Regional granulite facies metamorphism in the Ivrea zone: Is the Mafic Complex the smoking gun or a red herring?

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ABSTRACT

One widely accepted paradigm for the development of continental lower crust is that regional granulite facies metamorphism is caused by intrusion of mafic magma beneath or into the crust (magmatic accretion). The amphibolite to granulite facies supracrustal section exposed in the Ivrea zone (southern Alps, northern Italy) is commonly cited as a classic example establishing this postulated genetic relationship. Our interpretation of the pattern of metamorphic isograds, compositional trends in high-grade metasedimentary rocks, and textural evidence in metapelite, however, indicates that final emplacement of the mafic plutonic rocks (the Mafic Complex) occurred subsequent to the regional thermal maximum. Field and petrographic relations suggest that a spatially restricted contact-melting event in crustal rocks accompanied the emplacement of the Mafic Complex. This inference is consistent with leucosome compositions in migmatites and a low-pressure, high-temperature metamorphic overprint recorded by mineral assemblages in wall rocks proximal to the intrusion. Therefore, evidence of anatexis and metamorphism of crustal rocks associated unequivocally with emplacement of the Mafic Complex is found only within an ~2-km-wide contact aureole overlying the intrusion. The narrow aureole associated with emplacement of the Mafic Complex demonstrates that, in some cases, emplacement of large volumes of mafic magma within the crust does not inexorably lead to regional-scale granulite facies metamorphism and large ion lithophile element depletion by melt loss.

INTRODUCTION

One model for the large ion lithophile element (LILE) depletion of crustal rocks during granulite facies metamorphism is that extraction of melt attends emplacement of mafic magma under or near the base of the continental lower crust (magmatic accretion) (Harley, 1989). In this model, mantle magmatism, granulite facies metamorphism, and crustal anatexis are coupled processes that result in chemical differentiation of continental crust. Within the Ivrea zone (southern Alps, northern Italy), mantle-derived magma intruded metasedimentary and metaigneous rocks while the section was in the lower crust (Rivalenti et al., 1975; Voshage et al., 1990). Emplacement of mafic magmas within the supracrustal section has been traditionally interpreted as having caused or having accompanied the thermal maximum during regional granulite facies metamorphism (e.g., Schmid and Wood, 1976; Rivalenti et al., 1980; Sills, 1984). The exposure of mafic rocks thought to have caused regional metamorphism in the overlying granulite terrain has led some to consider the Ivrea zone a particularly important example of the purported relationship between regional metamorphism and magmatic accretion (e.g., Voshage et al., 1990).

In this study we provide evidence supporting an alternative model, in which the emplacement of the Mafic Complex occurred after the imposition of the regional pattern of metamorphic isograds (Zingg et al., 1990). Therefore, the heat supplied by the emplacement of the exposed part of the Mafic Complex is unlikely to have caused regional granulite facies metamorphism. The metamorphism and anatexis of weakly depleted, amphibolite to granulite facies crustal rocks associated with emplacement of the Mafic Complex occurred only within an ~2-km-wide zone overlying the upper parts of the intrusion. This narrow contact aureole demonstrates that extensive regional metamorphism and anatexis may not inexorably accompany emplacement of large volumes of mafic magma against fertile crustal rocks. Studies postulating that regional effects necessarily accompany magmatic accretion (e.g., Campbell and Turner, 1987; Huppert and Sparks, 1988) may underestimate the amount of basalt required to achieve the degree of melt depletion inferred for regional granulite terrains such as the Ivrea zone.

GEOLOGIC FRAMEWORK

Most regional studies interpret the Ivrea zone as a cross section through attenuated continental lower crust (Burke and Fountain, 1990). There are three major lithologic divisions in the Ivrea zone (Fig. 1): (1) supracrustal rocks of the Kinzigite Formation; (2) mantle peridotite; and (3) the Mafic Complex. The lowest grade rocks crop out along the southeastern margin of the Ivrea zone and contain upper amphibolite facies assemblages (Zingg, 1980). Granulite facies rocks are exposed in Val Strona, indicating that metamorphic grade increases toward the northwest, in accordance with pressure-temperature (*P-T*) estimates derived using geothermobarometry (Schmid and Wood, 1976; Sills, 1984; Henk et al., 1997).

The amphibolite facies of the Kinzigite Formation consist of migmatitic metapelite and metapsammite and subordinate metacarbonate and metabasite (Sills, 1984). The texture of the metapelite changes from lepidoblastic to granoblastic due to replacement of muscovite and biotite by K-feldspar and garnet with increasing grade (Zingg, 1980). In granulite facies rocks, massive quartz + hypersthene ± garnet granulite (charnockite), metacarbonate, and metabasite are interlayered with granoblastic graphite + sillimanite + garnet gneiss (stronalite), interpreted to be residual material from the partial melting of metapelite.

The Mafic Complex is as much as 10 km thick and comprises gabbroic to leucodioritic rocks intercalated with ultramafic rocks and thin

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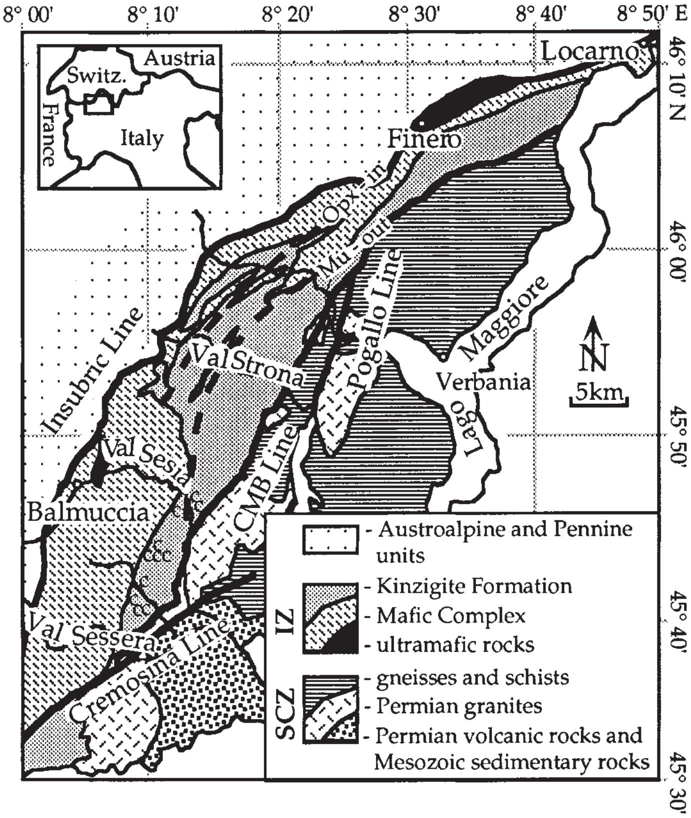

Figure 1. Simplified geologic map of southern Alps west of Lago Maggiore (modified from Zingg, 1980). Inset shows location of study area in northern Italy. IZ and SCZ refer to Ivrea zone and Strona-Ceneri zone, respectively. Mu - out represents muscovite–K-feldspar isograd in metapelite, and Opx - in represents first appearance of orthopyroxene in metabasite (Zingg, 1980). C indicates cordierite occurrences. CMB line indicates Cossato-Mergozzo-Brissago line, purported late Paleozoic fault separating Ivrea and Strona-Ceneri zones (Boriani et al., 1977).

layers of supracrustal rocks (Quick et al., 1994). The supracrustal rocks consist of <1- to ~100-m-thick layers of depleted granulite, referred to as septa, interpreted to be rocks excavated from the roof of the Mafic Complex during emplacement (Sinigoi et al., 1996). Four main rock types are recognized in the septa: (1) "stronalite"; (2) "charnockite"; (3) calc-silicate rock; and (4) minor metabasite (Rivalenti et al., 1975). Discontinuous layers of tonalite to granodiorite diatexite (≤200 m thick) containing blocks and schlieren of metabasite and metapelite separate the Mafic Complex from the overlying Kinzigite Formation (Bürgi and Klötzli, 1990; Quick et al., 1994). Potassium depletion of the diatexite may have partly resulted from chemical interaction between melts of the Mafic Complex and the roof-zone wall rocks (McCarthy and Patiño Douce, 1997).

RELATIONSHIP BETWEEN BASALTIC MAGMATISM, CRUSTAL ANATEXIS, AND GRANULITE FACIES METAMORPHISM

Field and Petrologic Evidence

Field and petrologic observations motivate an interpretation that the Mafic Complex intruded after the imposition of the regional pattern of metamorphic isograds. On the basis of a compilation of previous petrographic work, Zingg (1980) mapped mineral isograds that represent prograde reactions produced during regional metamorphism to granulite facies (Fig. 1). Two of these isograds are the muscovite to K-feldspar isograd in sillimanite-bearing paragneiss and the first appearance of clinopyroxene + orthopyroxene in metabasite (Fig. 1). Zingg (1980) noted that the distribution of mineral assemblages in metapelite and metabasite within septa in the Mafic Complex is not continuous with the regional isograd pattern. Thus, the northeastern margin of the Mafic Complex cuts across the strike of the prograde metamorphic isograds at a high angle. We concur with the inference of Zingg et al. (1990) that the disposition of the prograde metamorphic isograds in the Ivrea zone is consistent with granulite facies conditions imposed prior to the emplacement of the upper parts of the Mafic Complex.

In addition, if emplacement of the Mafic Complex supplied the heat for regional metamorphism in the Kinzigite Formation, the rocks close to the contact should have granulite facies mineral assemblages. However, granulite facies assemblages are predominantly confined to crustal levels of P >6 kbar in the Val Strona region on the northeast side of the Mafic Complex. In Val Sesia (Fig. 1), plagioclase-bearing metabasite contains the upper amphibolite facies assemblage hornblende ± biotite ± clinopyroxene (Zingg, 1980). The regional increase in metamorphic grade thus correlates with the across-strike increase from ~4 to ~9 kbar between the southeastern (Cossato-Mergozzo-Brissago line) and northwestern (Insubric line) tectonic boundaries of the Ivrea zone (Sills, 1984; Henk et al., 1997), rather than proximity to the Mafic Complex. Thus, the distribution of granulite facies rocks in the Ivrea zone is inconsistent with the emplacement of the Mafic Complex having caused regional granulite facies metamorphism.

Cordierite, hercynite, and relict andalusite appear in an ~2-km-wide zone (Fig. 1) surrounding the upper parts of the Mafic Complex south of Val Sesia (Zingg, 1980). In this zone, cordierite and hercynite overprint the assemblage biotite + garnet + sillimanite in metapelite. This suggests that the rocks proximal to the Mafic Complex south of the Val Sesia region reached final equilibration at a lower pressure than those along strike in lower Val Strona. We infer that intrusion of the exposed portion of the Mafic Complex took place during regional decompression, excising the preexisting granulite facies crustal rocks. Final emplacement of the Mafic Complex occurred at a high level in the section, juxtaposing the upper margin of the Mafic Complex against (only weakly depleted) amphibolite facies crustal rocks. The local thermal event associated with emplacement of the upper parts of the Mafic Complex overprinted the preexisting, higher pressure, amphibolite to granulite facies regional metamorphic zonation.

Geochemical Evidence

The composition of "stronalite" can be explained by extraction of 20–40 wt% of a granite component from the amphibolite facies metasedimentary rocks (Sighinolfi and Gorgoni, 1978; Schnetger, 1994). Because these rocks exhibit a limited range in bulk chemical composition, variability in protolith chemistry probably was not a first-order control on anatexis (Schnetger, 1994). The extent of depletion of stronalite correlates with the across-strike increase in metamorphic grade (Sighinolfi and Gorgoni, 1978; Schmid and Wood, 1976; Zingg, 1980) and original crustal depth to the northwest in Val Strona (Sills, 1984; Henk et al., 1997).

There is no apparent increase in the extent of depletion of stronalite with proximity to the Mafic Complex. Plots of weight percent (wt%) K versus K/Rb ratios of stronalite and amphibolite facies metapelite are shown in Figure 2. In agreement with general compositional trends in granulite facies rocks (Rudnick and Presper, 1990), the K/Rb ratio varies inversely with K content below 1.0 wt% K, reflecting the partitioning of K and Rb between crystalline and fluid or melt phases (Fowler, 1986). K/Rb ratios in stronalite with >2.0 wt% K are similar to those in amphibolite facies metapelite. Stronalite with <2.0 wt% K has K/Rb ratios approaching 1000, reflecting depletion relative to lower grade metapelite. Significant compositional overlap exists, however, for stronalite contained within septa in the Mafic Complex and within the granulite facies of Val Strona (Fig. 2). Assuming that stronalite represents the residues after anatexis of metapelite (Sighinolfi and Gorgoni, 1978; Schnetger, 1994), the similar elevation in the K/Rb ratio may reflect similar levels of melt extraction. Although alternative interpretations may explain these geochemical trends, according to the view that the depletion of stronalite is related to melt

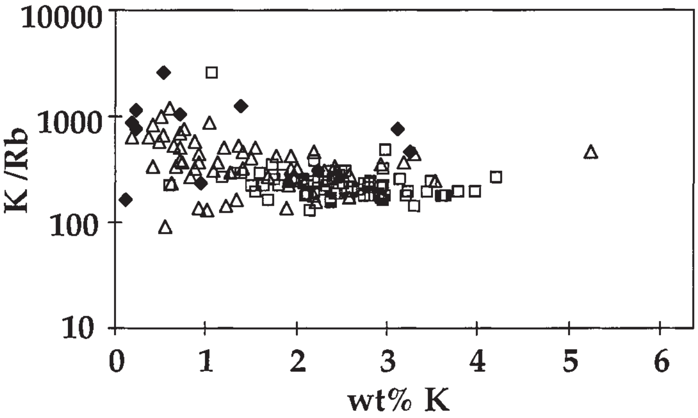

Figure 2. K/Rb ratio vs. weight percent K: "Stronalite" in Val Strona (triangles); "stronalite" within Mafic Complex (diamonds); and amphibolite facies, sillimanite-bearing metapelite (squares) (see text for details). Data include our own analyses, and those of Sighinolfi (1969), Mehnert (1975), Rivalenti et al. (1975), Dostal and Capedri (1979), Schnetger (1994), and Sinigoi et al. (1994, 1996).

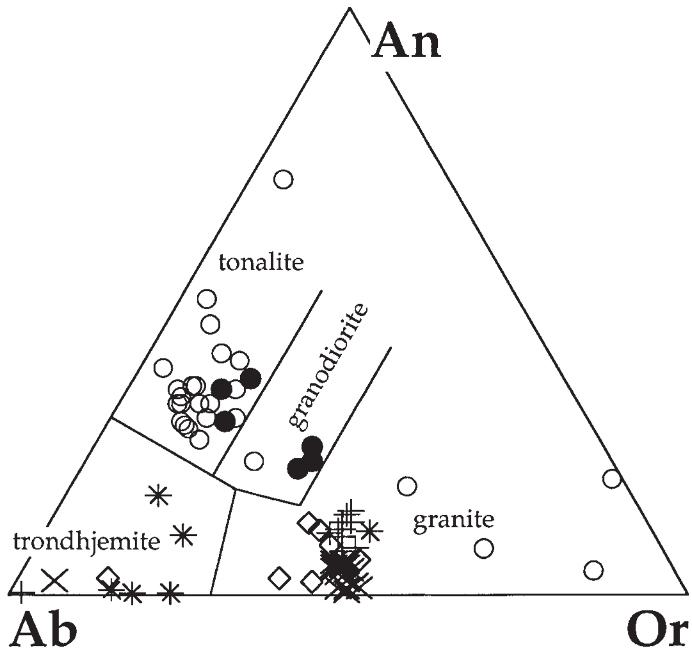

Figure 3. Classification of granitoid rocks in Ivrea and Strona-Ceneri zones according to normative An-Ab-Or compositions. White and black circles represent leucotonalite leucosomes and tonalite to granodiorite diatexite, respectively. Composition of Permian granites within Strona-Ceneri zone (diamonds = Roccapietra granite, x = Baveno pink granite, plus signs = Montorfano granite, and asterisks = Mergozzo granite) are similar to inferred composition of crustal melt extracted during regional metamorphism (Schnetger, 1994). Data include our own analyses and those of Boriani et al. (1992).

extraction (e.g., Schnetger, 1994), there is no significant increase in melt extraction with proximity to the Mafic Complex.

REGIONAL AND CONTACT MELTING

The inferred composition of the crustal component assimilated by the parental magmas of the Mafic Complex is consistent with regional metamorphism predating emplacement. Nd, Sr, and $\delta^{18}O$ data indicate that the magmas of the Mafic Complex were contaminated by assimilation of variable proportions of crustal material (Voshage et al., 1990; Sinigoi et al., 1994). Sinigoi et al. (1994) suggested that this crustal contaminant was probably derived from metapelitic rocks excavated from the supracrustal section and incorporated as septa within the Mafic Complex during emplacement. The unusually high Ba/K and Ba/Rb ratios of the Mafic Complex indicate that the overlying supracrustal section was depleted in Rb^+ and K^+ prior to or during emplacement of the Mafic Complex (Sinigoi et al., 1994). However, the progressive removal of Rb^+ and K^+ with increasing grade in stronalite is well documented, and no such depletion exists in rocks overlying the intrusion (Fig. 2). Therefore, we note that bulk assimilation of stronalite produced prior to emplacement of the Mafic Complex rather than amphibolite facies metapelite may explain the unusual K^+- and Rb^+-depleted composition of the contaminant.

Bulk compositions of stronalite are consistent with the extraction of 20–40 vol% granite melt (Schnetger, 1994) during regional granulite facies metamorphism. In contrast, leucosomes within metapelitic migmatite proximal to the roof of the Mafic Complex are leucotonalite in composition (Fig. 3). The contrast in leucosome composition proximal to the Mafic Complex with the putative composition of melt lost from stronalite suggests that there were multiple episodes of anatexis in the Kinzigite Formation. Lenses of tonalite to granodiorite diatexite ≤200 m thick are conformable with the contact between the Mafic Complex and the Kinzigite Formation (Quick et al., 1994), suggesting an increase in the volume of melting closer to the local heat source. We infer that heat released from the Mafic Complex caused the melting that produced the tonalite to granodiorite diatexite and the leucotonalite leucosomes in the Kinzigite Formation. The K-poor compositions of these products of metapelite anatexis could imply either melting under conditions of high H_2O activity (e.g., Conrad et al., 1988; Whitney and Irving, 1994) or hybridization of crustal rocks with melt from the Mafic Complex (McCarthy and Patiño Douce, 1997). In either case, leucotonalite leucosomes are not volumetrically significant and are restricted to the Kinzigite Formation overlying the Mafic Complex, coincident with the appearance of cordierite, hercynite, and andalusite in the restite assemblage. Thus, although a granite melt is inferred to have been extracted from the Kinzigite Formation to produce stronalite, only local anatexis that produced tonalite to granodiorite diatexite along the contact and leucotonalite leucosomes in the overlying migmatites can be directly linked to the emplacement of the Mafic Complex.

DISCUSSION

Five observations suggest that emplacement of the Mafic Complex did not cause regional granulite facies metamorphism in the Ivrea zone.[1] (1) The northeastern margin of the Mafic Complex cuts across the strike of regional prograde metamorphic isograds at a high angle. Along with the regional distribution of granulite facies rocks, this observation indicates that supracrustal rocks in the Ivrea zone equilibrated under amphibolite to granulite facies conditions prior to emplacement of the Mafic Complex. (2) Mineral assemblages in metapelite proximal to the intrusion preserve evidence of a low-pressure, high-temperature metamorphic overprint of the former amphibolite to granulite facies regional metamorphic zonation. (3) The extent of depletion of metasedimentary rocks in the Ivrea zone correlates with increasing crustal depth, and there is no apparent increase in the depletion of granulite with proximity to the Mafic Complex. (4) The composition of the Mafic Complex contaminant is consistent with anatexis and melt extraction in the supracrustal rocks having occurred prior to final emplacement of the Mafic Complex. (5) The composition of the leucosomes overlying the Mafic Complex is inconsistent with the composition of the melt inferred to have been extracted from the Kinzigite Formation to form stronalite. These observations are explained if regional granulite facies metamorphism preceded emplacement of the Mafic Complex.

[1]GSA Data Repository item 9938 is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

CONCLUSIONS

The Ivrea zone is often cited as a classic example of a lower crustal section (e.g., Fountain and Salisbury, 1981). One implication of our study is that the lower mafic component of the section did not necessarily cause the metamorphism of the upper crustal units. The metamorphic event associated with emplacement of the Mafic Complex is superimposed upon the preexisting amphibolite to granulite facies metamorphic zonation. The lower crust, as represented by the Ivrea zone, is composite, polybaric, and polymetamorphic, containing numerous juxtaposed units that are not necessarily genetically related. A hypothetical suite of lower crustal xenoliths produced from a section of crustal rocks like the Ivrea zone may contain both restitic crustal rocks and mafic to ultramafic granulites. However, the coincidence of these lithologies in a xenolith suite would not necessarily imply any relationship between emplacement of mafic magma and granulite facies metamorphism.

In the Ivrea zone, emplacement of the Mafic Complex generated only a modest volume of melt represented by tonalite to granodiorite diatexite and leucotonalite leucosomes in a restricted zone overlying the intrusion. The narrow zone of contact metamorphism and anatexis we associate with emplacement of the Mafic Complex suggests that voluminous intrusion of mantle-derived magma does not inexorably imply regional-scale metamorphism and anatexis of the lower continental crust. Therefore, calculated amounts of basaltic input to magmatic systems based on mass and enthalpy balances from continental magmatism (Grunder, 1995) are probably minimums. Reference to studies that call on anatexis and regional granulite facies metamorphism accompanying magmatic accretion (e.g., Campbell and Turner, 1987; Huppert and Sparks, 1988) should be tempered by an awareness that such effects are not apparent in the Ivrea zone, which has hitherto been regarded as a prime example of such a process.

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