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Tertiary migmatites in the Central Alps: Regional distribution, field relations, conditions of formation, and tectonic implications

Thomas Burri[1], *Alfons Berger*[1,*] and *Martin Engi*[1]

Abstract

This study investigates the Tertiary migmatite belt of the Central Alps of Switzerland and Italy. Regional field relations are presented and, based on structural, textural and petrologic arguments, the spatial and age distribution of the Alpine migmatites are discussed. Alpine migmatites are almost entirely confined to the Southern Steep Belt (SSB), the regional-scale, transpressional shear-zone at the southern margin of the Central Alps. Migmatites surfacing in more northerly parts of the Lepontine area are derived from pre-Alpine, probably Variscan or older periods of partial melting, connected to the intrusion of bodies of granitic to quartz-dioritic composition, as well as mafic and granitic dykes. Except for the Bergell and Novate intrusives, Tertiary igneous activity in the Central Alps is limited to *in-situ* migmatisation and to the intrusion of aplitic and pegmatitic dykes and smaller (<50 m) granitoid bodies. Two processes contributed to the origin of this migmatite belt: (1) In the course of regional Barrovian metamorphism, water-assisted partial melting of granitoid rocks was induced in a large part of the southern Lepontine area, commonly leading to a maximum of 10–25 vol% total leucosome. (2) In pelitic rocks of the southeastern Lepontine area, a smaller leucosome-fraction is found, which is essentially a result of muscovite dehydration melting. Pressure-temperature conditions of partial melting estimated for amphibole-bearing leucosomes are 0.6–0.8 GPa and 700 ± 50 °C, indicating mid-crustal partial melting. Thermally retentive chronometers set fairly tight limits for this event at 25–30 Ma. The spatial relationship between migmatites and SSB, as well as the styles of variable deformation in the leucosomes, indicate that partial melting and deformation were coupled processes. Observations suggest that the focused deformation in the SSB led to episodic injection of hydrous fluids, which in turn triggered water-assisted partial melting and associated strain partitioning into the "weak" partially molten rocks. Processes of partial melting in the migmatite belt appear to be continuous in time and space with the regional thermal history that produced upper amphibolite facies metamorphism without partial melting in adjacent areas to the north, i.e. outside the SSB.

Keywords: Central Alps, Migmatites, water-assisted melting, amphibole geothermobarometry.

Introduction

Migmatisation of the middle crust is usually associated with high ambient temperatures that may lead to the dehydration melting of muscovite, biotite or amphibole. Much effort over the last thirty years has been put into the study of high-temperature migmatite terrains, where migmatisation is related to magmatic intrusions or to unusually high heat flow (e.g., McLaren et al., 1999; Harrison et al., 1998). The role and consequences of partial melting have been investigated in the Himalaya (e.g, Beaumont et al., 2001; Harris et al., 2005). However, in the context of continental collision, particularly high temperatures may not be the main reason for the formation of extensive migmatite terrains. The common association of migmatisation with regional-scale shear zones suggests that migmatisation and deformation may be genetically related (Mogk, 1992; Brown and Solar, 1998). Because deformation and fluid flow are often coupled (e.g., Etheridge et al., 1984; Kerrich, 1986), water-assisted partial melting along such large-scale shear-zones may offer a viable explanation for the genesis of such migmatite terrains at comparatively low metamorphic grade.

The migmatite belt situated immediately north of the Insubric Lineament, i.e. the main tectonic boundary of the Central Alps, has long been recognised. Partial melting in this belt was variably attributed to Alpine and/or pre-Alpine metamorphism. Though the close spatial relation of the migmatites and the Southern Steep Belt (SSB) of the Central Alps was already recognised by several of the earlier authors, the implications have been subject to a fervent debate in more recent

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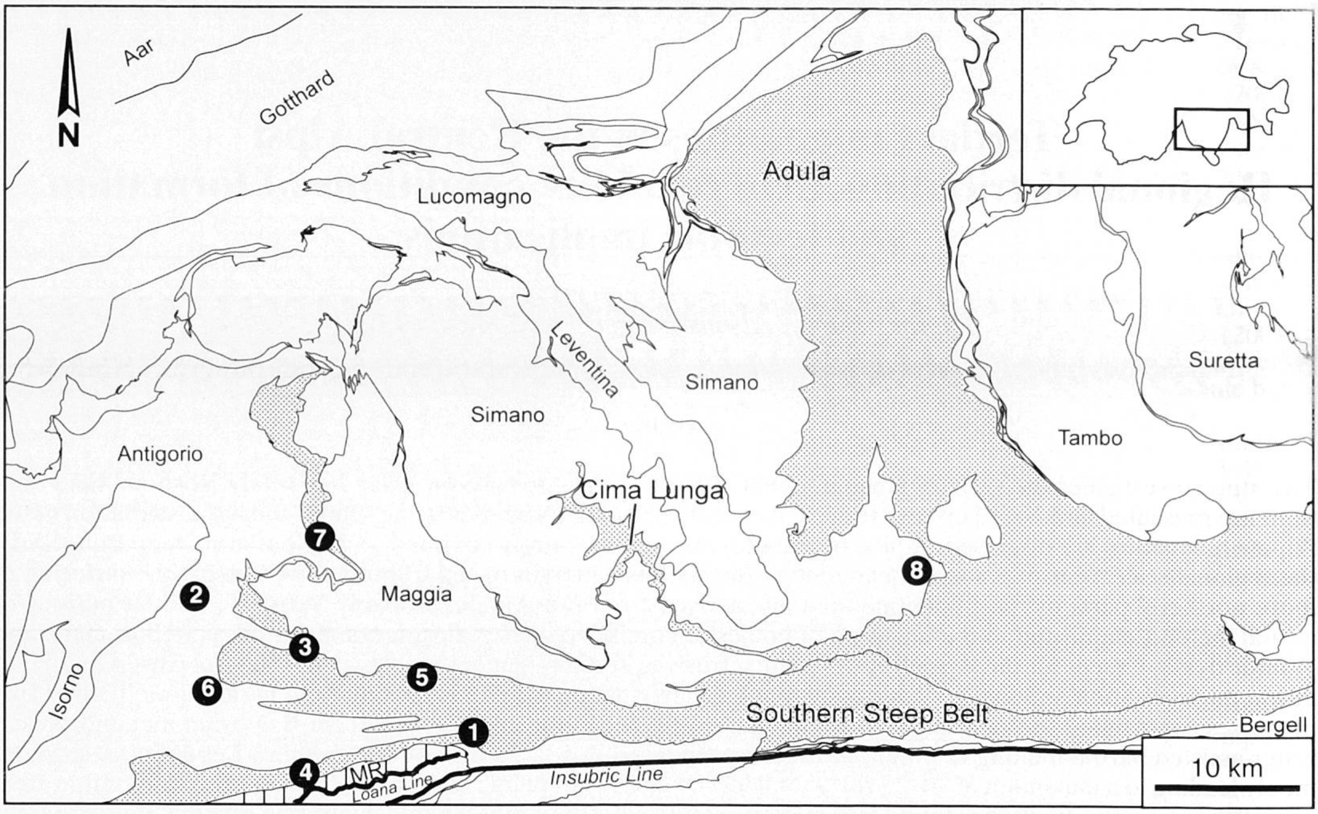

Fig. 1 Tectonic overview of the Central Alps. Numbers refer to localities described in text: 1: Ponte Brolla, 2: Alpe Ribia, 3: Gresso, 4: Camedo, 5: Capoli, 6: Bagni di Craveggia; 7: Riveo, 8: Verdabbio. MR – Monte Rosa nappe.

times (Niggli, 1950; Wenk, 1975). While several older studies portray in splendid detail the migmatites occurring in particular sections of the Central Alps (Kobe, 1956; Knup, 1958; Sharma, 1969; Blattner, 1965: Hänny, 1972; Hafner, 1993), no attempt had been made previously to examine the migmatite types and their field relations at the scale of the entire migmatite belt.

The present study provides an inventory of the Alpine migmatite types and documents their spatial distribution in the Central Alps. The conditions of partial melting in the migmatite belt are constrained by amphibole thermobarometry on suitable leucosomes, and causes of partial melting are examined based on observed phase relations.

Geology of the Southern Steep Belt (SSB) and adjacent areas

The Swiss–Italian Central Alps form an Alpine Barrovian-type metamorphic belt (Niggli and Niggli, 1965; Niggli, 1970; Wenk, 1975; Frey and Ferreiro-Mählmann, 1999; Engi et al., 2004). Temperature generally increases from north to south (Todd and Engi, 1997; Frey et al., 1999) reflecting the south-vergent subduction of the European plate below the Apulian plate and the subsequent uplift of hot subducted lithosphere during continent-continent collision (Fig. 1). In detail, P–T relations are complicated due to the relaxation of the isotherms that accompanies deformation and exhumation of the nappe stack (Engi et al., 2001; Burg and Gerya, 2005). In the internal part of the Central Alps, a moderately dipping nappe stack is exposed, which forms the metamorphic core of that part of the mountain belt, the so-called Lepontine Dome (Fig. 1). The Lepontine nappes consist of basement units, dominated by Variscan granitoids that intruded the metamorphic basement. Several of these nappes also contain migmatites, which appear to be genetically related to these intrusives. The most important units in the study area are classic basement thrust sheets (the Monte Rosa, Maggia, Antigorio, Simano and Leventina nappes) or very heterogeneous tectonic mélange units (e.g. Adula, Cima Lunga and Orselina units) containing abundant eclogite relics. These latter units include what Trommsdorff (1990) termed an *Alpine lithospheric mélange* and have collectively been interpreted as TAC-fragments (Tectonic Accretion Channel), accreated along the subduction plate boundary (Engi et al., 2001). The Lepontine Dome structure is bordered to the north and south by elongate steep belts. The east–west striking Southern Steep Belt (SSB) is the location of back-folding and back-thrusting of the Alpine nappe stack (Milnes, 1974; Heitzmann, 1987). The entire nappe stack swings from a flat-lying to moderately dipping orientation, into a subvertical and even overturned orientation. The SSB itself has classically been divided into different units, historically called "Zonen" or "Züge", i.e. elongate, discontinuous trails (e.g., Kern, 1947; Zawadynski, 1952; Knup, 1958). These map-scale subdivisions essentially reflect changes in the spectrum of rock types found in the mélange, thus emphasising local diversity. However, the different zones may have several characteristics in common, such as the occurrence of similar orthogneiss[1] rock types, of migmatites with variably deformed leucosomes, or of eclogite relics.

The SSB contains the most convincing evidence of Alpine anatexis and intrusion. Pegmatitic and aplitic dykes, meter to decameter-sized granitic bodies, as well as *in-situ* migmatites, are widespread within this belt stretching E–W from the Bergell to Domodossola (Fig.1). Especially in the central part of this E–W belt, high-T mylonites are common. In general, the observed grain sizes in many rock types are exceptionally small, given the high metamorphic grade.

To the south, the belt is truncated by the E–W running Insubric Line (termed Tonale-Line east of Locarno, and Canavese-Line west of Locarno (e.g., Schmid et al., 1989; Steck and Hunziker, 1994; Schärer et al., 1996), a major ductile to brittle shear zone of the Central Alps. This shear zone separates the Southern Alps (Apulian plate), which were weakly metamorphosed and moderately deformed during the Alpine orogeny, from the high-grade metamorphic Central Alps (European plate) to the north. North of the Insubric Line, metamorphic grade reached amphibolite-facies conditions on a regional scale (Trommsdorff, 1966; Wenk, 1970; Niggli, 1970; Engi et al., 1995), but relics of eclogite and granulite facies occur inside the TAC-units (Engi et al., 2001). West of Locarno the Insubric Line bends towards the southwest, whereas the SSB maintains its roughly E–W direction (Heitzmann, 1987; Schmid et al., 1989; Fig. 1). The opening gap between the SSB and the Insubric Line is taken up mostly by the Sesia-unit. In this western segment of the SSB, the Insubric Line did not correspond to the main boundary during subduction and back-thrusting, but rather transects this older element (Schärer et al., 1996). Due to major displacements along the younger ductile to brittle Insubric and Centovalli Lines, amphibolite-facies fabrics and assemblages in the SSB were locally severely overprinted by greenschist-facies brittle deformation.

Migmatites in the Central Alps

Migmatites surface in many parts of the Alps and, where they occur in units, which attained but low to moderate temperatures in the Alpine cycle, it is clear that these rocks are of pre-Alpine origin (Frey et al., 1999). Based on structural and petrologic arguments it is also well established, that within the Lepontine area, old basement units were overprinted by Alpine metamorphism (e.g. polycyclic metamorphism in the Suretta nappe, Nussbaum et al., 1998; basement in the Bodengo area: Hänny, 1972). Inside these basement units, migmatites of pre-Alpine age, apparently related to the intrusion of large granitoid bodies (Variscan intrusives), are widespread. In the southern part of the Lepontine Alps, temperatures over 650 °C were reached in the Tertiary, but the age of migmatisation has long been a matter of debate (e.g., Klemm 1906/1907; Grubenmann, 1910; Gutzwiller, 1912; Niggli, 1950; Wenk, 1970). The discussion of the relative age has in part revolved around the particularly abundant stromatic migmatites, where relations between deformation and partial melting are structurally complex. This debate inspired several detailed studies, which were carried out in the eastern part of the SSB (e.g., Blattner, 1965; Hänny, 1972) and in the central Valle Verzasca area (Sharma, 1969), located further north. Isotopic studies (Hänny et al., 1974) revealed older migmatites overprinted by local partial melting during Alpine metamorphism in the eastern SSB. In this same section of the belt, migmatisation is contemporaneous with magmatic activity related to the Bergell intrusion, the latter starting at 32 Ma (e.g., Berger et al., 1996). The deeper portions of the Bergell pluton (western end) preserve a protracted magmatic history with a final crystallisation at 28 Ma (Oberli et al., 2004). Monazite dating in the gneisses and migmatites yielded 29–26 Ma (Köppel et al., 1981; Hänny et al., 1974) and similar ages were obtained for discordant veins and dykes of the SSB (Schärer et al., 1996; Romer et al., 1996). Hence partial melting in the eastern and central part of the SSB most likely occurred in this time interval. This is further corroborated by isotopic ages obtained using other thermally retentive chronometers, which date the amphibolite facies metamorphism (Vance and O'Nions, 1992; Nagel, 2000), to which partial melting is related. The youngest in-

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[1] The term orthogneiss is used here for metamorphic rocks, where various evidences indicate a granitoid protholith.

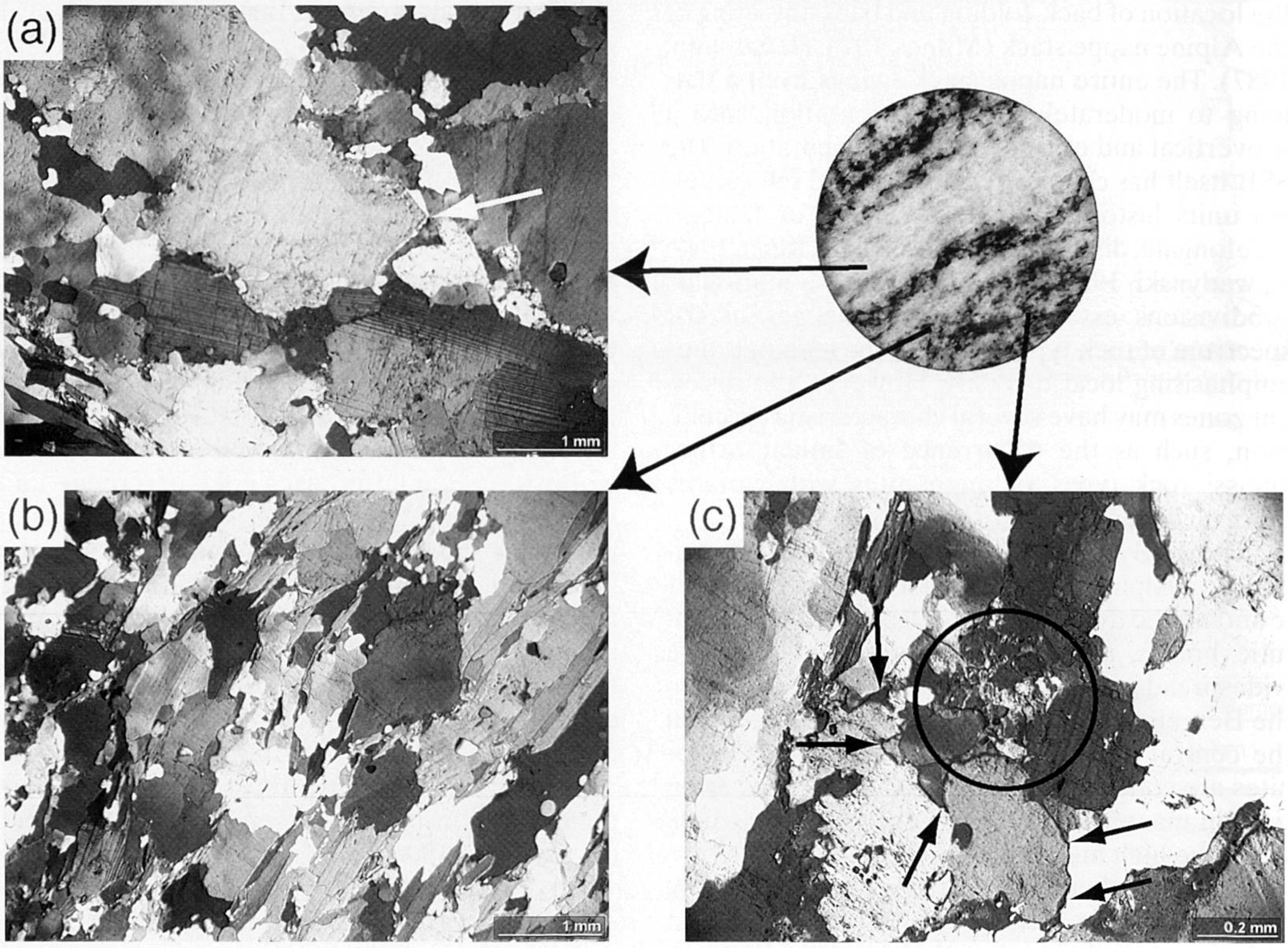

Fig. 2 Migmatites in thin section (Bordoglio, Valle Onsernone; 696'980/116'975). Figures A–C depict different domains of the sample, as indicated on the slab (diameter 2.5 cm). (a) Photomicrograph of the wide leucosome band with euhedral feldspars; (b) Gneissic domain with abundant biotite; (c) Small triple point aggregates and thin films of former melt, now present as small grains of K-feldspar and quartz (arrow). See text for further explanation.

trusives observed in the Alps crosscut the latest ductile Alpine structures and occur as aplites and small intrusions (i.e. Novate granite), which have been dated at ~25 Ma (Romer et al., 1996; Schärer et al., 1996; Liati et al., 2000). A particularly young, Miocene age of 20 Ma (lower intercept) was obtained for a completely discordant dyke at Lavertezzo (Romer et al., 1996).

Features of migmatisation: criteria and examples

Migmatites in the SSB range in scale from small to large; we distinguish three classes of features and processes:

a) Small-scale melt segregation into *in-situ* leucosomes (centimeters to decimeters).

b) Medium-scale melt segregation into pods and small bodies (decimeters to meters).

c) Dykes (pegmatites and aplites) and larger granitoid bodies (up to 50 m).

Transitions between these types are often gradational, and evidence of former melt is also found on the grain scale. Small-scale melt segregation processes are observed along grain boundaries, with segregation into millimeter-scale melt seams to small pools, up to the segregation into decimeter-size pockets and veins.

It is by no means always obvious that partial melts were involved in the formation of complexly deformed leucocratic segregates, particularly where these were subsequently deformed. Careful documentation of mesoscopic features and microscopic criteria is needed. In the last few years several authors have demonstrated how the presence of former melt can be inferred from the study of thin sections (Rosenberg and Handy, 2000; Rosenberg, 2001; Sawyer, 2000, 2001; Vernon, 2000). For example, straight grain boundaries may indicate undisturbed growth of a mineral into a melt; thin films of quartz or K-feldspar along two-grain boundaries or triple junctions may reflect locations where final crystallisation of melt took place. Another characteristic is the filling of transgranular fractures by quartz and K-feldspar, interpreted as a former filling of melt subsequent to grain fracturing.

Stromatic migmatites from the SSB typically show these and similar features; a few examples are presented below.

Figure 2 shows a thin-section of a rock sample (Ø 2.5 cm; sample from locality Bordoglio, Valle Onsernone, 696'980/116'975) with differentiation into a leucosome-rich domain, consisting mainly of K-feldspar + plagioclase + quartz, and a gneissic domain consisting of plagioclase + quartz + K-feldspar + biotite (Fig. 2). Inside the leucosomes, the rare biotites are of two types, which can be distinguished by their texture: (1) some grains are similar in size and shape as the biotites in the mesosomes, which is interpreted as relics swimming in the melt; (2) a few small, hypidiomorphic grains, which differ in grain size and grain shape significantly from the first group. The latter are interpreted as neoformed crystals in the melt (compare detailed study on biotites in migmatites: Milord and Sawyer, 2003). Gneissic domains are only slightly enriched in plagioclase, while K-feldspar as well as quartz remain present. Figure 2a shows the relatively coarse-grained and only slightly deformed leucocratic domain, which we interpret as crystallised partial melt. The white arrow points to an idiomorphic K-feldspar corner, lined by a thin film of quartz-grains on the lower straight grain boundary. The rest of the grain has more irregular grain boundaries, locally affected by myrmekite. Similar textures (except for myrmekites) are observed for plagioclase. Except for slightly undulose extinction of quartz, deformational features are absent from this leucocratic domain. Figures 2b and c are from the gneissic domain, where grains are typically smaller, but still remain on the order of millimeters, due to enhanced recovery at high temperatures. Micas, feldspar and quartz show a clear shape-preferred orientation (SPO), which defines the main foliation (Fig. 2b, foliation from lower left to upper right). At higher magnification, evidence of former melt is also found in the gneissic domains (Fig. 2c). Arrows indicate sites of former melt, now present as small grains of mainly K-feldspar and quartz, which are situated along two grain boundaries and triple junctions. Note the rounded habit of many grains, which may be an effect of their dissolution during partial melting. The circle indicates an area, where a K-feldspar grain was cataclastically deformed, after which the voids were filled with melt.

Grain-scale segregations are usually too small to be detected in the field, but melt pockets and veinlets are frequently observed in the SSB. While some leucosome was able to segregate into coarser grained patches (e.g., right side of Fig. 3a; sample from locality Berzona, Valle Onsernone, 694'000/117'450), others remained next to the site of melting, forming elongate quartz- and feldspar-enriched areas parallel to the foliation. This indicates that melt was present throughout the rock, but that only a certain fraction segregated at the sample scale. Note that the transition from leucosome to host rock is locally diffuse (e.g. upper part of larger segregation to the right). Leucosome segregations are often rimmed by elongate or chubby aggregates of biotite (black arrows), which suggests that the segregated melt was derived locally, leaving behind refractory biotite. Although many leucosomes exhibit a foliation-parallel orientation (Fig. 3a and f; locality Fressino, Valle Verzasca, 708'550/117'750), we emphasise that this commonly observed feature is insufficient evidence for a pre-Alpine age of migmatite formation. Instead we suggest that the preservation of the typically coarser leucosome grain size and of subtle transitions between leucosome and host rock are more conclusive indicators of an Alpine age of migmatisation. Furthermore, the feasibility of syn-kinematic foliation-parallel melt segregation has been demonstrated in several studies (Brown et al., 1995, and references therein; Barraud et al., 2004; Burri, 2005).

Other outcrops are better suited to demonstrate the temporal link of deformation and melt segregation, and thus the Alpine age of migmatisation. Melt-filled shear zones in Ponte Brolla form an *en-échelon* pattern, indicating a sinistral sense-of-shear (Fig. 3c and d; Ponte Brolla, entry of Valle Maggia 701'700/115'900). The existence of conjugate dextral and sinistral sets at the same locality indicates a dominantly pure-shear component. Entirely non-deformed veinlets crosscutting a strong Alpine fabric are observed at several localities. There, deformation had evidently ceased while melt was still present in the system. Typically, such veinlets are of local extent (cm–m scale) only.

Small-scale segregations such as those described in the previous section are often associated with more voluminous segregations (meter- to outcrop-scale) or grade into these (Fig. 3b and c). In some migmatites, the pervasive Alpine fabric becomes undulatory and grades into a more massive to igneous fabric. Rocks in such localities can be divided into a pervasively foliated melanosome, mesocratic domains (mesosome), which typically contain relics of the old foliation, and leucosome, which occurs as patches inside the mesosome. We interpret the melanosome as melt-depleted restite, the mesosome as a mix of refractory minerals and former melt, and the leucosome as former segregations of pure melt. Inside this

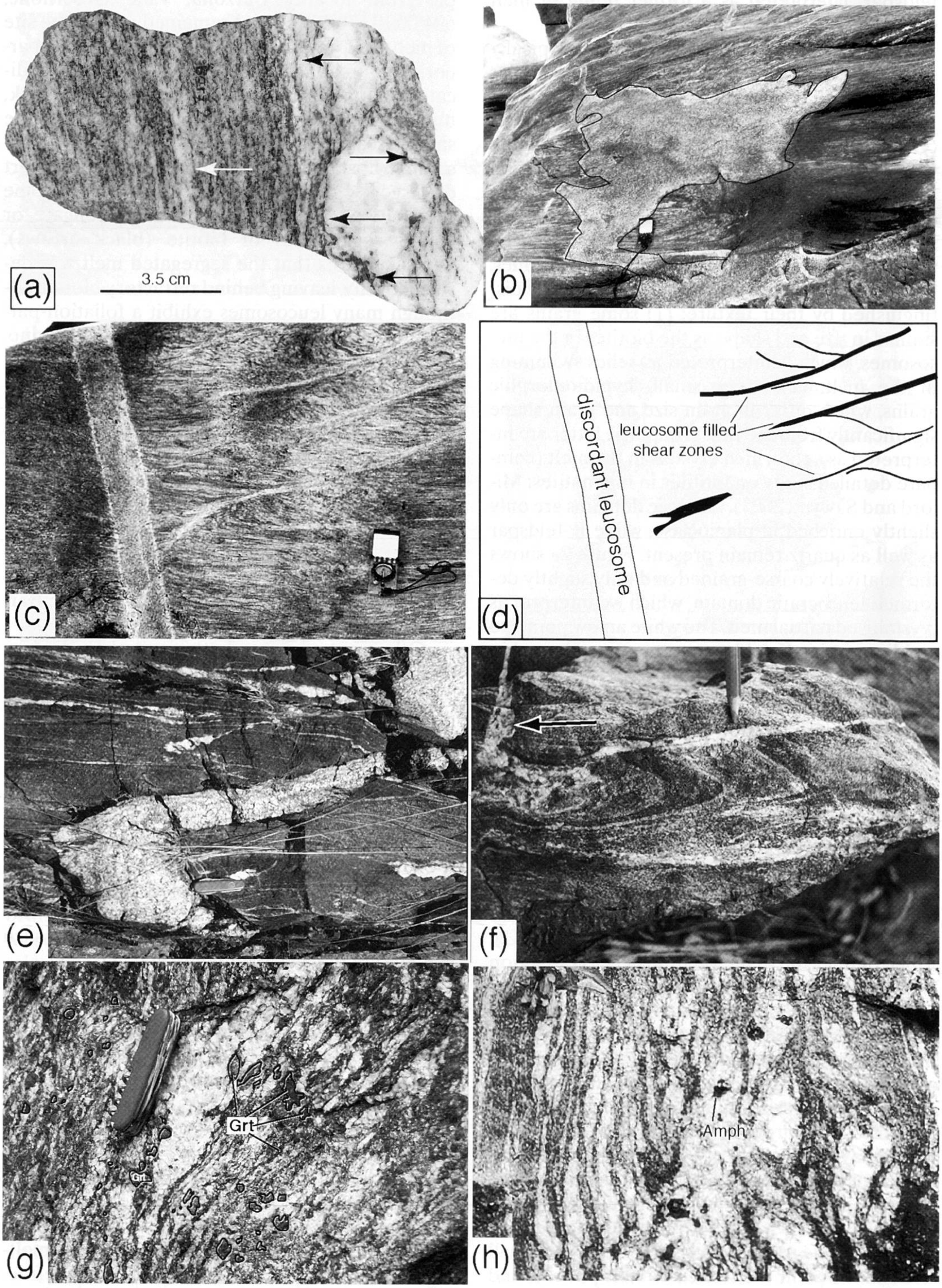
(a)
3.5 cm
(b)
(c)
discordant leucosome
leucosome filled shear zones
(d)
(e)
(f)
Grt
Grt
(g)
Amph
(h)

Fig. 3

type of migmatites, magnetite occurs as large crystals in the leucosomes together with biotite and ilmenite. The occurrence of similar but finer-grained magnetite in the surrounding gneisses indicates that oxygen fugacity in the melt and the host rock did not differ much.

At several localities a gradual transition into the common stromatic migmatites or into orthogneisses[1] devoid of leucosome occurs within a few meters. Such gneisses are usually more leucocratic than the melanosome in neighbouring migmatites, possibly indicating melt removal from the latter. Conditions for partial melting were locally satisfied, but the amounts of partial melting appear to have been spatially quite variable, even in compositionally similar rocks.

At several locations in the SSB distinct leuco- to mesocratic granitoid bodies (up to several *metre*s in size) occur, displaying magmatic fabrics and sharp contacts to host rocks and the Alpine gneissic fabric (Fig. 3b, Ponte Brolla). In many cases, schollen of the host rock are found enclosed in such granitoid masses. Leucocratic rims at the contact with the host rock or with enclosed schollen are a striking characteristic of the granitoid bodies. These rims may have formed due to enhanced melting along the borders as a result of an increased H_2O activity of the melt. Such an increase may occur upon decompression of migmatites, because the equilibrium water content of a melt may decrease, depending on the respective P–T path (see excellent discussions in Holtz et al., 2001; Johannes and Holtz, 1996). Alternatively, these rims may represent melt that migrated from the partially molten host rock into the magma body. At Ponte Brolla, a melt-filled shear zone ends at such a body and appears to expel melt into the granite, again indicating deformation contemporaneous with igneous activity in the SSB.

Granitoid dykes are omnipresent in the SSB and were recognised and described as Alpine products early on (Fig. 3c and e; Gutzwiller, 1912; Preiswerk, 1925; Kündig, 1926; Mittelholzer, 1936; Kern, 1947). Whereas some dykes can be traced for hundreds of metres, others appear to quickly die out laterally. Both granitoid pegmatites and aplites occur, and transitions from one to the other exist. The majority of pegmatites bear muscovite (± garnet), whereas biotite-pegmatites are less frequent. Aplites on the other hand, dominantly contain biotite or two micas. The dykes are usually composed of quartz, microcline and sodic plagioclase, with variable modes of muscovite, biotite, and often garnet. Typical pegmatite minerals such as tourmaline or beryl occur (e.g., Gutzwiller, 1912; Preiswerk, 1925; Taddei, 1940; Knup, 1958), but they are less common. The paucity of pegmatites enriched in these volatile-bearing phases argues against a genetic interpretation of these dykes as late stage magmatic liquids. The same conclusion is indicated by the observed REE-depletion, because most dykes contain only a few allanite grains, whereas other REE-phases are generally absent. This suggests that dykes most likely formed by liquid extraction in the course of partial melting, with accessory phases left behind in the restite. Crystallisation textures indicate that temperatures of host rocks and intruding dykes did not differ much (lack of chilled margins). Keeping in mind the water-saturated solidus of granitoid systems (e.g., Johannes and Holtz, 1996), we estimate that temperatures during crystallisation of the granitic dykes must have been 600–650 °C. Crystallisation temperatures may have been slightly lower, where the pegmatites contain beryl and/or tourmaline, due to fluxing volatiles (Li, Be, B, F), but this is restricted to a few occurrences only.

Extent of Alpine migmatisation

It has been postulated for a long time that partial melting had occurred at least locally in the Lepontine during the Tertiary. Interpretation di-

Fig. 3 Characteristic structures and types of migmatites at outcrop scale. (a) Polished slab shows small-scale melt segregations in granitoid orthogneiss (Onsernone unit; Berzona, Valle Onsernone; 694'000/117'450). Right side of slab: cm-scale melt segregation into irregular patches. The transition to the host rock is often diffuse and biotite is arranged in heap-like aggregates along the leucosome (black arrows). Left side: small-scale melt segregation indicates presence of melt throughout the rock (white arrow); (b) Discordant granitoid body cutting the main Alpine foliation (Ponte Brolla; 701'700/115'900). Outline of body redrawn in black line (compass for scale); (c) *En-échelon* melt-filled shear zones displace the main Alpine fabric (Ponte Brolla; compass for scale; 701'700/115'900); (d) Line drawing of (c); (e) Aplitic dyke, discordant at uppermost right, but folded during Alpine deformation (Val Arbedo; knife for scale); (f) Leucosome bands parallel to fold axial planes. Note discordant part at upper left (arrow), pencil for scale. Fold near highway restaurant „Mövenpick“, Bellinzona; Pictures in (e) and (f) are rotated by 90° with respect to original orientation. (g) Metapelitic migmatite (in rock climbing area outside Bellinzona) with newly grown garnet and irregular leucosome pockets (knife for scale; Garnets are marked with black lines). (h) Stromatic migmatites with additional discordant leucosomes (near Mergoscia, Val Verzasca; 708'550 / 117'750). Note euhedral amphibole prisms in leucosome (width ca. 40 cm).

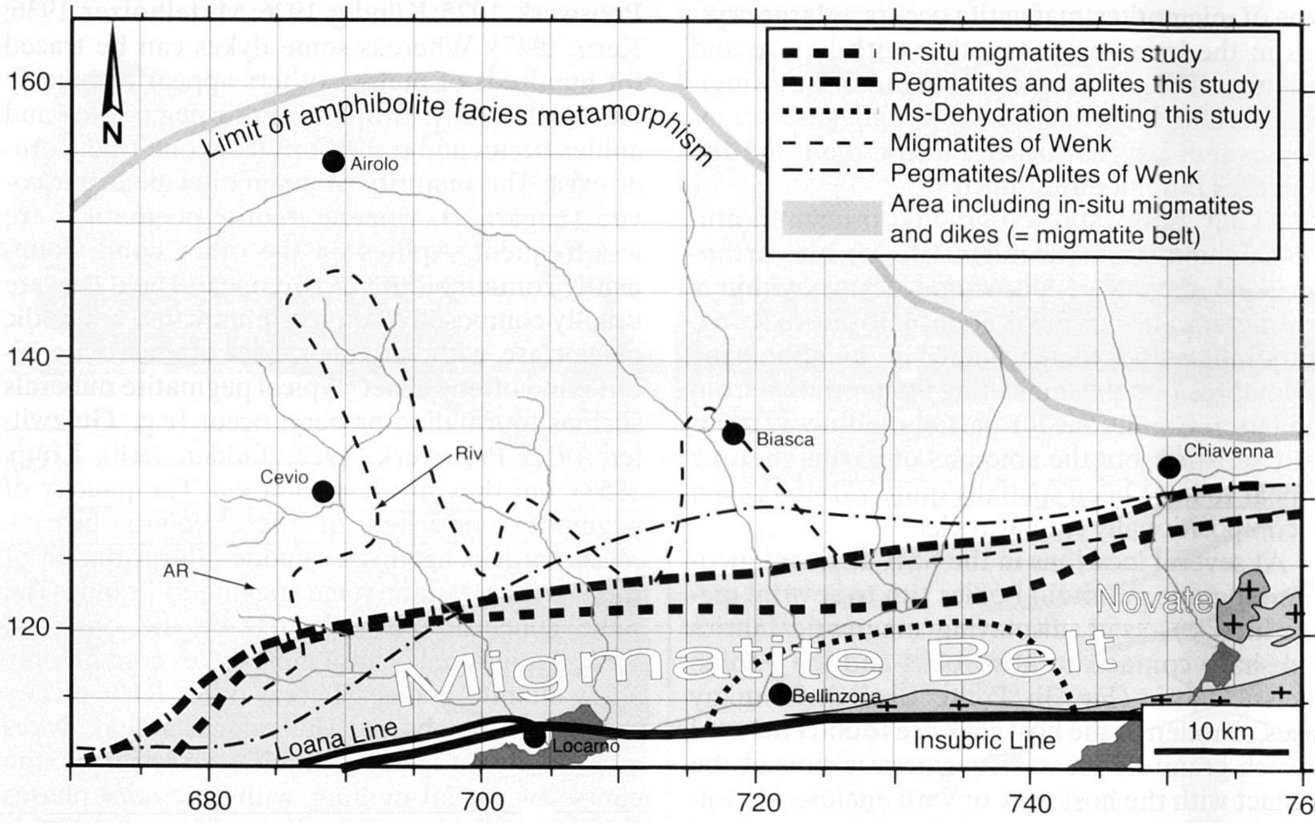

Fig. 4 Delimitation of Alpine migmatite belt in the Lepontine area. Thick dashed lines depict limits established in this study, thin dashed lines are from Wenk (1970). Continuous lines are major shear zones. AR – Alpe Ribbia, Riv – Riveo

verged mainly with respect to the extent of migmatisation. In order to establish the distribution of Alpine migmatisation in the Central Alps, we performed extensive fieldwork and made use of existing literature data. In the field we applied mainly structural and textural criteria to distinguish between Alpine and pre-Alpine migmatites. The generally strong and pervasive Alpine deformation facilitated discrimination to some extent, because many of the observed migmatites are at least partially discordant to the strong Alpine fabric. Nevertheless ambiguity remained in some cases. We took the following criteria as indicative of Alpine migmatite formation:

– Discordance of dykes, veins or small-scale melt segregations with respect to the main Alpine foliation.

– The presence of coarse-grained and almost undeformed leucosomes inside highly deformed finer grained rocks.

– Leucosome-filled shear zones or boudin necks, attributable to Alpine deformation.

As demonstrated by other authors, age relationships are not always unequivocal, especially where several generations of migmatites coincide (Blattner, 1965; Hänny, 1972; Romer et al., 1996; Schärer et al., 1996). In such localities unequivocal Alpine intrusives or *in-situ* leucosomes can typically be identified. The pre-Alpine age of the older and more strongly deformed migmatites, though probable, cannot always be unambiguously proven (Hänny, 1972; Hänny et al., 1975). For these reasons, our map (Fig. 4) – for which we applied the above criteria – probably reflects the minimum extent of *in-situ* partial melting. However, due to the very characteristic features of Alpine migmatites, we are convinced that Alpine partial melting did occur within the mapped (minimum) border. In contrast to *in-situ* migmatisation, the spatial extent of Alpine dyke intrusions is easily mapped. Fieldwork and a comprehensive study of the relevant literature allowed us to delineate three major limits (Fig. 4):

(1) limit of the intrusions of aplite and pegmatite dykes
(2) limit of *in-situ* melting
(3) limit of dehydration melting of white mica.

(1) *Limit of aplitic and pegmatitic dykes*: In the SSB, aplites and pegmatites often crosscut the main Alpine foliation. Because dykes often intruded subvertically, they commonly show orientations similar to the local, steep foliation. Discordance is therefore best visible towards the north of the SSB, where foliations retained flat-

lying orientations. Dykes generally increase in abundance towards the southern parts of the SSB, but accumulations of Alpine pegmatites have been reported as far north as Verdabbio in Valle Mesolcina (Kündig, 1926). Towards the south dykes often occur in intersecting swarms, which can coalesce to larger bodies, tens of *metres* in size (e.g. near Camedo; see also Kern, 1947, Knup, 1958, Reinhardt, 1966). Discordant, tube-like or isometric granitoid bodies are restricted to the SSB. Dykes as well as granitoid bodies are abundant in the south, decrease in number towards north, and hardly any are found outside the SSB. Our mapped border (Fig. 4) encompasses all of the observed and reported dykes of unequivocal Alpine age.

(2) *Limit of in-situ melting: In-situ* migmatisation is often observed in the form of concordant or discordant leucosomes (veins or pods), are generally coarser grained than the country rocks and are also observed inside dm- to m-scale shear zones. Melt segregations in spatially limited locations reach the extent of diatexis, where the Alpine fabrics become diffuse and locally disintegrate. In many cases, although textural evidence for partial melting is unequivocal, unambiguous mineralogical evidence for dehydration melting is lacking, i.e. typical reaction products of dehydration melting like sillimanite, orthopyroxene, cordierite or garnet are completely absent from strongly migmatitic orthogneisses. This implies that partial melts in orthogneiss must have formed by fluid-assisted partial melting if they show evidence of a high former melt fraction. We delimited the border of *in-situ* migmatisation using the widespread occurrence of unequivocal Alpine leucosomes (applying the criteria listed above). Spatially limited, isolated occurrences of concordant and more questionable leucosomes (some of which are discussed in more detail below) to the north of the limit shown in figure 4 were not included, because of their ambiguity.

(3) Limit of dehydration melting of white mica: This limit outlines the area where white mica breakdown led to the production of K-feldspar, sillimanite (or kyanite) and melt, according to the model reaction: Ms + Qtz = Sill + Ksp + Melt. For several reasons this border is not easy to map: Many sillimanite-bearing rocks from the study area do not contain K-feldspar, hence their sillimanite was more likely formed by subsolidus reactions, and thus recognition of sillimanite alone does not allow one to map out the limit of muscovite dehydration melting. In other words, the second sillimanite isograd does not necessarily coincide with the limit of muscovite dehydration melting. The latter limit, shown in figure 4, encompasses only localities satisfying two conditions: structural evidence of partial melting is observed at the outcrop *and* samples contain sillimanite+K-feldspar. The sillimanite+K-feldspar+*melt*-isograd had not previously been mapped in the Alps, and our limit represents a first attempt. In addition to our own field observations and sample collection, this map is based on data from the literature, notably Thompson (1976), Brouwer (2000), and Nagel et al. (2002).

Limited role of biotite dehydration melting

Few occurrences of cordierite-bearing assemblages are known in the Lepontine (Blattner, 1965; Wenk, 1968; Irouschek, 1980; Brouwer, 2000), and a single example of a sapphirine-orthopyroxene-cordierite-bearing assemblage (Gruf-complex: Droop and Bucher-Nurminen, 1984). The latter study proposed the production of melt due to biotite-dehydration reactions such as:

2Bt + 6Ky = 3Saph + 3Qtz + 2Kfs + Melt
and/or
Bt + Ky + H_2O = Saph + Qtz + Melt.

The survival of biotite was explained by the complete consumption of Al-silicate, at conditions below the upper thermal stability limit of biotite at metamorphic conditions of are around 830 °C/1.0 GPa. However, the small occurrences of these bodies are located in anatexites, which developed by water-present melting. One may thus question the Alpine age of that assemblage. Zircon inside these rocks is characterised by a Variscian core and an Alpine growth rim, which cannot be unambiguously related to the complex metamorphic history (Liati and Gebauer, 2003; Droop and Bucher-Nurminen, 1984). The possibility of a pre-Alpine precursor of these exceptional rock bodies may be invoked to explain their restitic character.

Cordierite and garnet bearing rocks, which are similarly restitic in character, also occur near Alpe Arami (Brouwer, 2000), but their age has not been investigated. These rocks, as those described from the Gruf body, are exceptional when compared to the vast majority of metamorphic samples from the SSB, in which biotite appears as a stable main phase in all granitoid and pelitic to semipelitic gneisses. Thus, evidence of Alpine biotite-dehydration melting is missing in virtually all of the Central Alps.

Special migmatite associations

A few local leucosome occurrences of probable Alpine age have been documented to the north of our limit of *in-situ* migmatisation. These occurrences appear to be unrelated to the partial melting processes described above for the SSB. The spatial isolation of these leucosomes leads us to suggest that they may owe their formation to particular circumstances, such as fluxing agents (e.g. Li, B, F). For example, in a quarry at Riveo (Valle Maggia, Fig. 1; 691'350/128'250), a few coarser grained leucocratic segregations in the form of cm–dm sized irregular pockets and veins are observed. The preservation of such coarse grain sizes in small veinlets, in surroundings, which show mylonitic and fine-grained Alpine fabrics, suggests an Alpine (post-mylonitic) crystallisation of these leucosomes. The melt fraction in these rocks must have been very low overall, and no other indications of anatexis have been found. We suggest that deformation may have enhanced melt segregation and that post-kinematic crystallisation of the leucosome resulted in the observed coarse fabric. In a second location, near Alpe Ribia (Valle Vergeletto; ~684'950/122'850) migmatitic orthogneiss occurs within non-migmatitic orthogneisses. Borders between migmatite and orthogneiss are gradational, indicating a common protolith for the two rocks. The migmatites are stromatic, and leucosome occurs in the form of irregular, foliation-parallel pods. These migmatites are notably situated in the top part of an inhomogeneous trail, comprising amphibolites and metasediments. Rocks from this trail may have released volatiles through dehydration reactions. Liberated fluids did not induce partial melting in the amphibolites and metasediments, but local eutectic melts formed upon entry of the fluids into the overlying K-feldspar + plagioclase + quartz -bearing orthogneisses. Similar relations between heterogeneously composed trails and enhanced rates of partial melting in associated orthogneiss have been observed in metasedimentary trails below Gresso (Valle Vergeletto; 690'600/119'980). Here, the contact between metasediments and adjacent orthogneiss is delineated by an orthogneiss layer, which is several decimetres thick and enriched in leucosome. Again, partial melting appears to have occurred in the K-feldspar bearing orthogneisses due to the release of volatiles from the adjacent metasediments.

Summary of the migmatisation in the SSB

– The extent of Alpine *in-situ* migmatisation and small-scale intrusive activity roughly coincide spatially, but the northern limit of dyke intrusions generally extends beyond that of *in-situ* partial melting by a few hundred metres to several kilometres. Alpine migmatisation is generally restricted to the SSB and areas immediately adjacent to the north. To the south it is sharply delimited by the Insubric line and, to the west of Locarno, by the Saas-Zermatt-zone s.l. immediately south of the Monte Rosa unit. Between Santa Maria Maggiore and Domodossola, the abundance of dykes decreases, and the northern limit of the Monte Rosa unit delimits the Alpine intrusive activity (Reinhardt, 1966). A single Alpine dyke has been reported from the western side of Valle d'Ossola, in the Moncucco unit (Locality Tappia, L. Keller pers. comm.). Towards north, the border of migmatisation is more gradual and difficult to map, but the abundance of Alpine migmatites and intrusives decreases rapidly north of the SSB.

– Alpine migmatisation commonly produced stromatic migmatites; metre-scale diatexitic structures occur, but they are rare, as are agmatites. Such schollen-type migmatites do occur extensively, also within the SSB (see Blattner, 1965; Hänny, 1972; Hänny et al., 1975), but they have been found to be pre-Alpine in age, and probably related to pre-Alpine intrusive activity. In the eastern part of the SSB, such pre-Alpine migmatites have again been affected by Alpine partial melting in several areas.

– Migmatites are not only observed in "fertile" lithologies like metasediments, but also in rather "unfertile" granitoid orthogneiss. Furthermore, migmatisation locally appears linked to the occurrence of heterogeneous, metasediment-bearing trails (e.g. at Alpe Ribia and at Gresso, Valle Vergeletto).

– Textural and mineralogical evidence for dehydration melting of white mica is restricted to the area of maximum Alpine metamorphic heating (around Bellinzona); it disappears near Locarno to the west, and between Bellinzona and Novate to the east. Outside this area, reaction products of muscovite dehydration melting (sillimanite + K-feldspar) are generally lacking or appear related to subsolidus processes rather then partial melting. Intriguingly however, recent experimental and thermodynamic studies indicate that orthogneisses similar to those found in the SSB, may partially melt through the vapour-absent melting of white mica, without formation of sillimanite (e.g. Patiño Douce and Harris, 1998; Thompson, 2001; Fig. 3g). Burri (2005) suggests the vapour absent melting of white mica+epidote+quartz to form K-feldspar, plagioclase, biotite and melt without the development of sillimanite (caluclated by thermodynamic modelling using DOMINO and the melt bearing database of Holland and Powell, 1998; see also White et al., 2001, 2005). Such a modelling approach in these systems indicates melt fractions of 13–14 vol% (Burri, 2005). As a result of such a reaction, minerals characteristic for dehydration-melting would be absent, and the only indication of this type of partial melting is the lack of white mica, a common feature in such rocks.

– Evidence of biotite dehydration-melting is constrained to but a few outcrops. Reaction products of biotite dehydration melting (such as orthopyroxene, sapphirine, spinel or cordierite) are generally lacking; or their local occurrence is related to subsolidus reactions or pre-Alpine migmatite formation.

– The restricted evidence of dehydration melting is in line with the observation that muscovite and biotite occur commonly in leucosomes and country rocks.

Tectonic implications of the observed spatial limits of the Alpine migmatite belt

As detailed above, anatexis and intrusion are sharply delimited to the south, and the limit is more gradual in the north. East of Locarno, Alpine magmatic activity is truncated along the Insubric Line. West of Locarno, *in-situ* migmatisation and intrusive activity occur no further south than in the ophiolitic Zermatt-Saas zone. The Sesia zone shows no sign of Alpine *in-situ* migmatisation, nor of the intrusion of Alpine pegmatites and aplites, but it does carry characteristic Tertiary porphyritic dykes of mafic composition (Beccaluva et al., 1983), which have not been found in the northerly adjacent Lepontine units. Nevertheless, the sharp delimitation of Alpine migmatisation between the Sesia unit and its northerly neighbours suggests that the Sesia unit and the Lepontine nappes were juxtaposed after the migmatisation and related intrusive activity had ceased, less than 24 Ma ago, based on age data from Romer et al. (1996).

Based on this evidence, we recognise an extensive shear zone situated between the Sesia unit in the south and the back-thrusted Lepontine nappes to the north. Considering the extremely strong and pervasive deformation of the Monte Rosa unit in the Centovalli area, the Monte Rosa unit and probably also the Sesia and Orselina units may be regarded as integral parts of this shear zone. Handy et al. (2005) indicate a high strain zone in the same position, which continues further west into Val Gressoney. However, similar to the important transpressional deformation along the Tonale Line, the above shear zone may have accommodated transpressional deformation with strike-slip, as well as a strong backthrusting component (Fig. 1 and 4). In the area around Arcegno, pegmatitic dykes commonly show a strong mylonitic overprint (e.g., Barbescio, 700'500/114'000), whereas dykes in the adjacent Orselina unit are undeformed or show an irregular, "mega-ptygmatic" fold style on the meter to tens of meter-scale (e.g. Ponte Brolla, 701'700/116'000). This change in deformation style of Alpine dykes indicates an increase in strain from north to south. Further to the west, we suppose that the shear zone continues along the contact between the Sesia unit and the Saas-Zermatt ophiolites.

We suggest that the proposed shear belt at the southern margin of the western part of the migmatite belt is not connected kinematically (or in time) to the Simplon-Rhône line, but rather to movements along the Tonale line. However, since the Tonale line in the east has traditionally been linked with the Canavese line in the west, a new name is necessary for the tectonic boundary along the southern Monte Rosa border. We propose to call it *Loana line*, and we link its kinematics with the Tonale line in the east, whereas its western continuation remains unclear. This interpretation is primarily based on migmatisation and further fieldwork is necessary to better constrain direction and characteristics of this shear zone.

Hornblende thermobarometry

Establishing metamorphic conditions during partial melting in the Central Alps is difficult because the rocks most affected by partial melting, i.e. granitoid gneisses do not contain mineral assemblages suitable for thermobarometry. Luckily, amphibole-bearing migmatites occur frequently in the SSB (Fig. 3h), and for these amphibole thermobarometry allows conditions of migmatisation to be determined.

Methods

Minerals were analysed on a Cameca SX50 electron microprobe at the University of Bern. Natural silicate standards were used. Analytical conditions were 15 kV and 20 nA; PAP corrections were applied. We analysed the compositions of small-scale local assemblages to avoid problems resulting from variations in mineral and effective bulk compositions.

To estimate pressure, we applied the Al-in-hornblende barometer of Anderson and Smith (1995), a calibration, which takes into account the effects of temperature on the amphibole Al-content. The required mineral assemblage of hornblende + biotite + plagioclase + K-feldspar + quartz + titanite + Fe-Ti-oxide + melt + fluid

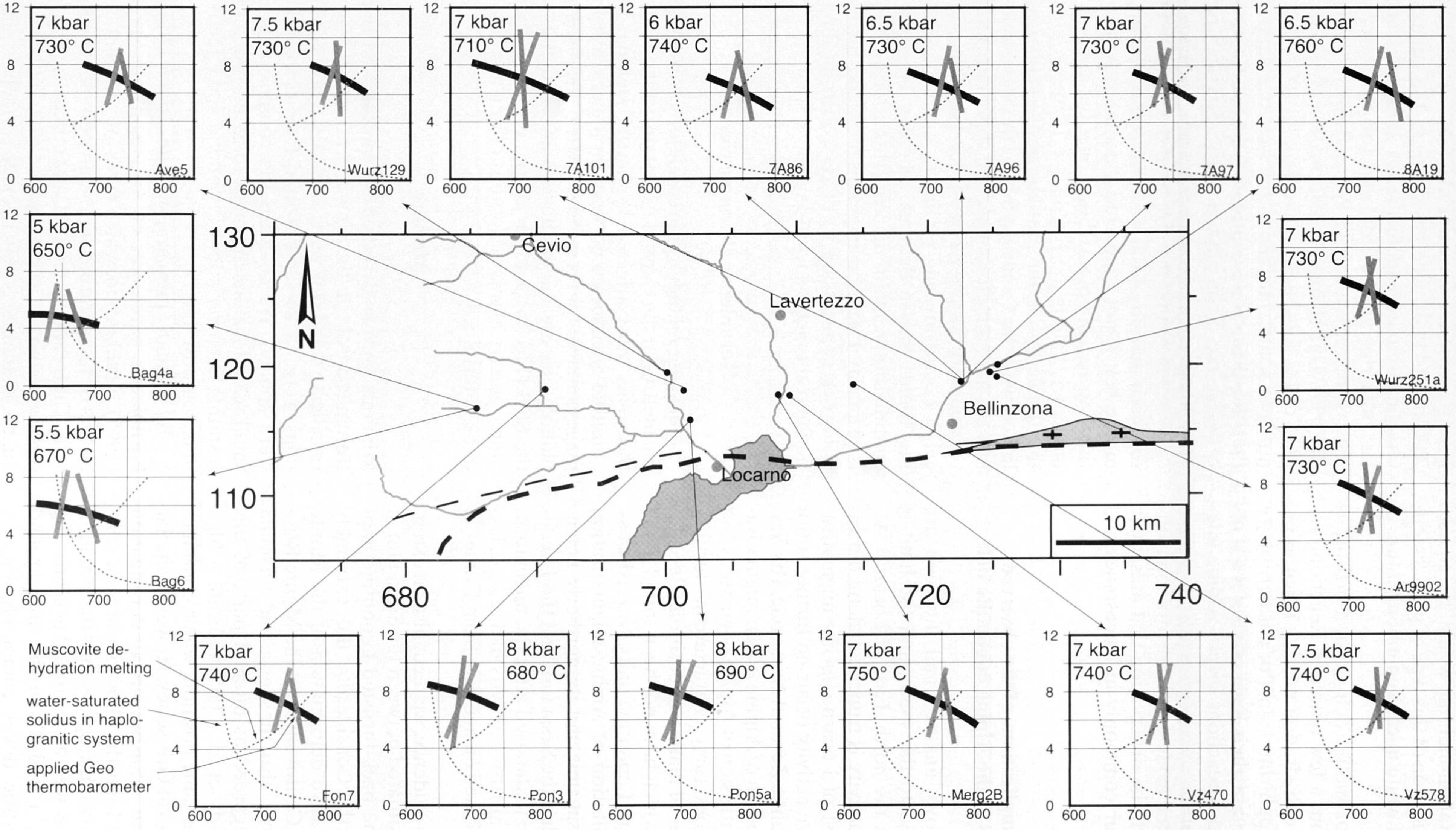

Fig. 5 Compilation of P–T-estimates for Alpine migmatisation in the SSB (see Table 1). P and T of amphibole-bearing leucosomes estimated using the Hbl-barometer (Anderson and Smith, 1995) and the Ampibole-Plagioclase-thermometers (Holland and Blundy, 1994). Black line represent geobarometer, the gray lines are thermometers A (edenite-tremolite) and B (edenite-richterite) of Holland and Blundy (1994). P–T diagrams depict results, i.e. relevant sections of the barometer and the two thermometers for each sample. The thin stippled lines indicate the water-saturated solidus of the haplogranitic system and muscovite dehydration melting in a KASH system (redrawn from Johannes and Holtz, 1994, and literature therein).

Table 1 Locations of samples used for Amphibole-thermobarometry.

Sample	X-ccord.	Y-coord	Location	Description
7A101	722.500	118.775	Mövenpick-highway-restaurant, near Bellinzona	Amphibole-bearing leucosomes in migmatitic gneiss
7A86	722.500	118.775	Mövenpick-highway-restaurant, near Bellinzona	Amphibole-bearing leucosomes in migmatitic gneiss
7A96	722.500	118.775	Mövenpick-highway-restaurant, near Bellinzona	Amphibole-bearing leucosomes in migmatitic gneiss
7A97	722.500	118.775	Mövenpick-highway-restaurant, near Bellinzona	Amphibole-bearing leucosomes in migmatitic gneiss
8A19	725.225	120.250	Roadturn NE of Arbedo, Valle Mesolcina	Amphibole-bearing leucosomes in migmatitic amphibole-rich-gneiss
Ar9902	725.125	119.325	Road-tunnel below Aragno, Valle d'Arbedo	Amphibole-bearing leucosomes in migmatitic gneiss
Ave5	701.260	118.160	Avegno, Valle Maggia	Amphibole-bearing synconcordant vein in migmatitic gneiss
Bag4a	685.300	116.750	Bagni di Craveggia, Valle Onsernone	Amphibole-bearing discordant vein in migmatitic gneiss
Bag6	685.300	116.750	Bagni di Craveggia, Valle Onsernone	Amphibole-bearing discordant vein in migmatitic gneiss
Fon7	690.625	118.225	Ponte Oscuro, Valle Vergeletto	Amphibole-bearing leucosomes in migmatitic gneiss
Merg2B	708.550	117.750	Fressino near Mergoscia, Valle Verzasca	Amphibole-bearing leucosomes in migmatitic gneiss
Pon3	701.750	115.920	Ponte Brolla	Amphibole bearing pegmatitic vein
Pon5a	701.750	115.920	Ponte Brolla	Amphibole bearing pegmatitic vein
Vz470	709.400	117.700	S. Cazza, Valle	Amphibole-bearing leucosomes in migmatitic gneiss (E.Wenk, MPI Basel)
Vz578	714.250	118.550	S of Forcola Valle di Cugnasco	Amphibole-bearing leucosomes in migmatitic (Cocco) gneiss (E.Wenk, MPI Basel)
Wurz129	700.000	119.500	Road between Dunzio-Aurigeno, Valle Maggia	Amphibole bearing aplite (E.Wenk, MPI Basel)
Wurz251a	724.650	119.700	Road between Arbedo Traversagna	Amphibole-bearing leucosomes in migmatitic gneiss (E.Wenk, MPI Basel)

(Schmidt, 1992) was always ascertained. Textural evidence was used to infer the former presence of melt, and a fluid phase must have been present at least during crystallisation of the segregated melt, as fluid saturated-assemblages formed.

Anderson and Smith (1995) proposed that the barometer may be applied only if the ratio of $Fe_{tot}/(Fe_{tot}+Mg)$ in amphibole varies between 0.4 and 0.65. Most analysed amphibole grains fulfill this requirement, a few are slightly outside this range (by ≤0.03). An additional limit is X_{An} in plagioclase, which must be between 0.25 and 0.35. Again, most analysed grains fulfill this requirement or are less than 0.03 outside. The only exceptions are two samples collected at Bagni di Craveggia, where X_{An} is only 0.08-0.13. Anderson and Smith (1995) suggest, however, that the accuracy of the barometer should be diminished only if plagioclase is too high in anorthite or K-feldspar too low in orthoclase. Both phases in the Bagni di Craveggia samples deviate in the opposite direction, and hence calculated pressures should be reliable.

To estimate temperatures we applied the two amphibole-plagioclase thermometers of Holland and Blundy (1994). All criteria they list regarding mineral composition were met by our samples.

Results

One problem inherent to amphibole thermobarometry in partially molten systems is the significance of the calculated P–T conditions, i.e. their interpretation. Because amphibole in anatectic granitoid systems is a reaction product of a water-assisted melting reaction, it is not clear whether the amphibole composition reflects the conditions of nucleation and growth, or the condition of crystallisation of the entire melt. Several reactions are proposed (e.g., Viruete, 1999; Mogk, 1992), where a mixed-mode melting reaction fits most with the observed textures in the investigated migmatites (Mogk, 1992). A possible reaction may be:

$$\text{Bio} + \text{Plag}(1) + \text{Qtz} \pm \text{Epi} + H_2O = \text{Hbl} + \text{Plag}(2) + \text{Melt (Kfs-rich)}$$

If hornblende re-equilibrated as long as a melt phase was present in the system (Schmidt, 1992), hornblende compositions should reflect conditions close to the crystal-

Table 2 Representative amphibole-analysis used for geothermobarometry and related plagioclase compositions.

sample	Fon7	Merg2B	Ave5	Wurz129	Vz470	Pon3	Pon5a	Bag6	Ar9902-1	8A19
SiO_2	39.361	39.436	39.594	40.219	40.426	42.16	41.98	42.75	41.201	40.553
TiO_2	0.722	1.104	0.997	0.924	1.136	0.87	0.79	0.89	1.01	1.099
Al_2O_3	12.763	13.241	12.557	13.485	13.167	13.14	13.15	10.48	13.313	12.856
FeO	23.064	20.943	21.485	21.083	20.379	17.89	17.38	22.06	20.065	17.795
MnO	0.55	0.659	0.865	0.629	0.485	0.65	0.62	0.56	0.705	0.452
MgO	6.301	7.179	6.999	7.111	7.916	8.98	8.98	7.91	8.162	9.523
CaO	11.136	11.259	11.154	11.413	11.489	11.50	11.74	10.676	11.56	11.7
BaO	0.036	0.027	0.058	0.015	bdl	0.031	0.074	n.d.	n.d.	n.d.
Na_2O	1.414	1.454	1.374	1.407	1.337	1.28	1.322	1.736	1.128	1.375
K_2O	1.812	1.895	1.803	1.648	1.854	1.68	1.68	1.57	1.43	1.695
F-	0.18	0.128	0.117	0.122	0.229	0.18	0.166	0.284	n.d.	n.d.
Cl-	0.021	0.02	0.033	0.014	0.023	0.005		0.011	n.d.	n.d.
Total	97.36	97.345	97.036	98.07	98.441	98.366	97.38	98.82	98.57	97.05
xK [Or]	0.02	0.01	0.01	0.01	0.06	0.01	0.01	0.01	0.02	0.01
xNa [Ab]	0.74	0.71	0.73	0.68	0.65	0.63	0.61	0.88	0.67	0.66
xCa [An]	0.24	0.28	0.25	0.31	0.30	0.36	0.37	0.11	0.31	0.33

lisation of the last melts along the water-saturated solidus. Further re-equilibration of hornblende might have occurred if the fluid released from the crystallising melt could not immediately escape the system. We argue that several of the observed retrogressed domains are due to such stagnant fluids, but as we avoided analysing such domains, estimated P–T conditions should best reflect the final crystallisation of leucosomes. In several samples, plagioclase grains included in amphibole were also analysed to track a possible change in P–T conditions during amphibole growth. Differences between matrix or inclusion pairs of amphibole and plagioclase were always <25 °C within a single sample, thus within error. This suggests that amphibole continuously equilibrated with the melt, or that they recorded only a short segment of the PT path for any sample.

Results of thermobarometry are collected in figure 5, and sample locations are given in Table 1. Most results indicate that the veins and leucosomes crystallised at 700–750 °C and 0.6–0.8 GPa. Two samples from Ponte Brolla (Pon3 and Pon5a) indicate slightly lower temperatures of 680–690 °C at 0.8 GPa. Samples from Bagni di Craveggia (Bag4a and Bag6) exhibit even lower temperatures of 650–670 °C at pressures around 0.5–0.55 GPa, which could reflect a real P–T difference of these two samples or a bias introduced by the low anorthite contents of plagioclase (~An 0.11, Table 2).

Several conclusions can be drawn from figure 5:

- All analysed samples indicate overstepping of the water saturated solidus of granitic to tonalitic rocks by as much as 100 °C. Provided that crystallisation occurred along the water saturated solidus, the overstepping appears to question the postulate that amphibole reflects conditions during final crystallisation of the melt (note discussion below).
- At several localities inside the SSB, muscovite dehydration melting was possible, whereas conditions of biotite dehydration melting were not reached.
- The data indicate no clear P–T gradient from E to W nor from N to S (but note the small N–S spread of samples). However, the lowest temperatures are measured in the western part of the migmatite belt.

Discussion of thermobarometric results

Most of our P–T estimates indicate conditions considerably above the water-saturated solidus of granitic to tonalitic rocks (Johannes and Holtz, 1996). According to Schmidt (1992), however, amphibole should equilibrate as long as melt is present, thus until the solidus of the system is reached. If so, the high temperatures obtained indicate that the leucosomes solidified above their water-saturated solidus, i.e. a reduced water activity in the melt. Experimental results, however, demand the presence of a free hydrous fluid for amphibole to be stable in granitic melts (Naney, 1983; Gardien et al., 2000). This leads to the contradictory requirement of a high activity of H_2O for the formation of amphibole, and of a low activity of H_2O to explain the crystallisation of the melts above their respective water-saturated solidus. To resolve the apparent discrepancy, we propose a scenario of water-rich fluid (or melt) injection into water-undersaturated rocks near their peak metamorphic temperature. Injection of a water-rich fluid may induce local water saturation and trigger the formation of amphibole-bearing partial melts. As rocks close to the site of partial melting remain fluid-undersaturated, at lower activity of H_2O, the induced chemical potential (μ_{H2O}) gradient between melt and solid rock would diffusively flatten out with time. Water-undersaturated host rocks would effectively act as sponges, extracting water from the melt until equilibrium is achieved. Decreasing water activity in the melt must then lead to the crystallisation of the melt above the water-saturated solidus. Further equilibration of amphibole is then inhibited due to the lack of melt. One consequence of this scenario is that leucosomes of a single outcrop may not all have formed (or crystallised) at the same time. The volume of leucosome observed at any individual outcrop would likely overestimate the melt fraction present at a single point in time. For a very similar migmatite terrain in the Gallatin Range (USA), it was in fact suggested that "at any one time there *was* only a small melt fraction present in any part of the system, and melt *was* constrained to localised envelopes around shear zones" (Mogk, 1992).

Discussion of the partial melting

Reported metamorphic conditions for the Central Alps would have allowed water-assisted partial melting over a considerably larger area of the Lepontine than currently observed (e.g., Todd and Engi, 1997; Fig. 4). By contrast, Tertiary partial melting and migmatisation occurred almost exclusively inside a spatially limited and structurally controlled area, which largely coincides with the SSB. The migmatites observed in this area share important characteristics: (1) they frequently contain melt segregations in structurally controlled positions (fold hinges, axial planes, shear zones etc.); (2) partial melts formed to a large extent as a result of fluid-assisted melting (± in addition to dehydration melting); and (3) they developed in a definite P–T interval. The combination of the above observations has implications for the geodynamic evolution of the Alps and similar migmatite belts in collisional orogens (e.g., Abalos et al., 2003).

Consequences for the Alps

The SSB, along with being the location of strong transpressive deformation, is also the locus of a partial melting of mid-Tertiary age. Estimated P–T conditions suggest that dehydration melting was not the only important migmatite-forming process. Instead, water-assisted partial melting has occurred outside, and probably also inside the small area where muscovite dehydration melting was possible. This suggests interdependence between partial melting, focussed deformation, and the availability of hydrous fluids. Thus, the focused deformation in the SSB may have induced an enhancement of fluid flow, which triggered water-assisted partial melting inside the deforming units (in addition to local dehydration melting). Partial melting and intrusions of dykes occurred over a protracted period between 32 Ma (intrusion of Bergell and related dykes) and 20 Ma (youngest undeformed dyke at Lavertezzo). Most data, however, indicate ages of around 29–25 Ma for the phase of migmatisation and intrusion (Hänny et al., 1975; Köppel et al., 1981; Schärer et al.,, 1996; Romer et al., 1996; Liati et al., 2000; Oberli et al., 2004). The ubiquity of locally deformed, as well as completely undeformed dykes and leucosomes, demonstrates that deformation, partial melting and intrusive activity occurred simultaneously.

Implications for other migmatite belts

The SSB of the Central Alps represents an example of a tectonic accretion channel (TAC, Engi et al., 2001). The SSB and similar TAC's typically show (1) evidence of partial melting, and (2) evidence of an earlier subduction history (e.g., Abalos et al, 2003). This subduction history as well as the subsequent, rapid extrusion of hot fragments to higher crustal levels (Roselle et al., 2002), may be essential for the creation of collisional migmatite belts. Thus, a combination of a high (advective) heat flux and deformation-assisted fluid access are thought to be key factors initiating a phase of partial melting in collisional orogens. The formation of melt drastically reduces the strength of the rocks undergoing partial melting (e.g., Rosenberg and Handy, 2005), but also of the migmatite belt on a regional scale. The initial melts produced must have suddenly and drastically reduced the strength of the crustal section in key positions of the orogen, thus exerting an essential control on the strength of orogens (e.g., Ellis et al., 1999; Pfiffner et al., 2000; Beaumont et al., 2001). Intriguingly, exhumation rates in the Central Alps increased after the onset of partial melting, and decreased after that phase (e.g., Sinclair et al., 1991; Schlunegger, 1999). Although this increase may to a large degree be the result of changing kinematics in the Central Alps (from nappe stacking to backthrusting), the lowering of the rocks' viscosity may additionally have increased the rate of exhumation of the Lepontine Alps.

An investigation on the significance of partial melts in orogen-wide kinematics is, however, complicated by several factors:

(a) The amount and distribution of melt throughout the migmatite belt may have varied considerably in space and time as a function of bulk composition and the availability of infiltrating fluids. This results in an inhomogeneous distribution of melt on different scales, and in preferred partitioning of deformation into the rheologically weakest, melt-bearing domains.

(b) As outlined above, leucosomes observed in one outcrop may not all have been in the partially molten state at the same time and P–T conditions.

(c) Strain accommodated inside melt-rich zones may not be visible after crystallisation of the melt. For example, in many of the stromatic orthogneisses with estimated melt fractions of ≥15%, fabrics appear magmatic rather than metamorphic. Rocks from such zones typically lack the tight and pervasive foliation or lineation observed in adjacent leucosome-poor rocks.

It thus appears that certain domains of the SSB behaved as a crystal-rich mush, whereas other areas behaved as essentially solid rocks. As strain partitions into the rheologically weakest section, considerable amounts of strain may be taken up by more pervasively molten rocks. However, after crystallisation of the melt, the high accommodated strains may no longer be inferred from such outcrops. Therefore, much care must be taken when inferring the influence of partial melts on orogen-wide kinematics when using field-based evidence.

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