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The Geological Map of Valmalenco

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Abstract

The 'Carta Geologica della Valmalenco' (Montrasio et al., 2005) is the result of a thirty five-year cooperation between ETH and University of Zürich and the University and CNR-Italia at Milano. The map covers an area of about 350 km^2 with the mapping having been carried out by over fifty people, mostly as part of students' theses. The Valmalenco area contains one of the largest ultramafic masses of the Alps, which occurs together with a well preserved, Jurassic to Cretaceous ocean floor suite. These units are sandwiched in between nappes derived from the Adriatic microplate and the European plate. The ultramafic rocks are of subcontinental origin and preserve on their top a Permian, continental, crust-mantle transition. During Jurassic rifting these rocks were exposed at the Adriatic margin of the Piemontese-Ligurian ocean basin. Two orogenic cycles affected the Adriatic margin: the first is related to Late Cretaceous nappe stacking, whereas the second is due to the Tertiary continental collision. At the end of collision, the Malenco rocks were, in their southwestern part, intruded by the calc-alkaline, Oligocene, Bergell complex. The Bergell rocks present an exceptionally rich variety of magmatic phenomena and a well-defined contact aureole. The area affected by contact metamorphism is an outstanding natural laboratory to study metamorphic and metasomatic processes. Isograds of prograde metamorphism of serpentinite and of ophicarbonate rocks were mapped for the first time in the Valmalenco, and the results integrated into a consistent petrological model.

1. Introduction

In 1865, Gottfried Ludwig Theobald (1810–1869) published the first coherent geological map of Valmalenco, exactly 139 years before the present map was printed in November 2004. Theobald's geological map comprised an area from the Swiss Engadine Valley down to the Valtellina Valley in northern Italy. As topographic basis served sheet XX, Sondrio-Bormio of the famous Dufour map, which, at a scale of 1:100'000, was the first official map of Switzerland.

A great step ahead was subsequently the Bernina map 1:50'000 by Rudolf Staub (published in 1946), which covers a major part of the Malenco area and which was based upon lithological as well as on tectonic criteria. Many of the crystalline rocks were given local names and not petrographic ones. Despite these shortcomings Staub's work remains a masterpiece of Alpine geologic mapping and the effort of one man to map such an enormous area deserves high appreciation.

Between 1969 and 1970, three sheets of the Carta Geologica d'Italia were published at a scale of 1:100'000. These sheets, i.e. 7–18: Pizzo Bernina-Sondrio (1970); 9: Tirano (1969) and 8: Bormio (1970) cover the whole Malenco area. The base mapping in Valmalenco for these sheets was carried out at a scale of 1:25'000 by Montrasio and by Venzo and co-workers, who published an additional map in 1971 (Venzo et al., 1971). The tectonic units given in these maps are essentially the same as in Staub's map, but a number of rock units had to be redefined, in particular for the crystalline basement rocks.

With Rudolf Staub's map and the Carta Geologica d'Italia as a basis and with the introduction of the concept of plate tectonics to Geology, the Malenco area received increasing attention. This area contains one of the largest ultramafic masses in the Alps, belonging to the Malenco unit, and a well-preserved ocean floor suite, the Forno unit. Both these units are sandwiched in between crystalline nappes, respectively, derived from the Adriatic microplate and from the European plate.

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A calc-alkaline igneous complex, the Bergell Intrusives, cross-cuts adjacent units during the Oligocene. The Valmalenco area has become an exceptional area for geological studies owing to its large variety of rock types, including mantle peridotites, continental lower and upper crust, oceanic crust and sedimentary rocks, all occurring together in a major suture zone of the Alpine orogeny. In order to understand the complex geologic evolution of the Valmalenco area, detailed remapping of the area was required.

2. Mapping procedure and criteria

The map of Valmalenco 1:25'000 presented here (Montrasio et al., 2005) covers an area of about 350 km^2 and reaches from the Bernina mountains at the Swiss-Italian border in the North to Sondrio in the Valtellina Valley in the South, and from Val Poschiavo in the East to the area of Val Masino in the West. The map covers the entire exposure of the Valmalenco ultramafic rocks. It is the result of a 35-year collaborative research between scientists from the Italian National Research Center (CNR) and the University at Milano and scientists from the Swiss Federal Institute of Technology (ETH) and the University of Zürich. Under the guidance of the scientific coordinators, over fifty students were involved in the mapping project, with Diploma and Ph.D. theses from Zürich and Tesi di Laurea from Milano, respectively. All names of researchers involved in the detailed mapping campaign are listed on the map and the titles of their diploma and Ph.D. theses are given in the references.

The base mapping for the published sheet was performed throughout the area at a scale of 1:10'000. Some critical regions were re-mapped to ensure consistency. The authors involved in the scientific coordination and in compiling the map supported the students and checked their work in the entire area. They also mapped the gaps remaining between individual thesis areas. After their Ph.D. theses, the three compilers were employed for one year each to combine the individual base maps into a coherent 1:25'000 map sheet.

Mapping has been based strictly on lithologic criteria, i.e. petrographic, structural and lithostratigraphic observations. In the legend, individual lithological units are grouped in the order of their superposition and according to a tectonic scheme, which is given in the lower left corner of the map sheet. Boundaries between different tectonic zones are not shown on the main map. However, individual lithological units from the different tectonic units can easily be distinguished by the numbers given in the legend and correspondingly on the map. For each tectonic zone, lithological units are listed in their stratigraphic sequence. The various magmatic rocks of the Bergell Intrusive are listed according to their temporal sequence of intrusion.

As a result of the Alpine collision, continental upper crust with its sedimentary cover as well as continental lower crust and subcontinental mantle are exposed in a restricted area together with oceanic crust and associated sedimentary rocks. Most of these rocks were deformed and metamorphosed during the Alpine orogeny. One goal of the mapping campaign was to reconstruct the original setting of these rocks. A schematic profile of the reconstructed Lower Cretaceous paleogeography of the Adriatic continental margin is shown in the top left corner of the map. This reconstruction summarises the most important relationships between the major rock types (apart from the younger Bergell intrusive rocks) of the Valmalenco region (labelled with the same numbers as used in the legend and in the map) and serves as a guide for a better understanding of the pre-Alpine evolution of the rocks. In this profile, the positions of future nappes are indicated, providing a link between the present day nappe stack and the reconstructed paleogeography.

Due to the great structural complexity of the region, strike and dip of the main foliation changes over a very short distance. This makes it impractical to show such structural data on a map, which is already loaded with lithological details. Instead, the main structural features are illustrated in a set of four cross sections at a scale of 1:50'000. The traces of the cross-sections are indicated on the map. Section B–B' was extended outside the mapped area to the South to permit correlation with section A–A' to the Insubric line. Additionally, the traces of major syn- and antiforms, which overprint the nappe stack, are shown on the tectonic map. Numerous late-stage faults with an offset of 10–100 m exist in the mapped area. However, the various students have mapped these faults inconsistently and hence these structures are not reported on the map.

For the mapping of the Quaternary, morphological and stratigraphic criteria have been used. The limits of the glaciers correspond to the state of 1995, except for those of Vedretta di Scerscen inferiore and superiore, which reflect glaciation in 2002. The Quaternary has been given a consistent picture by Lodovica Folladori.

Special symbols on the map show the locations of active and abandoned mines and quarries, because these localities have or had a profound economic impact on the population of Valmalenco.

On the other hand, localities, where collector-quality mineral specimens have been found, are not shown; readers are referred to the excellent books by Bedogné et al. (1993, 1995).

The topographic basis of the map has been reproduced with the authorisation by swisstopo (nr. BA 046150), as indicated on the map. The coordinates are the kilometer grids of the Swiss national map. The map is fully digitised.

3. The geological evolution of the Valmalenco

In the following, we provide a brief overview on the variety of main rock types that occur in the Valmalenco and highlight their geologic history. For this purpose the oldest rocks are described first and then progressively younger rocks and units are discussed. The number of the rock type as it appears on the map will be put in parenthesis when discussed in the text.

A detailed description of most rock types and of the general geology of the area is given in the comments to the Swiss Geologic Map 1:25'000, sheet Piz Bernina (Spillmann and Trommsdorff, 2005, 2006), which covers the area adjacent to and North of the Valmalenco map. In addition, rock types of the Bergell Intrusion, and the surrounding units, have been described by Schmid et al. (1996), the explanatory paper for the Bergell map of Berger (1996).

3.1. The crystalline basement nappes

The rock types of the basement nappes have been subdivided into late- to post-Variscan magmatic rocks and older, polymetamorphic rocks. The Suretta nappe is discussed separately as it is entirely overprinted by contact metamorphism of the Bergell intrusion.

3.1.1. Polymetamorphic rocks

The polymetamorphic rocks occur in the Southalpine and the Austroalpine nappes as well as in the Suretta nappe. They consist of paragneisses and micaschists (8, 13, 18, 27, 32, 37, 43, 44, 61) with associated amphibolites (15) and rare marbles. Occasionally, pre-Alpine metamorphic relics, presumably related to the Variscan orogeny, are preserved within paragneisses. The best example of such rocks can be found at M. Palino where the outcrops of the preserved pre-Alpine metamorphic schists are large enough to be mapped (37). Garnet-bearing amphibolites and calcsilicate rocks often preserve pre-Alpine metamorphic relics. A series of orthogneisses (14, 19, 29) of presumably pre-Variscan age are associated with paragneisses and micaschists. A large body – the M. Canale orthogneiss (28) – has been mapped separately and is found in the southern part of the Bernina nappe. In the southern and eastern part of the Margna nappe there are amphibole-bearing gabbros and diorites (42) of alkaline affinity that occasionally preserve magmatic textures and minerals, especially close to the type locality of Lago d'Arcoglio. No crystallisation age is available for these gabbros.

3.1.2. Late and post-Variscan intrusives

The northernmost part of the map comprises the highest peaks of the Valmalenco area culminating in the Piz Bernina (4048 m). These peaks are formed by magmatic rocks, which intruded into old, perhaps Proterozoic (von Quadt et al., 1994) basement rocks. In the Bernina nappe, these intrusive rocks are slightly deformed and display a limited Alpine metamorphic overprint. They form two chemically distinct suites. An older (333 Ma; von Quadt et al., 1994) calc-alkaline suite intruded during a late stage of the Variscan orogeny and consists of diorites (22) and granodiorites (23) (Rageth, 1984; Spillmann and Büchi, 1993). This suite is partly cross-cut by syenites (24), leucogranites (25) and alkali granites (26), which document a younger (296 Ma, von Quadt et al., 1994), post-Variscan alkaline magmatic activity (Spillmann and Büchi, 1993). Meta-rhyolites (21) have an Early Permian crystallisation age (288 Ma, von Quadt et al., 1994; Büchi, 1987) and display an alkaline affinity. They are regarded as the subvolcanic to effusive members of the alkaline intrusive suite. Similar meta-rhyolites (16, 31, 34, 38) occur in other Austroalpine nappes. Based on lithological correlations to the Bernina meta-rhyolites and the lack of pre-Alpine metamorphism, these rocks are collectively assumed to be of post-Variscan origin. In the Margna and Sella nappes, granodiorites (36) and granites (35, 39) belonging to the calc-alkaline suite are mostly transformed into orthogneiss. Only in the core of large intrusive bodies such as in the chain between Piz Glüschaint and Piz Sella (36) or in the Cime di Musella (35), the magmatic minerals and textures are preserved. Occasionally, basaltic-andesitic dikes (20, 33) with alkaline affinity cross-cut the Late Variscan intrusives. The dikes are 2–3 m thick (and thus are exaggerated on the map) and can be followed over several hundred meters.

3.1.3. The Suretta nappe

In terms of paleogeography, the Penninic Suretta nappe represents the Briançonnais realm (Schmid et al., 1990) and is exposed in the western part of the mapped area. It underlies both the Forno and the Malenco units, and is discordantly cut by the Bergell Intrusives. In the mapping area, the rocks of the Suretta nappe occur primarily as isolated xenoliths within Bergell tonalite and granodiorite. These xenoliths, like those of the Forno unit, have various dimensions (10 cm to 100 m across), and their spatial arrangement is systematic, indicating only minor displacement of the xenoliths during magma intrusion (Drescher-Kaden and Storz, 1926; Gyr, 1967; Gieré, 1984, 1985; Puschnig, 1996). A kilometer-sized mappable block of Suretta basement and cover is preserved at Cima di Vazzeda. Further to the South, from Monte Disgrazia to Valle di Preda Rossa, the Suretta nappe is preserved as a very thin band along the contact between Bergell tonalite and Malenco unit (Gieré, 1985; Pfiffner, 1992; Weiss, 1992; Pfiffner and Weiss, 1994). This attenuated band runs parallel to the Preda Rossa shear zone, a major syn-magmatic shear zone, which follows and deforms the margin of the pluton (Berger and Gieré, 1995; Berger et al., 1996).

Within the map area, biotite schist and gneiss, metapelite, and some amphibolite of alkali basaltic composition are the predominant rock types in the polymetamorphic Suretta basement (Wenk, 1974; Wenk et al., 1974; Gieré, 1985; Pfiffner and Weiss, 1994). The sedimentary cover (60) of the Suretta basement (61) comprises metaconglomerate and fine-grained quartzite, probably of Permo–Triassic age (Staub 1918, 1921), followed stratigraphically by thick beds of pure and impure calcite and dolomite marbles (Gyr, 1967; Bucher, 1977; Gieré, 1985; Pfiffner and Weiss, 1994). The presumably Triassic marble sequence also contains intercalations of green amphibolite, which probably represents former tuffs, tuffites or sills (Gieré, 1985). All Suretta rock types occurring in the area covered by the map exhibit a distinct contact metamorphic overprint.

3.2. Preserved Permian continental crust-mantle transition

The Malenco unit, which contains a preserved Permian crust-mantle transition NW of Chiesa and S of Chiareggio, is predominant in the map area (Trommsdorff et al., 1993; Müntener and Hermann, 1996; Hermann et al., 1997; Hansmann et al., 2001). Lower crustal metapelitic rocks (58) are welded to upper mantle ultramafic rocks (Malenco peridotites, 59) by a Permian gabbro, which intruded at ~30 km depth. The gabbro displays a tholeiitic differentiation trend and consists of predominantly Mg-rich gabbroic cumulates with a flaser texture (54) and finer-grained, more differentiated Fe-Ti-rich gabbros (55; Hermann et al., 2001). A detailed description of the weakly metamorphosed ultramafic rocks (59; spinel peridotites, garnet pyroxenites, dunites) is given in Müntener and Hermann (1996), and the distribution of pre-Alpine structures and their relationship to Alpine structures is given in Hermann and Müntener (1996). The gabbro intrusion caused partial melting of the country-rock metapelites, and some of the resulting leucogranites reach a mappable size (58). U–Pb determinations on single zircons from differentiated gabbros yield an age of 281±19 Ma. Zircons separated from leucogranites yielded an upper intercept age of 278±2.6 Ma (Hansmann et al., 2001). Ion microprobe dating of zircon from a kyanite-garnet-plagioclase granulite resulted in apparent ages of inherited cores between 520 and 3050 Ma and of three metamorphic overgrowths at 280±5, 270±5, and 258±4Ma (Hermann and Rubatto, 2003). Monazite records the same metamorphic ages within error. These data indicate that granulite-facies metamorphism lasted for at least 20 m.y. For the subsequent 30–50 m.y. neither petrographic nor geochronological data could be obtained for the granulites of the crust-mantle transition. It is possible that the crust-mantle transition was stable into late Triassic.

Within the core of the Margna nappe (see profile C–C') an association of gabbros (40, 41) and lower crustal granulites (44) occurs and is identical to the lower crustal section exposed in the Malenco nappe. However, the Margna rocks display a much higher degree of Alpine metamorphic overprint and only locally the pre-Alpine textures, and – even more rarely – the granulite-facies minerals are preserved (Bissig and Hermann, 1999).

3.3. Rifting and denudation of Malenco mantle and continental margin formation

Retrograde hydration of Malenco granulite assemblages was triggered by the influx of aqueous fluids and caused formation of amphiboles and other hydrous minerals at 0.9 GPa and 650 °C (Müntener et al., 2000). This hydration event marks the starting point of a nearly isothermal decompression that is related to the exhumation of lower crustal rocks and the attached subcontinental Malenco mantle. Dating of early amphiboles by Villa et al. (2000) resulted in Late Triassic to Early Jurassic ages. These ages indicate that hydration and concomitant exhumation mark the beginning of rifting, which ultimately led to the separation of the Adriatic and European continents. The exhumation of the lower crustal rock association and the subcontinental Malenco mantle was initiated by an extensional fault system dipping towards the Adriatic continent (Spillmann, 1993; Hermann and Müntener, 1996). A remnant of this fault system – the Margna Normal Fault – is exposed between the Fedoz Gabbro (40) and the Margna Orthogneiss (39). This fault excised 10 to 20 km of mostly intermediate to lower crust and accommodated a displacement of ~50 kilometers (Hermann and Müntener, 1996; Bissig and Hermann, 1999). Extensional low angle faulting in the lower crust is linked to, and contemporaneous with, rift-related basins in the upper crust (Spillmann, 1988, 1989, 1993; Zingg, 1988; Müntener and Hermann, 2001), as schematically shown in the paleogeographic reconstruction in the top left corner of the map. Along the fault system, ductile shear zones (Hermann and Müntener, 1996; Müntener and Hermann, 2001) and later breccias developed with components of crustal and mantle rock, analogous to the situation along the Err-Platta nappes (Manatschal and Nievergelt, 1997) and the Galicia margin (Boillot et al., 1995). The Malenco breccias (59) were named Ur-breccia after the type locality Pass d'Ur. The exhumation of Malenco mantle was accompanied by (a) low-temperature (<300 °C) serpentinisation of Malenco ultramafic rocks with the formation of chrysotile (now included as relics in antigorite, Mellini et al., 1987); (b) intrusion of basaltic dikes and sills of the Forno unit into the Malenco mantle; and (c) formation of ophicarbonate rocks as breccias and debris flows on top and in fracture zones of the Malenco mantle. Rodingitisation of mafic dikes and ophicarbonate breccias bear a marine stable isotope signature (Burkhard and O'Neil, 1988; Benning, 1990; Pozzorini and Früh-Green, 1996) indicating oceanic metasomatism and metamorphism.

3.4. Permo-Mesozoic sedimentary rocks

The Permo-Mesozoic sedimentary rocks mark the boundaries between the different basement nappes. These sedimentary rocks document the formation of the Tethys ocean basin due to the separation of Africa and Europe during the Mesozoic. The sedimentary rocks can be subdivided into a pre-rift, syn-rift and post-rift sequence, and their ages are inferred from lithostratigraphic correlation with non-metamorphic Austroalpine sedimentary rocks. The pre-rift sedimentary sequence starts with detritic rocks of presumably Upper Permian to Triassic age, which are mapped as quartzite intercalated with marbles and micaschists (12). These rocks are overlain by dolomite marble, locally accompanied by cornieules (11) originating from a Triassic shallow marine shelf region. Quartz-rich calcschists (10) locally contain dolomite breccias and presumably represent Lower Jurassic syn-rift sediments documenting the fragmentation of the Triassic platform in an extensional setting. The Upper Jurassic to Lower Cretaceous post-rift sequence consists of quartzschists with local Mn-rich horizons, calcite marbles and calcschists (9). Lithologically similar quartzschists, micaschists and quartzites (45, 46, 47, 48) – although metamorphosed to higher grade due to the Bergell intrusion – form the sedimentary cover of the Forno Unit metabasalts (49). A schematic distribution of different sedimentary profiles along the ocean-continent transition is given in the Lower Cretaceous paleogeographic reconstruction. It is important to note that the Mesozoic sedimentary rocks that are listed in the legend in the Malenco Unit (51, 52, 53) are not in stratigraphic contact with the serpentinites, but rather represent an allochthonous block of continental sedimentary rocks tectonically emplaced on top of the exhumed mantle rocks during rifting.

3.5. Forno unit, and its relation to the Malenco unit, ophicarbonates

The Forno unit consists of a suite of metamorphosed mid ocean ridge-type basalts with locally preserved pillow lavas, pillow breccias, and Fe–Cu–Zn mineralisations (49; Montrasio, 1973; Ferrario and Montrasio, 1976; de Capitani et al., 1981; Peretti, 1985; Puschnig, 2000). Dikes of Forno basalts intrude the Malenco ultramafic rocks at Alpe Zocca (Ulrich and Borsien, 1996). A large amphibolite body SW of P. Cassandra represents a metamorphosed sheeted dike complex of Forno basalts, emplaced within the Malenco ultramafic rocks. Numerous smaller dikes associated with the complex are mapped, and these dikes often display an intense rodingitisation, indicating oceanic metasomatism of mafic rocks during serpentinisation of the peridotites (Puschnig, 2000). A metasedimentary sequence of presumably Late Jurassic to Early Cretaceous age is associated to the Forno metabasalts and comprises metaquartzites with Mn-mineralisations (48), garnet-andalusite-biotite schists (47), quartzites (46) and calcareous micaschists (45). Most Forno rock types covered by the geological map exhibit a strong contact metamorphic overprint. The inferred age of the meta-sedimentary rocks is based on lithological correlation to weakly metamorphosed Penninic sedimentary rocks covering the Platta unit in the NW of the mapped area (see tectonic map in the lower left corner).

A distinct boundary between the Malenco and Forno units cannot be located in the field. They appear on the same tectonic level below the Margna nappe, and the Forno unit was likely the oceanwards continuation of the Malenco unit as shown in the palaeogeographic reconstruction. The ophicarbonate zone (59) of Val Ventina (SSW of Chiareggio) does not seem to be a nappe boundary as the main Alpine foliation is discordant to the zone. For this reason, the ophicarbonates might be related to a former oceanic fracture zone (Pozzorini, 1996). It is possible, however, that the ophicarbonate zone of Val Ventina delineates an intra-serpentinite thrust fault. Other ophicarbonates appear to be situated on top of the serpentinites and occasionally display sedimentary structures, indicating that some ophicarbonates represent sedimentary rocks deposited on the exhumed Malenco mantle rocks (Pozzorini, 1996).

The Malenco and Forno units, together with the Lizun unit and the Platta nappe (see tectonic inset), represent the South-Penninic ophiolite suture zone between the Adriatic microplate and Europe. It is worth noting that the Malenco and Forno units do not preserve the full classical ophiolite sequence, as there are no significant amounts of oceanic gabbros, no extensive sheeted dike complex, and no genetic link between the mantle rocks and the overlying oceanic crust (Müntener et al., 2004). The rock types rather define a reduced ophiolite sequence consisting from bottom to top of serpentinites, ophicarbonates, local pillow basalts and sedimentary rocks.

3.6. The Lanzada-Santa Anna Zone

The Lanzada-Santa Anna zone crops out in two tectonic windows and underlies the Malenco unit: one at Lanzada in the centre of the map (see profile A–A' and D–D') and one close to the southern termination of the Malenco unit (see profile B–B'). The Lanzada-Santa Anna zone consists predominantly of metasedimentary rocks of inferred Permo-Mesozoic age (Montrasio, 1984). This unit is quite enigmatic because it contains metamorphosed pre-rift sedimentary rocks such as quartzites (66), dolomite marbles (65) and calc-schists (64), as well as rocks with affinity to oceanic crust including prasinites (67) and ophicarbonates (68) with associated sedimentary rocks, such as micaschists (62) and quartz-schists with Mn-mineralisations (63). This unit is possibly derived from the ocean-continent transition of the Briançonnais realm as evidenced by a similar metasedimentary sequence in the Penninic Suretta nappe (Montrasio, 1984; Gieré, 1985).

3.7. Bregaglia (Bergell) Intrusives

The Bregaglia Intrusives, better known as Bergell Intrusives, are one of the most fascinating calc-alkaline complexes in the Alps. Early controversies considering the field relationships, age and genesis of the Bergell Intrusives have been summarised by Trommsdorff and Nievergelt (1983). Many of these controversies have been resolved during the Malenco mapping project (Gyr, 1967; Riklin, 1977, 1978; Peretti, 1983, 1985; Gieré, 1984; Diethelm, 1984). It is impossible to report in this context the numerous field phenomena of the Bergell Intrusives. The reader is referred to the literature cited above and to the volume 76 of the Schweizerische Mineralogische und Petrographische Mitteilungen (Gieré, 1996), a special volume that contains relevant articles and literature plus a map (Berger, 1996; Schmid et al., 1996) of most of thdñIntrusives.

The main intrusive body is located at the western end of the mapped area (see tectonic inset). The two main rock types of the Bergell Intrusives are a medium-grained hornblende tonalite (3), dated at 32 Ma (Von Blankenburg, 1992) and characterised by the occurrence of magmatic epidote farther to the W (Cornelius, 1915; Reusser, 1987); and a younger (30 Ma; Von Blankenburg, 1992) granodiorite (2), characterised by large potassium feldspar phenocrysts. Various generations of granitic pegmatites and aplites (1) cross-cut the intrusive rocks as well as the country rocks. The details of the extremely complex intrusive phenomena cannot be displayed at the scale of the presented map. The intrusive phenomena have, however, been described in detail by Reusser (1987) and Diethelm (1989). Especially interesting field phenomena are swarms of basic xenoliths and schlieren, which occur in bands that grade into basic dikes. They are interpreted as mingling products between an injected basic magma and the crystallising magma of the main intrusion (Diethelm, 1989). Boudinaged sills, folded dikes, foliations and deformed enclaves further document substantial syn-intrusive deformation, particularly in the area of upper Valle Sissone, in the western part of the map (Berger and Gieré, 1995).

A smaller intrusive body related to the Bergell intrusion – the Triangia pluton – crops out NW of Sondrio and consists of tonalite (6) and granite

(5). Basaltic to andesitic dikes (7), which are presumably related to the Bergell intrusion, are distributed over a wide area in Valmalenco (Bangerter, 1978; Gautschi and Montrasio, 1978).

As for the depth of intrusion, Reusser (1987) determined the solidus pressure of the Bergell tonalite in the map area as 0.5 GPa and 60 km farther to the West as 0.75 GPa. These values correspond to a difference in depth of 9 km over which the intrusion can be studied. Also in the West, Oberli et al. (2004) have shown that the tonalitic melt persisted over a period of ~5 m.y., suggesting that it must have been a major controlling factor for the Oligocene evolution of the adjacent Insubric line.

4. Alpine deformation and metamorphism

Two Alpine orogenic cycles affected the former passive margin. An E–W directed thrusting and a subsequent extension of Late Cretaceous age produced the South Penninic-Austroalpine nappe stack (Hermann and Müntener, 1992; Spillmann, 1993; Froitzheim et al., 1994; Handy et al., 1993; Handy, 1996; Villa et al., 2000). Younger S-directed thrusts and E–W trending folds, related to the Tertiary continent-continent collision, overprinted the Cretaceous nappe stack (e.g. Handy et al., 1993, 1996; Froitzheim et al., 1994; Hermann and Müntener, 1992), but in general did not disrupt the continuity of the Cretaceous structures in the cross sections C–C' and D–D', respectively. The tectonic evolution of the South-Penninic and Austroalpine units differs from that of the underlying middle Penninic units (Briançonnais: Tambo and Suretta nappes, Tertiary flysch), where only the Tertiary evolution has been preserved (Liniger and Nievergelt, 1990; Puschnig, 1996).

The main deformation in the Austroalpine and South-Penninic units is related to W-directed thrusting and nappe stacking. The position of the nappes was probably already predestined in the Cretaceous by fault-bounded blocks resulting from Jurassic rifting (see paleogeographic profile). The Alpine deformation generally increases with increasing depth in the nappe stack. In the uppermost Bernina nappe, deformation is concentrated close to the nappe boundaries or occurs in discrete shear zones within the nappe itself, whereas in the lower units of the Bernina nappe, and in the Margna nappe and Malenco unit, only rare high-grade metamorphic rocks or primary magmatic textures escaped pervasive Alpine deformation. Alpine thrusting resulted in W-facing sedimentary synclines that separate the basement blocks. The most prominent of these synclines crops out in the Valle Scerscen and forms the peaks of P. Malenco and P. Tremoggia, linking the Margna and the Sella crystalline basements (profile C–C'). The thickness of the Margna nappe and the sedimentary syncline is drastically reduced from the West to the East (profile C–C'), due to large-scale, post-thrusting low angle normal faulting and stretching of the nappe stack (Hermann and Müntener, 1992, Spillmann, 1993). In fact, not all of the present nappe boundaries display exclusively thrust-related structures. Along most of the nappe boundaries (Bernina-Corvatsch, Corvatsch-Sella, Bernina-Sella), that contain only relics of Mesozoic sedimentary rocks (see tectonic inset), shear zones with kinematic indicators that point to a top-to-the-E sense of movement are observed (Spillmann, 1993). These shear zones are interpreted as low-angle normal faults related to a Cretaceous extensional event postdating nappe stacking. It is possible that the sudden termination of the Sella nappe in the southern part of the mapped area is related to such a shear zone.

This first orogenic cycle is responsible for the main Alpine metamorphism observed in the Austroalpine and South-Penninic units. The metamorphic conditions increase from lower greenschist-facies conditions in the Bernina nappe to epidote-amphibolite conditions in the Margna nappe and in the Malenco and Forno units. Maximum temperatures (Trommsdorff and Evans, 1974; Mellini et al., 1987; Trommsdorff and Connolly, 1996; Peretti, 1988; Benning and Sidler, 1992) and pressures (Bissig and Hermann, 1999) are around 450–500 °C and 0.5 GPa. These values indicate that the rocks derived from the Adriatic margin of the Piemontese ocean basin, now exposed in Val Malenco, were only moderately buried during Alpine metamorphism in the late Cretaceous (Villa et al., 2000).

In the Malenco-Forno and the overlying Austroalpine units N–S shortening is documented in S-vergent folds and shear zones (attributed to a first phase of backfolding; Sidler and Benning, 1992; Hermann and Müntener, 1992). This deformation may be linked to the formation of the main foliation in the underlying Tambo and Suretta units, which affected Tertiary flysches. However, the contrasting style of deformation indicates that the Austroalpine, together with the uppermost Penninic ophiolitic units, acted as an 'orogenic lid' suffering only minor deformation. Crustal thickening was later followed by orogen-parallel extension (Turba mylonite; Nievergelt et al., 1996; Froitzheim et al., 1994), which was strongly localised in the Austroalpine and South-Penninic units, but more penetrative in the Briançonnais domain (Liniger and Nievergelt, 1990; Huber and Marquer, 1996). A shear zone at the base of the Mesozoic sedimentary rocks between Margna and Sella nappes (Btta. delle Forbici) is likely related to this deformation phase (Hermann and Müntener, 1992). A potential southeast directed extension of the Turba mylonite zone could be responsible for the drastic thinning of the Malenco unit at its southern border (Puschnig, 1998). The Malenco unit is reduced to a few hundred meters between the Suretta nappe and the Margna nappe at Sasso Arso and between the window of St. Anna and the Margna nappe (profile B–B').

Ongoing N–S convergence produced large-scale, E–W trending open folds (attributed to a second phase of backfolding) and a pronounced steepening of the nappe stack towards the South. This deformation phase produces prominent features of the map. It is responsible for the tectonic window of Penninic rocks within the Austroalpine nappe stack. Traces of the axial planes of these folds are shown on the tectonic scheme in the lower left corner of the map and the general feature of the deformation is visible in the N–S profiles B–B' and D–D'. This deformation is cut by the Oligocene Bergell tonalite (32 Ma, Von Blankenburg, 1992; Spillmann, 1993; Puschnig, 1996). The last regional deformation caused NE–SW trending folds (transverse folding). Interference of the transverse folding with the second phase of backfolding forms a dome and basin structure (see inserted tectonic map). The Lanzada window exposing the Penninic Lanzada-Santa Anna unit is situated in such a dome structure (see profile A–A', D–D'). On the other hand, the Margna klippen exposed at Mt. Roggione and at Chiesa are situated in basins. The Bergell tonalite and its contact aureole are partially overprinted by the transverse folding. However, the younger granodiorite (30 Ma, Von Blankenburg, 1992) cuts this deformation phase (Puschnig, 1996). The observation that the main structures are older than the Bergell intrusives is also confirmed by discordant, Eocene to Oligocene andesitic to basaltic dikes (7). These dikes are largely undeformed, cross-cut the main foliation of the country rocks, and are younger than the regional metamorphism (Nievergelt and Dietrich, 1977), but they are overprinted by contact metamorphism within the aureole of the Bergell tonalites (Gautschi and Montrasio, 1978; Gautschi, 1980).

At the SE border of the Bergell, the Preda-Rossa shear zone occurs between the tonalite and the gneisses of the Suretta nappe (Berger and Gieré, 1995). The tonalite displays an intensive subsolidus deformation in this area and shows a vertical stretching lineation (Berger et al., 1996). A vertical offset of several kilometers (tonalite up) has been inferred, and this deformation is likely responsible for the verticalisation of the second backfolding in this area (Puschnig, 1998). A major brittle fault – the Muretto line – can be followed from the Passo di Muretto towards Chiareggio, where it disappears (see tectonic inset). The Insubric Line, a major Alpine tectonic boundary separating the Southalpine from the Alpine nappes (see tectonic inset), crops out just N of Sondrio.

5. Contact metamorphism and metasomatism

Mapping of the mineral assemblages of ultramafic and ophicarbonate rocks (59) in the contact aureole of the SE Bergell tonalite (3) has led to an exceptionally well constrained picture of thermal metamorphism. The contact aureole thus has become an excellent example of a natural laboratory. For the first time, reactions occurring during prograde dehydration of serpentinite were derived from field observations, and the corresponding isograds were mapped (Trommsdorff and Evans, 1972). Along the first isograd, the regional metamorphic assemblage serpentine + diopside is replaced by tremolite + olivine (+chlorite); coincident with this reaction, titanian clinohumite reacts to form olivine + ilmenite (Trommsdorff and Evans, 1980). Along the second isograd, talc + olivine was formed at the expense of antigorite. This isograd is easily recognised in the field, and therefore, the high-temperature side of the isograd is marked in the map (59 with spotted pattern). Trommsdorff and Evans (1977) further mapped isograds for the devolatilisation of serpentine + carbonate rocks and derived a corresponding phase diagram from their field observations. The phase diagram was later refined (Trommsdorff and Connolly, 1990) and served to extract thermodynamic data for some of the minerals. All this information was then integrated into a thermal model (Trommsdorff and Connolly, 1996), which indicates that temperature increases from ~350 °C outside the aureole to ~570 °C at the contact. Pressure of contact metamorphism was determined at ~0.35 GPa, which is somewhat lower than the pressure derived for the Bergell tonalite solidus (0.5 GPa, Reusser, 1987).

The Bergell contact metamorphism was accompanied by widespread metasomatic activity. In particular, the carbonate rocks of the upper Val Sissone, which belong to the middle Penninic Suretta nappe, contain abundant hydrothermal veins with variable mineral assemblages (Bucher, 1972, 1977; Ried, 1994). Some of these veins document high-temperature metasomatic transport of titanium, zirconium, rare earth elements and actinides (Gieré, 1986; Ried, 1994).

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