MÜLLER, 1983). In spite of this, essential mineral and textural features of the present-day upper and lower porphyric granite-granodiorite bodies are identical, so that a nearly concurrent emplacement cannot be ultimately excluded. Alternatively, a long period of igneous activity may be envisaged.

In any case, field evidence shows that these principal igneous bodies, mainly porphyric, are followed by younger leucogranitic intrusions (with magmatic breccias as in the Gran Paradiso basement; CALLEGARI et al., 1969), and then by various systems of aplitic and pegmatitic dykes, whereas there is no trace of intermediate and mafic rocks like those in the various Permian and Tertiary calc-alkaline suites of the Alps.

In conclusion, whatever the main intrusion age may be, the high-T evolution of the Monte Rosa crust from the Carboniferous–Permian boundary onwards is clearly supported by the monazite population age of 288 ± 32 Ma, regionally documented in roofing metapelites by ENGI et al. (2001b).

Lastly, a very old history is suggested by the Cambrian zircon age (510 ± 5 Ma) recently obtained in a mafic boudin from the Loranco valley (LIATI et al., 2001b). This single datum is a promising starting-point for future advances, but at present nothing else may be inferred on the igneous, metamorphic and deformation features of the pre-Variscan crust, as no significant mineral relics are preserved.

6.2. SEDIMENTARY COVER

BEARTH's Gornergrat zone is the metasedimentary cover of the Stokhorn basement unit, recently taken from the Monte Rosa nappe and correlated to the Mont Fort upper unit of the Gran St. Bernard system, and in turn overlain by the Permian–Cretaceous Cimes Blanches nappe (ESCHER et al., 1997; STECK et al., 1997, 1999). In this view, the Monte Rosa post-Variscan cover is restricted to the Late Carboniferous–Permian and/or Mesozoic sequences locally associated with the frontal crystalline basement or mainly sliced inside the northern Furgg zone (JABOYEDOFF et al., 1996; ESCHER et al., 1997).

Although I was one of the authors of the tectonic map prepared by STECK et al. (1999), I do not believe that the upper part of Bearth's Gronergrat zone is the northern extension of the Cimes Blanches nappe, named Pancherot-Cime Bianche décollement unit on the Italian side (DAL PIAZ, 1999, and refs. therein). Nor do I agree with its paleogeographic interpretation, mainly because: (i) there is no trace of this ophiolite-free Permian–Mesozoic unit along the southern and western margins of the Monte Rosa nappe; (ii) in the Gressoney-Ayas-Valtournanche area, it occurs inside the lower part of the Combin zone (composite nappe) or along its contact (Combin fault; BALLÈVRE and MERLE, 1993) with the underlying Zermatt-Saas nappe, nearly at the same structural level as the cover-free lower Austroalpine eclogitic basement slices (Mt. Emilius, Etirol-Levaz, Chatillon, etc.) which are probably the best candidates for the origin of this décollement nappe (DAL PIAZ, 1999; DAL PIAZ et al., 2001), previously also referred to the Sesia-Lanzo domain (CABY et al., 1978). In any case, the Mesozoic facies analogy may be explained by originally contiguous basements, later displaced into independent units from rifting and development of extensional allochthons to nappe generation.

Lastly, available data also indicates that the generally accepted Stockhorn-Mont Fort correlation cannot be ultimately established, although it may be supported by the Stockhorn-Portjengrat position (beyond the Furgg zone) and proper reinterpretation of isotopic dating provided by RUBATTO and GEBAUER (1999). Indeed, more information is needed on the protoliths of pre-Eotriassic–Permian basement rocks and their Alpine metamorphic features, particularly concerning the occurrence of blueschist or possible eclogitic relics which are peculiar in the Mont Fort unit and Monte Rosa nappe, respectively. The kyanite-chloritoid silvery schists reported by BEARTH (1952) inside the Stockhorn basement must be reappraised as possibly conclusive markers of its high-P evolution and regional correlation.

6.3. ALPINE EVOLUTION AND RESTORATION PROBLEMS

The Alpine evolution is characterized by an eclogite-facies imprint, diachronously developed in the Austroalpine-Penninic nappe stack. In my opinion, the best dating of the eclogitic metamorphism in the Zermatt-Saas ophiolite (50–43 Ma) is that given by MAYER et al. (1999), by integration of the Sm–Nd age on garnet-omphacite pairs (49 ± 4 Ma) and Rb–Sr cooling ages (46 Ma) on associated white micas. In the underlying Monte Rosa nappe, the high-P imprint is scattered in mafic and felsic rocks with massive to mylonitic fabrics and mainly preserved in the southern side of the Monte Rosa massif (DAL PIAZ and LOMBARDO, 1996). It developed at the beginning of continental collision (DAL PIAZ et al., 1972), underwent rapid exhumation, and was then followed and widely obliterated by a well-dated (Late Eocene–Early Oligocene, Mesoalpine; HUNZIKER et al., 1992; ENGI et al., 2001) greenschist- to amphibolite-facies regional overprint, which increases down across the nappe pile. On the whole, the metamorphic evolution predates the emplacement of the post-metamorphic calc-alkaline to ultrapotassic dykes (30–32 Ma) and the brittle activity of the Aosta-Ranzola and other Late Oligocene fault systems (BISTACCHI et al., 2001). Indeed, the subduction climax of the Monte Rosa nappe was probably attained in Early and/or Middle Eocene times, nearly coeval with or just after that in the overlying Zermatt-Saas eclogites, but before the blueschist-facies imprint in the more external Grand St. Bernard domain, which is constrained by the Lutethian age of top sediments (MICHARD et al., 1996, and refs. therein). The Cretaceous Rb–Sr white mica age (PAQUETTE et al. 1989) has no geological meaning and the ^{40}Ar–^{39}Ar ages (CHOPIN and MONIÉ, 1984) are influenced by argon excess. This is confirmed by the absence of Cretaceous–Paleocene monazite ages among those systematically obtained across the Monte Rosa nappe (ENGI et al., 2001), which range from 46 to 31 Ma and probably represent partial re-equilibration upon decompression and cooling after the Mesoalpine climax.

In this view, the origin of Monte Rosa from the active Adriatic margin must be abandoned. Equally unreliable is a more external origin with respect to the Briançonnais domain, especially if the Valais basin is envisaged between them (FROITZHEIM, 2001). Indeed, the Monte Rosa nappe could not have entered the subduction zone in the Late Eocene–Early Oligocene (RUBATTO and GEBAUER, 1999) because at that time it was overprinted at a relatively shallow level by the Barrovian re-equilibration, cooled nearly to 250 °C (FT zircon; HURFORD et al., 1991) and then cut by post-metamorphic Oligocene dykes. In addition, it may be empasized that the unfolding result obtained by FROITZHEIM (2001; Monte Rosa below Gran St. Bernard) deals only with post-nappe folds, i.e., the last steps of the complex deformational history recorded by the collisional nappe stack. Indeed, nothing is known about the mutual position of these continental units and intervening oceanic slices during prograde evolution and ductile exhumation from different subduction depths (eclogitic vs. blueschist) to the structural level where the ultimate tectonic juxtaposition in greenschist-facies conditions was accomplished (e.g., GOSSO et al., 1979; VAN DER KLAUW et al., 1997).

In conclusion, I prefer to believe that, at the beginning of Alpine contraction, the inner Penninic Monte Rosa-Gran Paradiso-Dora Maira nappe system was one or more thin continental crust fragments located in the European lower plate, probably along the ocean-facing pre-Piedmont inner margin of the Briançonnais domain, or even a ribbon continent-extensional allochthon lost within the ocean (e.g., DAL PIAZ and GOSSO, 1994; DAL PIAZ, 1999).

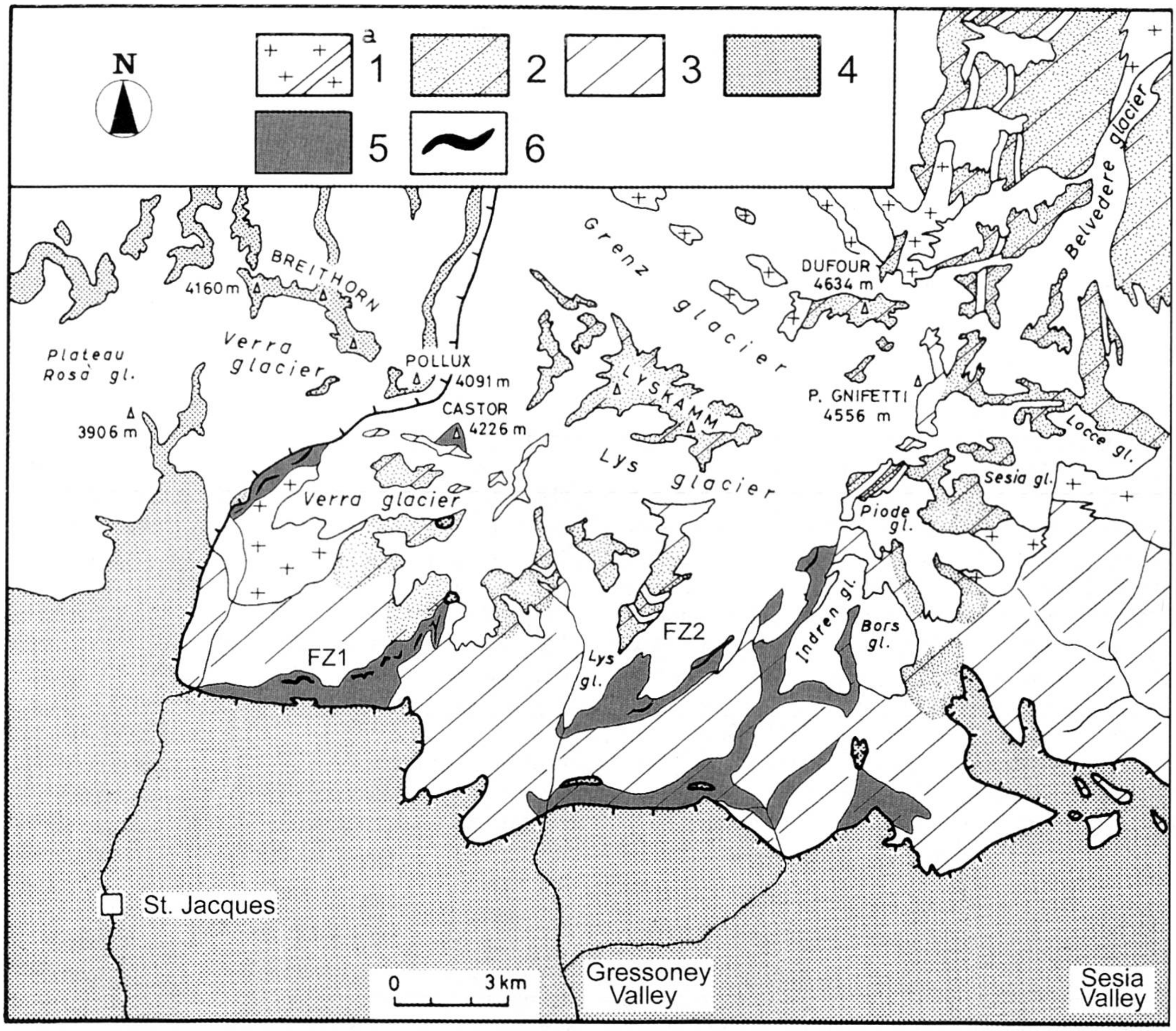

Fig. 8 Association of mafic boudins and minor marbles from pre-granitic protoliths (Furgg zone) inside polymetamorphic paraschists with minor gneissic leucocratic dykes on Italian southern side of Monte Rosa massif (mainly from Dal Piaz, 1966). (1 to 4) as in Fig. 4; (5) Furgg zone on top of Monte Rosa nappe (FZ1, Verra cirque) and inside polymetamorphic basement (FZ2, Gressoney). (6) major occurrences of marbles, enlarged. Note the presence of ophiolitic klippen (metabasalt, mylonitic serpentinite, minor oceanic cover) as sheared synformal cores of recumbent backfolds along Ayas-Gressoney and Gressoney-Sesia divides, clearly distinguished from Furgg-Zone mafic boudins.

6.4. FURGG ZONE

Nowadays, this seems to be the principal problem of the Monte Rosa massif, as various interpretations were suggested after the Furgg zone was conceived by Bearth along the Monte Rosa-Portjengrat boundary, extended southwards by myself, and corroborated by Wetzel in the northern side (Furgg zone s.s.). The matter of debate concerns its location, composition and geological meaning.

1. Bearth's view pointed for an extremely deformed suite of Monte Rosa micaschists, albitic schists and leucocratic gneisses of presumed Permian–Carboniferous age including mafic boudins and multiple interfingerings of Mesozoic metasediments and ophiolites wholly or mainly from the Antrona unit.

2. Dal Piaz's (1964, 1966) study in the Alagna-Gressoney-Ayas area suggested the existence of pre-granitic protoliths, free of evident Mesozoic components and pervasively reworked by the Alpine overprint in eclogite to greenschist-facies conditions. This interpretation is corroborated by Liati et al. (2001), showing that it would also be suitable in the north-eastern side of the massif, at least locally.

3. The Lausanne team (Jaboyedoff et al., 1996; Escher et al., 1997; Steck et al., 1999, 2001)

regarded the northern Furgg-Zone as the real cover of the Monte Rosa basement (instead of BEARTH's Gornegrat zone), represented by a pervasively deformed sequence which originated from terrigenous to carbonate and volcanic protoliths of Permian–Mesozoic age.

4. FROITZHEIM (1997, 2001) sustained the hypothesis that the Furgg zone, as a whole, may be the inner (southern) trace of the Valais suture.

5. KRAMER (2000) favoured a tectonic mélange between continental (Monte Rosa, Portjengrat) and oceanic (Zermatt-Saas, Antrona) units, developing early as a shear zone during nappe transport. The same continental feeders mixed with Antrona ophiolites were recognized by KELLER and SCHMID (2001) in the Loranco valley.

FROITZHEIM's global interpretation is contradicted by the arguments discussed above, like that sustained by the Lausanne team. Whatever is interpreted, the heterogeneous shear zone at present interposed between the Monte Rosa northern margin and the Portjengrat-Stockhorn units cannot be merely reported as a sequence *of "marbres et flysch à blocs"* (STECK et al., 1999). Moreover, the leucocratic intercalations frequently occurring inside the boudin-rich micaschists of the Furgg zone *(s.s.)* are transposed aplitic-leucogranitic dykes rather than Permian metasediments (in my opinion, this is at least the case of some sequences in the Stockknubel and Mattmark areas which closely recall the southern Furgg zone).

The existence of a tectonic mélange (KRAMER, 2000) may fit the northern Furgg zone (*s.s.*), although it may hardly be compared with the classic Ligurian mélanges in Northern Apennines. In any case, this hypothesis cannot be extended to the boudin-rich zones in the Italian side of the massif (southern Furgg zone), which display different features (DAL PIAZ, 1964, 1966).

The southern Furgg zone (Fig. 8) is a ductile shear zone made particularly evident in the field by decimetric to pluridecametric mafic boudins, in places very abundant, and minor saccharoid to impure marbles, both inside strongly alpinized paraschists (high-P garnet micaschists to greenschist-facies two-mica albitic schists) and some dykes of gneissic aplite and leucogranite, now parallel to the Alpine schistosity, without clear evidence of post-granitic (Permian) clastic and carbonate metasediments. Marbles display Ca-Mg amphiboles, epidote, garnet and relict pre-Alpine (?) clinopyroxene, and include boudinaged thin interbeddings of impure quartzite only in the Plateau del Lys area, Gressoney valley. These marbles are probably pre-Mesozoic in age, recalling those of the Austroalpine kinzigites and eclogitic micaschists. In any case, the volcano-sedimentary sequence described by JABOYEDOFF et al. (1996) is completely missing.

The macroscopic features of the mafic boudins are similar to those of the Zermatt-Saas and Antrona metabasalts, all including eclogites and dominant retrogression products (albite-rich amphibolite ± relict garnet). In spite of this analogy and the mutual occurrence of minor white mica, the Monte Rosa eclogitic bodies often display a mylonitic high-P fabric (occasional in ophiolites), recorded by very fine aggregates of sodic pyroxene.

In addition, on the Italian side there is no trace of other peculiar lithologies of a potential oceanic suite, like serpentinite, metagabbro, Mn-metachert or calcschist, which would be expected from a tectonic mélange involving the Piedmont zone, nor of Mesozoic continental cover sequences. Nevertheless, it may be noted that in the Verra cirque (Ayas valley) the Furgg zone is thrust by Mesozoic metabasalts which constitute a strongly sheared lower subunit of the Zermatt-Saas nappe, at the base of the huge Breithorn-Monte Rosso di Verra serpentinitic body. It is unlikely, however, that these metabasalts acted as mélange feeders, because: (i) the present tectonic juxtaposition of Monte Rosa and Zermatt-Saas lithologies is not representative of their relationships during subduction and telescoping exhumation; (ii) most of the mafic boudins and marbles occur inside coherent basement sequences which are extensively transposed but do not display clues of Alpine tectonic mixing; (iii) host rocks are garnet micaschists clearly derived from high-grade paragneisses, and minor leucocratic dykes. All this indicates the pre-granitic age of protoliths (e.g., mafic granulites and/or amphibolites) for most mafic boudins, locally also occurring as cogenetic enclaves within massive metagranites (Sesia valley; DAL PIAZ and GATTO, 1963).

In addition to the Cambrian zircon age found in the Andolla area (LIATI et al., 2001), decisive proof of this chronological interpretation would be the finding of high-grade mineral relics which, unfortunately, have never been found in the southern Monte Rosa massif, but this may simply be due to pervasive shearing, fluid activity, and the sensitiveness of mafic mineral systems to eclogitic re-equilibration. The only exception is the relict brown hornblende found in the Anzasca valley (LADURON, 1976), and its regional significance is corroborated by very similar occurrences in the Gran Paradiso basement (DAL PIAZ and LOMBARDO, 1986, and refs. therein) and by the clinopyroxene in the Lys marbles, if really of pre-Alpine age.

Lastly, the southern Furgg zone is represented by two or more belts located at different structural levels of the Monte Rosa nappe (Dal Piaz, 1966; see also Wetzel's general map, based on these data). The upper belt (FZ-1 in Fig. 8) extends from the Verra cirque to the top of the Gressoney-Ayas divide, near the contact with the overlying Zermatt-Saas nappe. The second, deeper belt (FZ-2) extends from the bottom of the Gressoney valley (Plateau de Lys) to the Indren glacier, Gnifetti ridge and Piramide Vincent southern wall, inside the polymetamorphic basement and far from the Zermatt-Saas ophiolites. Other (deeper) occurrences of mafic boudins and some marbles may be recognized discontinuously in the core of the Monte Rosa nappe (upper Sesia and Anzasca valleys), even inside the Stelli zone (Pizzo Bianco). No essential lithological differences are noted among them.

In conclusion, I prefer to maintain that at least most of the mafic boudins and associated marbles in the southern Monte Rosa basement are not related to the ophiolitic Piedmont zone, and that therefore the southern Furgg zone is not an Alpine tectonic mélange, even though it was affected by severe Alpine shearing. It is very different from the Riffelberg-Garten mélange in the upper part of the Zermatt-Saas nappe (Dal Piaz, 1965; Dal Piaz and Ernst, 1978) consisting of small inclusions of dominant eclogitic metabasalts inside high-P carbonaceous micaschists derived from Mesozoic trench deposits (not pre-Permian basement).

In this view, the southern Furgg zone is a lithotectonic complex of pre-granitic (pre-Permian) age, characterized by abundant mafic boudins and minor marbles inside paraschists ± leucocratic dykes (Permian), like those in other Penninic and Austroalpine basements. Its boundaries may be roughly traced only on the basis of the presence/absence of mafic and marble inclusions, whereas the host paraschists are essentially the same as the surrounding ones, free of inclusions. The marked lithological differences often evident in the field are mainly related to the different extents of polyphase Alpine imprint, which generated eclogitic silvery mylonites, high-P garnet micaschist and greenschist-facies albite-rich schists from the same protoliths.

Second, it is an Alpine shear zone characterized by extreme boudinage which developed in eclogitic conditions and was further reworked by post-nappe foldings and greenschist-facies re-equilibration. The Alpine shear zones generally extend from the southern Furgg zone, involving large areas of paraschists free of inclusion markers which are partly to completely converted to high-P or greenschist-facies schists.

Third, this complex along the nappe boundary during subduction and/or exhumation may have been eventually accreted by a few tectonic slivers (only basalts) scraped off the nearby (at that time) ophiolitic units. This interpretation may be suitable for Bearth's northern Furgg zone and possibly exotic material in the Ayas upper southwestern units (FZ-1), but not in the deeper ones (FZ-2) inside the pre-granitic basement and far from the ophiolitic thrust.

In conclusion, the term Furgg zone is currently used to describe different objects or contrasting interpretations and, in this view, the question arises as to whether the term may usefully be maintained in a general sense.

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