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Autor(en): **Trommsdorff, Volkmar / Connolly, James A.D.**

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The ultramafic contact aureole about the Bregaglia (Bergell) tonalite: isograds and a thermal model

by *Volkmar Trommsdorff*[1] and *James A.D. Connolly*[1]

Abstract

Thermodynamic calculations for the lherzolitic bulk composition of the Malenco serpentinite reproduce the observed mineral compositions and assemblages with great fidelity. The resulting petrogenetic grid predicts narrow temperature intervals for the serpentinite "isograd" reactions, in agreement with sharp isograds observed in the Bergell aureole. The thermodynamic calculations indicate that large enthalpic (> 400 MJ/m^3) and volume (> 25%) effects are associated with the serpentinite metamorphism. The solid volume reduction associated with the terminal antigorite dehydration reaction alone is ca. 18%, and probably caused the olivine + talc-filled extensional veins observed on the low temperature side of the corresponding isograd. Incorporation of latent heat effects and variation in thermal conductivity due to metamorphism in a simple heat conduction model results in consistency between geothermometers and the computed thermal profile. It would not be possible to obtain the same degree of consistency if the slab-like Bergell tonalite was emplaced in an orientation more horizontal than indicated by its present-day exposure. The pre-intrusive ambient temperature is constrained to be in the vicinity of 350 ± 20 °C, requiring a geothermal gradient of 28 ± 2 °C/km. As peak regional metamorphic temperatures (ca. 450 °C) occurred at 65 Ma prior to the Bergell emplacement at 32 Ma (JAEGER, 1973; VON BLANKENBURG, 1990) this implies an average cooling rate of 3 °C/Ma over this time interval. It is unnecessary to invoke free advection, i.e., buoyancy driven, of a fluid phase to explain the temperature distribution in the aureole, suggesting that fluid movement was probably forced during metamorphism. Thermal modeling does not predict temperatures adequate to drive talc and anthophyllite decomposition reactions in a pure H_2O fluid. That these reactions occurred sporadically near the contact is most likely related to decarbonation reactions in the contact zone that lowered the thermodynamic activity of water in the metamorphic fluid phase. This implies that the fluid phase present in the aureole was not well-mixed, and therefore also supports the conclusion that fluid flow was forced.

Keywords: contact metamorphism, regional metamorphism, heat conduction, thermal model, antigorite, Malenco serpentinite, Bergell (Bregaglia) tonalite, Central Alps.

Introduction

Over the past 20 years considerable effort has been made toward mapping and interpreting the metamorphic isograds developed in the ultramafic and ophicarbonate rocks about the Bergell intrusion. As a result of these efforts, the thermal profile that developed in the aureole is unusually well constrained. The goal of the study reported here was to determine whether these observations can be reconciled with a simple heat conduction model; and, if so, the geologically relevant conclusions that can be drawn from this. This paper begins with a review of the general geology and metamorphism of the Bergell intrusive and Malenco serpentinite. This is followed by presentation of petrological and thermodynamic models for the serpentinite and tonalite, aspects of which are subsequently incorporated in a heat-conduction model.

In an earlier attempt to model the contact aureole, TROMMSDORFF and EVANS (1977) concluded that the thermal profile in the aureole recorded by metamorphic mineral assemblages was too diffuse to be consistent with heat transfer by conduction. There are three reasons why this conclusion should be re-examined: (i) TROMMSDORFF and EVANS did not take into account metamor-

[1] Institut für Mineralogie und Petrographie, Eidgenössische Technische Hochschule, ETH-Zentrum, CH-8092 Zürich, Switzerland. E-mail: vtro@erdw.ethz.ch.

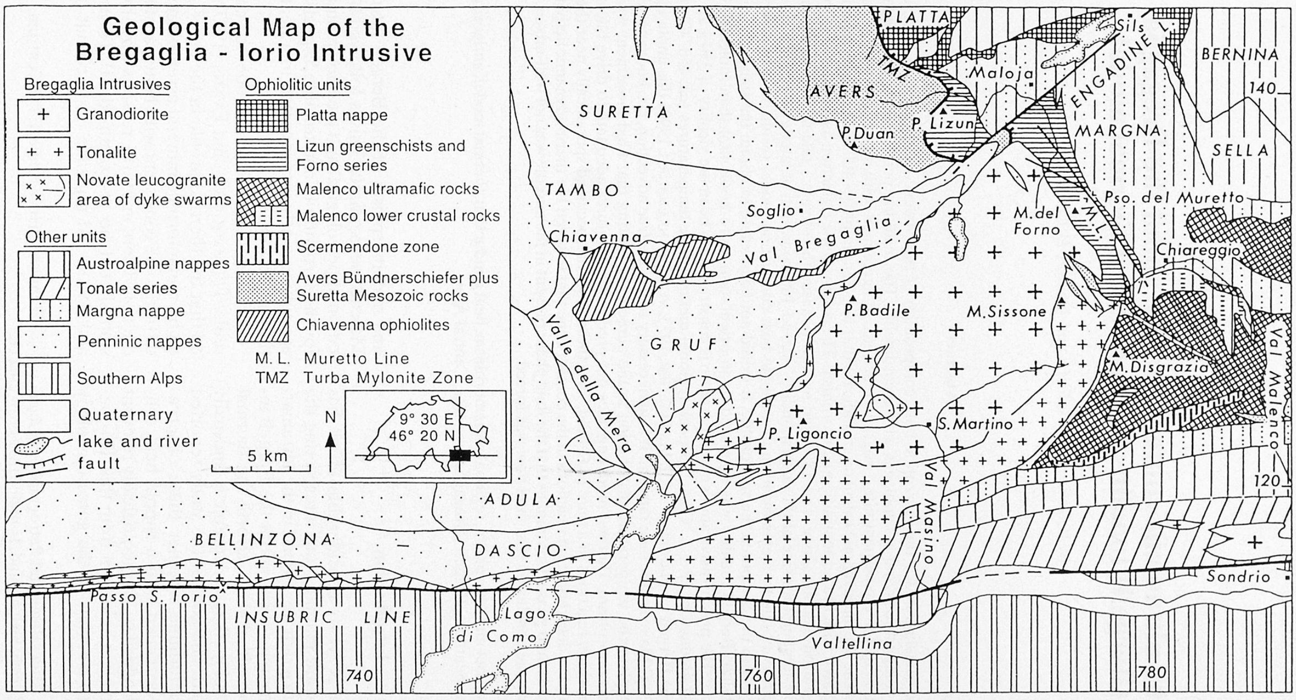

Fig. 1 Geological map of the Bregaglia-Iorio intrusive modified from TROMMSDORFF and NIEVERGELT (1983). Coordinates refer to the Swiss reference frame.

phic effects on thermal conductivity or the energy budget of heat flow; (ii) TROMMSDORFF and EVANS had no thermodynamic data for antigorite, the stable serpentine phase in the aureole, and consequently underestimated its thermal stability; and (iii) in recognition of the uncertainties in their analysis, TROMMSDORFF and EVANS did not distinguish between the instantaneous thermal gradient and that recorded by the mineral assemblages. FERRY (1995) fit prograde metamorphic temperatures in ophicarbonate rocks of the aureole to a simple two parameter equation intended to represent the maximum temperatures achieved during conductive cooling of a radially symmetric pluton. As discussed here, lateral symmetry is a more appropriate model, and this leads to less rapid temperature variation with distance from the contact than implied by Ferry's model. POZZORINI (1996) calculated temperatures from stable isotope measurements in the ophicarbonate rocks which suggest apparent thermal gradients along the isograds of contact metamorphism. He attributed this inconsistency to fluid infiltration from the dehydrating serpentinites into the ophicarbonate zone.

General geology

The Oligocene calc-alkaline Bergell intrusive (Fig. 1, TROMMSDORFF and NIEVERGELT, 1983) is composed of an outer, elongate (> 50 km) tonalite body (REUSSER, 1987), minor gabbroic bodies, and a central 20 × 10 km mass of porphyritic granodiorite. The tonalite and granodiorite intrusive phases have been assigned ages of 32 and 30 Ma, respectively (VON BLANKENBURG, 1990).

The tonalite is bordered along its southeastern margin by a large mass of ultramafic rocks, the Malenco serpentinite (Fig. 1). The contact zone between these units is marked by < 10 m thick lenses of carbonate rocks and gneisses belonging to the Penninic Suretta nappe (GIERÉ, 1985). The contact is exposed over a distance of ca 10 km (Fig. 2) and is vertical except for the area east of Monte Disgrazia, where it dips about 70° east.

Northwest of the contact, the tonalite forms a 2.2–3.5 km thick "sheet" (REUSSER 1987; BUCHER, 1977), the northern part of which contains abundant roof pendants of the Suretta nappe. The ultramafic rocks to the east and southeast of the contact are continuous with two exceptions: (i) south of Monte Disgrazia the ultramafics are overlain by a thin sheet of MOR basalts belonging to the Forno unit, an ophiolite suite (PERETTI, 1985) that borders the Bergell intrusive (Figs 1 and 2); and (ii) near the northeastern edge of the tonalite, two, near vertical, subparallel zones of gneissic and ophicarbonate rocks, of the Margna and Malenco nappes, respectively, strike normal to the intrusive contact (Fig. 2). REUSSER (1987) showed that solidus pressures for the tonalite were 7.5 kbar at its westernmost extension near Bellinzona (Fig. 1) and 5 kbar in the east near Chiareggio. As the tonalite crosscuts Austroalpine units, the so-called Tonale suite, in the west, and tectonically deeper, upper Penninic units in the east, the variation in solidus pressures can only be explained if the tonalite intruded these units in its present vertical orientation.

Regional metamorphism

Alpine regional metamorphism in the vicinity of the Bergell intrusive is polyphase. In the Austroalpine Margna nappe, which forms the lid of the tectonic edifice intruded by the Bergell rocks, late Cretaceous to early Tertiary ages (ca 65 Ma, JAEGER, 1973) have been determined for the regional metamorphism. P-T (see Tab. 1 for notation) conditions peaked at about 6 kbar and 450 °C (GUNTLI and LINIGER, 1989). In the deeper seated Penninic crystalline nappes west of the intrusion, regional metamorphism is of Oligocene age, and peaked after the Bergell intrusion, reaching amphibolite-granulite facies conditions (SCHMUTZ, 1976; TROMMSDORFF and NIEVERGELT, 1983; REUSSER, 1987). West of Valle della Mera the tonalite becomes increasingly schistose and contact metamorphism becomes indistinguishable from the regional metamorphic overprint.

The Malenco ultramafics are in a tectonic position between these two extremes. TROMMSDORFF and EVANS (1972) demonstrated that the regional metamorphic assemblage in this unit predates the Bergell intrusion. The dominant regional metamorphic assemblage in the Malenco serpentinite is At + Ol + Di + Chl + Mt, with Ti-rich clinohumite, brucite, Fe–Ni alloys, and sulfides as accessory phases.

Contact metamorphism

The contact metamorphism of the regional metamorphic serpentinite assemblage is reflected by five isograds (TROMMSDORFF and EVANS, 1972; RIKLIN, 1978; TROMMSDORFF and NIEVERGELT, 1983; PFIFFNER and WEISS, 1994). These are, in order of increasing metamorphic grade: (i) the formation of tremolite and olivine (Tr-isograd), at the expense of diopside and antigorite, which pro-

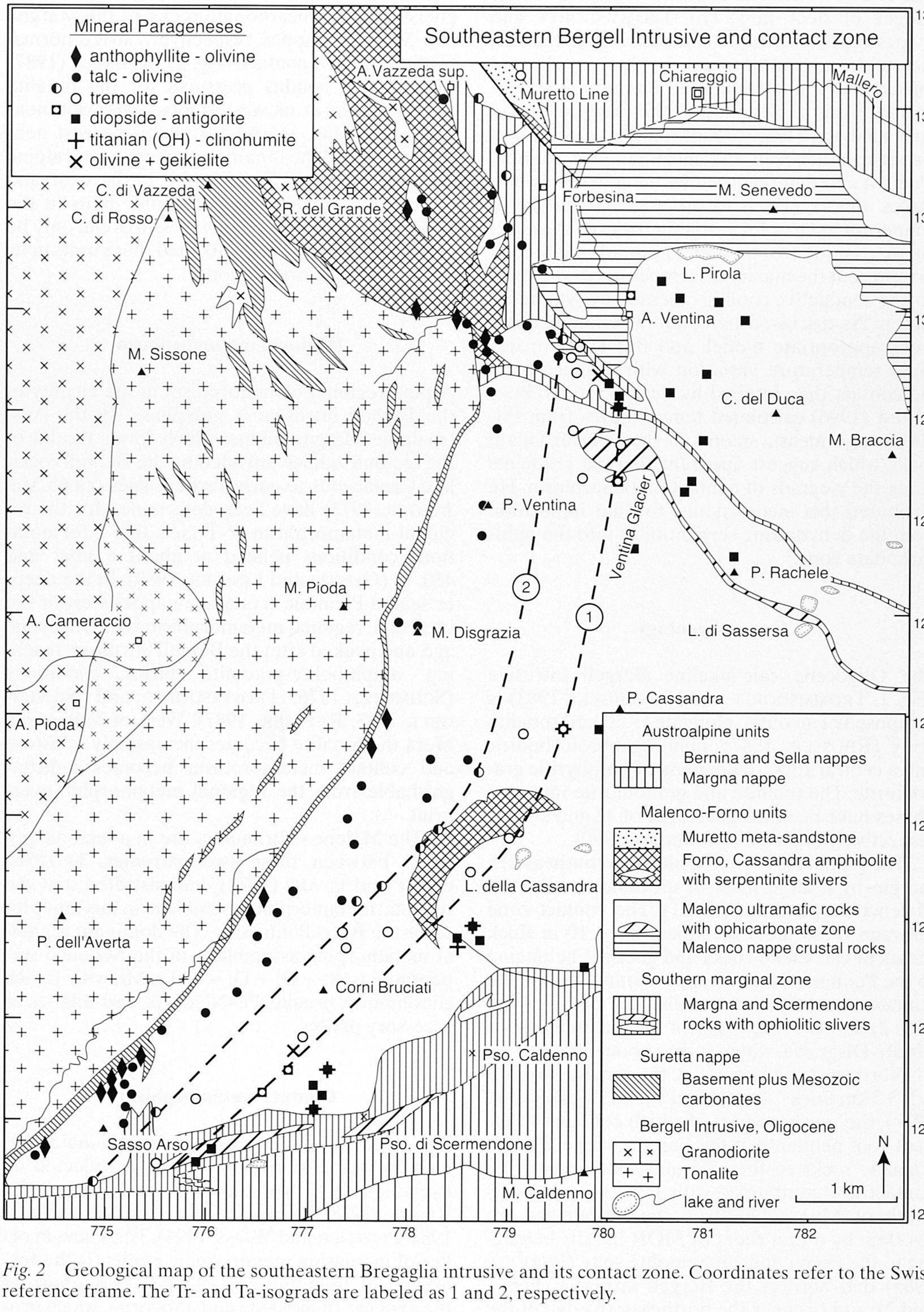

Fig. 2 Geological map of the southeastern Bregaglia intrusive and its contact zone. Coordinates refer to the Swiss reference frame. The Tr- and Ta-isograds are labeled as 1 and 2, respectively.

duces a At + Ol + Tr + Chl + Mt rock (isograd 1, Fig. 2); (ii) the breakdown of Ti-clinohumite to olivine and geikielite, which is essentially coincident with the Tr-isograd; (iii) the formation of Ta + Ol (Ta-isograd), at the expense of At, which produces a Ta + Ol + Tr + Chl + Mt rock (isograd 2, Fig. 2); (iv) the formation of Ap + Ol (Ap-isograd), at the expense of Ta, which produces an Ap + Ol + Tr + Chl + Mt rock; and (v) the formation of En + Ol (En-isograd), at the expense of anthophyllite, which produces an En + Ol + Tr + Chl + Mt rock. Because anthophyllite and enstatite occur only sporadically in the immediate vicinity of the intrusion, the latter two isograds cannot be drawn accurately and have been omitted from figure 2. The Tr- and Ta-isograds are continuous and 700 m apart in the north and 500 m apart in the south. The aureole is wider in the vicinity of Monte Disgrazia where the intrusive dips toward the ultramafic mass. As the contact is approached from the country rock, Ta + Ol is observed in straight veins before it occurs pervasively in the rock matrix. This mode of occurrence is interpreted to have resulted from dehydration induced by a reduction in fluid pressure consequent to fracturing and is not taken to indicate the thermal isograd. Outcrop scale (dm-m) open folds trending NE–SW have deformed contact metamorphic assemblages, but predate (REBER, 1995) the intrusion of the granodiorite (30 Ma, VON BLANKENBURG, 1990) indicating that the contact metamorphic assemblages formed in response to the tonalite intrusion (32 Ma, VON BLANKENBURG, 1990) alone.

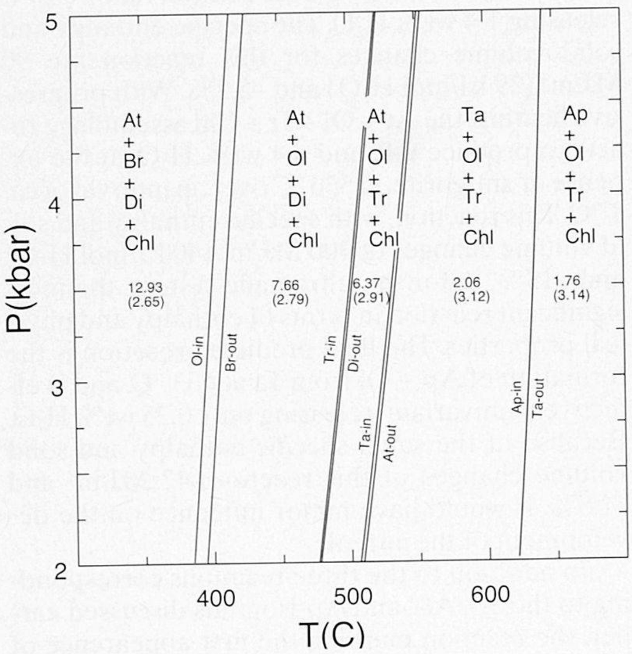

Fig. 3 Predicted phase relations for the Malenco serpentinite (lherzolite) bulk composition as a function of pressure and temperature as discussed in the text and table 2. In each field the approximate water content (wt%) and, in parentheses, density (g/cm^3) are given. Because of solution behaviour none of the phase fields are bounded by univariant reactions, rather each 4-phase field is bound by a narrow 5-phase field in which the modal mineralogy varies rapidly. These 5-phase fields correspond to the isograds observed in the Malenco serpentinite.

Isograds have also been mapped in greater detail within the Malenco ophicarbonate zone (TROMMSDORFF and EVANS, 1977; TROMMSDORFF and CONNOLLY, 1990; FERRY, 1995), i.e., the southernmost discordant layer shown in figure 2. In these rocks four additional isograds can be recognized. With increasing grade, these correspond to the reactions (TROMMSDORFF and EVANS, 1977): (vi) Di + Cc = Tr + Ol + At + Fluid; (vii) At + Cc = Do + Ol + Tr + Fluid; (viii) At + M = Ta + Ol + Fluid; and (ix) At + Do = Tr + Ta + Ol + Fluid. TROMMSDORFF and CONNOLLY (1990) demonstrated that the conditions of (vi)–(ix) are known with a high degree of confidence. This is corroborated by calcite-dolomite thermometry (TROMMSDORFF and EVANS, 1977). The thermobarometric determinations in the ophicarbonate rocks are taken to be indicators of the maximum temperatures achieved during contact metamorphism. The uncertainties in these indicators cannot be assessed with statistical rigor, but are unlikely to be > ± 20 °C.

Pressure in the Bergell aureole, at its present level of exposure, has been estimated to be 3.5 kbar (TROMMSDORFF and CONNOLLY, 1990), with an upper limit of ca 4 kbar imposed by the sequence of prograde isograds in the ophicarbonate rocks (CONNOLLY and TROMMSDORFF, 1991). This compares well with depth estimates of 8–12 km from tectonic reconstructions (CORNELIUS, 1928). An uncertainty in pressure of ± 0.5 kbar corresponds to an uncertainty of ± 7 °C in the predicted conditions for the serpentinite isograds (Fig. 3).

Petrological model: serpentinite

Metamorphic reactions can influence the thermal development of a contact aureole in three ways: enthalpic effects associated with devolatilization, modification of the rock thermal conductivity, and introduction of a fluid phase that may advect heat. To schematize these reactions, the system $CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O$ has been adopted as a petrological model. In this system the serpentinite dehydration reactions are trivariant, and the temperature interval over which they occur is dependent on bulk composition.

Calculations reported here are based upon the bulk chemical composition (lherzolite) of a Malenco Br-At-Ol-Chl-Mt serpentinite from Chiesa (sample Mg 65, TROMMSDORFF and EVANS, 1972). To express the lherzolite composition in the $CaO–FeO–MgO–Al_2O_3–SiO_2–H_2O$ system, the total ferrous oxide content was estimated from the average weight fraction of ferrous oxide relative to total iron oxides (76%) measured by TROMMSDORFF and EVANS for Malenco ultramafic rocks. It was then assumed that all ferric iron is contained in magnetite, and the ferrous oxide content was corrected accordingly. Based on this procedure the molar proportions CaO : FeO : MgO : Al_2O_3 : SiO_2 are 0.0319 : 0.0783 : 1.475 : 0.0212 : 1 for the model serpentinite. The water-content, density, and mineralogy of this bulk composition were computed by thermodynamic methods as a function of pressure and temperature by assuming unit water-activity and isochemical metamorphism with respect to the non-volatile components. Phases considered in these calculations, in addition to the water fluid, were anthophyllite (Ap), antigorite (At), brucite (Br), chlorite (Chl), enstatite (En), olivine (Ol), talc (Ta), and tremolite (Tr). All these phases were treated as ideal iron-magnesium solutions, with site occupancies as given by HOLLAND and POWELL (1990). The calculations were done using the PERPLEX computer program (CONNOLLY, 1990) with thermodynamic data taken from HOLLAND and POWELL (1990, 1991). Since HOLLAND and POWELL (1990) do not provide data for At, or the iron end-member of Br, the properties of these end-members were estimated as described by TROMMSDORFF and CONNOLLY (1990) and CONNOLLY (1995). Furthermore, the ferro-anthophyllite end-member properties given by HOLLAND and POWELL (1989) do not yield Fe–Mg inter-phase partitioning consistent with that observed by TROMMSDORFF and EVANS (1972). To correct for this deficiency the standard state Gibbs energy of the fictive ferro-anthophyllite end-member was reduced to a value (–8994.418 kJ/mole) such that

$$X_{Mg}^{Ol} \approx X_{Mg}^{Ap}$$

at conditions where Ol + Ta + Ap + Chl are in equilibrium. The inconsistency is probably due to non-ideal solution behaviour, but the approach taken here is reasonable for the very limited extent of Fe-solution in the silicate mineralogy. This simplistic approach cannot be justified more generally, as there is substantial evidence for azeotropic behavior in anthophyllite (EVANS and GHIORSO, 1995).

Results of the phase equilibrium calculations are summarized in figure 3 and table 1. The excellent agreement between observed and predicted mineral compositions and rock densities suggests that the calculations are reliable. These calculations show that the serpentinite mineralogy undergoes dehydration over a series of narrow (< 10 °C) divariant (5-phase) intervals corresponding to isograds recognized in the field. These divariant regions have nearly identical pressure dependence.

At the pressure determined for the aureole, 3.5 kbar, and the lowest temperatures represented in figure 3, the serpentinite is composed of At + Br + Di + Chl and contains 12.9 wt% H_2O. From 399–410 °C, this assemblage reacts, consuming brucite and forming olivine, releasing 5.6 wt% water[1]. The specific enthalpy and solid volume changes for this reaction are 356 MJ/m^3 (36 kJ/mol H_2O) and –14%. Pre-intrusive regional metamorphism drove this reaction to completion, and there is little evidence of retrogressive metamorphism, presumably due to the absence of a fluid phase (TROMMSDORFF and EVANS, 1974). This At + Di + Ol + Chl rock (Tab. 2) is the model protolith prior to contact metamorphism. Diopside in the protolith is predicted to decompose to form olivine and tremolite at 500 °C over an interval of < 2 °C releasing 1.4 wt% H_2O. The specific enthalpy and solid volume changes for this reaction are 90 MJ/m^3 (39 kJ/mol H_2O) and –5.2%. With progressive heating, the At + Ol + Tr + Chl assemblage reacts to produce talc and 4.4 wt% H_2O, at the expense of antigorite, at 530 °C over an interval of ca. 3 °C. This reaction, with specific enthalpy and solid volume changes of 300 MJ/m^3 (40 kJ/mol H_2O) and –18%, is, for the ultramafic system, the most significant reaction in terms of enthalpy and physical properties. The final predicted reaction is the formation of Ap + Ol from Ta at 633 °C, and is effectively univariant, releasing only 0.25 wt% H_2O. Because of the small specific enthalpy and solid volume changes of this reaction, 42 MJ/m^3 and –1.8%, it would have minor influence on the development of the aureole.

In addition to the three reactions corresponding to the Tr-, At-, and Ap-isograds discussed earlier, the reaction marking the first appearence of enstatite (Fig. 2 of TROMMSDORFF and EVANS, 1972) is predicted to occur at 731 °C. This is considerably above temperatures likely to have been attained during contact metamorphism. The probable cause of this discrepancy is that reduced wa-

[1] To compute weight loss and volume changes from the data in table 1 or figure 3 it is necessary to renormalize the analyses and densities to a common basis for the nonvolatile components.

Tab. 1 Mineral notation, symbols, and characteristic values (see text for sources). In mineral notations, where given, the subscript X indicates the % mole fraction Mg/(Mg + Fe).

Symbol	Mineral		
Ap_X	anthophyllite		
At_X	antigorite		
Br_X	brucite		
Chl_X	chlorite		
Cc	calcite		
Di_X	diopside		
Do	dolomite		
En_X	enstatite		
M	magnesite		
Mt	magnetite		
Ol_X	olivine		
Ta_X	talc		
Tr_X	tremolite		
Symbol	**Meaning**	**Units**	**Characteristic Value**
C_{melt}	specific heat, tonalite	J/m³/K	2×10^6
$C_{ultramafics}$	specific heat, Ta-bearing rocks	J/m³/K	2.5×10^6
k_{melt}	thermal conductivity, tonalite	W/m/K	2.0
k_{Ta}	thermal conductivity, Ta-bearing ultramafics	W/m/K	2.26
k_{At}	thermal conductivity, At-bearing ultramafics	W/m/K	1.75
H_{M}	specific enthalpy of crystallization, tonalite	J/m³	220×10^6
H_{Ap}	dehydration enthalpy, Ap-isograd	J/mol H_2O	95×10^3
H_{Ol}	dehydration enthalpy, Ol-isograd	J/mol H_2O	36×10^3
H_{Tr}	dehydration enthalpy, Tr-isograd	J/mol H_2O	39×10^3
H_{Ta}	dehydration enthalpy, Ta-isograd	J/mol H_2O	40×10^3
P	pressure	bar, kbar	
t	time	s, Ma	
T	temperature	°C	
T_0	pre-intrusive ambient T	°C	330–370
X_{Mg}	mole fraction Mg/(Mg + Fe)		
x	horizontal distance coordinate	m	
ρ	density	g/c m³	

ter activity near the contact destabilized hydroxylated minerals. Reduced water activity is likely to have resulted from decarbonation in the contact zone (Fig. 2).

In light of the uncertainty in the pressure of the aureole, for purposes of thermal modeling, the Tr-, At-, and Ap-isograd reactions are assumed to occur over 10 °C intervals centered on the predicted equilibrium dehydration temperatures.

Petrological model: tonalite

It is commonly argued that granitic magmas become immobile when the liquid fraction of the magma falls below ca. 35 vol.% (e.g., WICKHAM, 1987). Assuming a thermodynamic activity of unity for water in the melt phase, this state occurs within 15 °C of the water saturated solidus, which lies at 685 °C at 3.5 kb (PIWINSKII, 1968), implying an emplacement temperature of 700 °C. The latent heat of crystallization of the melt phase between the emplacement temperature and the solidus was estimated to be 220 MJ/m³ assuming the final liquid phase to be feldspathic (BURNHAM and NEVASKIL, 1986) and the densities of this liquid and the tonalite to be 2.5 and 2.8 g/cm³, respectively. In comparison to this heat effect, it is reasonable to neglect the heat of exsolution of water from the melt phase (CLEMENS and NAVROTSKY, 1987).

Thermal properties

The thermal conductivity and specific heat (in the absence of reactions) of all rocks (Tab. 1) were taken from WENK and WENK (1969)[2] with the exception of the thermal conductivity of the Bergell tonalite. The data of WENK and WENK are inade-

[2] Thermal conductivities reported in WENK and WENK (1969) were incorrectly converted to cgs units. Correct values can be obtained by multiplying their values by 4.184^{-2}.

Tab. 2 Mineral modes (vol.%)/compositions (X_{Mg} %), water content (wt%), and bulk densities (ρ, kg/m³) calculated at 3.5 kbar as a function of temperature (Fig. 3) for the Malenco ultramafic bulk composition (lherzolite) as discussed in the text. Calculations done with PERPLEX (CONNOLLY, 1990) and thermodynamic data from HOLLAND and POWELL (1990). Calculated tschermaks substitution in Ta and Chl is insignificant at conditions considered here. Observed properties (TROMMSDORFF and EVANS, 1972; PERETTI, 1988; WENK and WENK, 1969) for Malenco serpentinites with parageneses idendical to those calculated are given in parentheses.

T°C	Ap	At	Br	Chl	Di	Ol	Ta	Tr	H_2O	ρ
350 M120		80.1/96 (–/94)	8.1/91 (–/92)	8.0/96 (–/94)	3.8/95 (–)				12.93	2.65
450 Mg 104		58.6/98) (–/97)		9.1/98 (–)	4.3./97 (–/98)	28.0/90 (–/93)			7.66	2.85 (2.79)
510 Mg 102a		45.8/98 (–/96)		9.4/98 (–)		35.6/92 (–/94)		9.2/97 (–/97)	6.37 (6.3)	2.91
580 Mg 105b				10.6/98 (–)		63.1/94 (–/92)	16.1/99 (–/98)	10.3/98 (–/96)	2.06	3.12
675	17.61/94			10.7/98		61.4/95		10.4/98	1.76	3.14

quate to permit resolution of thermal conductivity among all the serpentinite mineralogies, but suggest a significant difference exists in the conductivity of talc and antigorite bearing rocks. Accordingly, the conductivity of the antigorite-bearing rocks is taken as 1.75 W/m-K, and 2.26 W/m-K to be that of all the higher grade ultramafics. The thermal conductivity of the tonalite given by WENK and WENK (1969) appears anomalously low (1.3 W/m-K), perhaps due to a weathered sample, a value of 2 W/m-K has been adopted here consistent with values obtained for other tonalitic rocks (e.g., CLARK, 1966; TURCOTTE and SCHUBERT, 1981). It is well known that both the specific heat and thermal conductivity of rocks may depend on temperature (SCHATZ and SIMMONS, 1972) and, to a much lesser extent, on pressure (e.g., FURLONG and CHAPMAN, 1987). These effects are poorly constrained and the dependencies are thought to be similar for most lithologies (CHAPMAN and FURLONG, 1992). In view of this there is little to be gained by attempting to treat them with greater rigor.

Thermal modeling and Discussion

A difficulty in modeling the thermal evolution of the Bergell aureole is the composite nature of the intrusion. In particular, petrologic and structural evidence (REBER, 1995; BERGER and GIERÉ, 1995) that the second phase of the intrusion, i.e., the granodiorite, did not influence the aureole in the ultramafic rocks, indicates that the present geometry of the intrusive as a whole should not be taken as a basis for modeling, and that thermal modeling should be based on the presumed nature of the original tonalite intrusion. From the present exposure of the tonalite, its vertical contact with the serpentinite, and evidence that at least the southern portion of the tonalite has been thinned parallel to the contact, a plausible geometric model is that of a vertical tabular body with a minimum thickness of 3.5 km (near the locality of ophicarbonate rocks, Fig. 2). Because the metamorphic isograds are essentially parallel to the tonalite contact over much of the present exposure, it appears reasonable to model the intrusive as having infinite lateral extent. The vertical dimension of the tonalite is unconstrained; thus it is impossible to model this aspect of the intrusion. Pure conduction models of cooling intrusives show that the effect of the vertical dimension on the lateral development of isotherms is surprisingly small in many cases (FURLONG et al., 1991). Consequently, as a first approximation, the tonalite intrusive is modeled as an infinite 3.5 km wide vertical sheet emplaced instantaneously in the serpentinite at an ambient temperature T_0. The thermal evolution for this geometry is described by the 1-dimensional equation for heat conduction:

$$\frac{dT}{dt} = \frac{K}{C}\frac{d^2T}{dx^2} + \frac{1}{C}\frac{dK}{dx}\frac{dT}{dx} \tag{1}$$

where x is the distance orthogonal to the plane of the intrusive, and C is the volumetric heat capacity of the rock. To account for the enthalpic effects associated with a reaction occurring over a temperature interval δT, the heat capacity in Eq. 1 is replaced (PRICE and SLACK, 1954) in the appropriate place by

$$C' = C + \frac{\Delta H_{rxn}}{\delta T}.$$

Eq. 1 was solved by the Crank-Nicolson finite difference method applying no-flow (mirror symmetry) boundary conditions at the center of the sheet and at a distance of 25 km from the intrusive (for all reported calculations the temperature perturbation at this boundary was < 0.2 °C). The accuracy of the numeric method was tested by comparison with analytic solutions to similar, but simpler problems provided by CARSLAW and JAEGER, (1959). As noted earlier there are substantial volume changes associated with antigorite dehydration. To accommodate these, a dilational strain of ca 25% would be necessary and this is not accounted for in the solution of Eq. 1. If this strain were homogeneous it would lead to an advective heating effect that would steepen the thermal gradients in the vicinity of the contact. In view of other uncertainties, this effect is unlikely to be important.

The only parameter that has not been discussed previously is the temperature prior to contact metamorphism, T_0, which was taken as a vari-

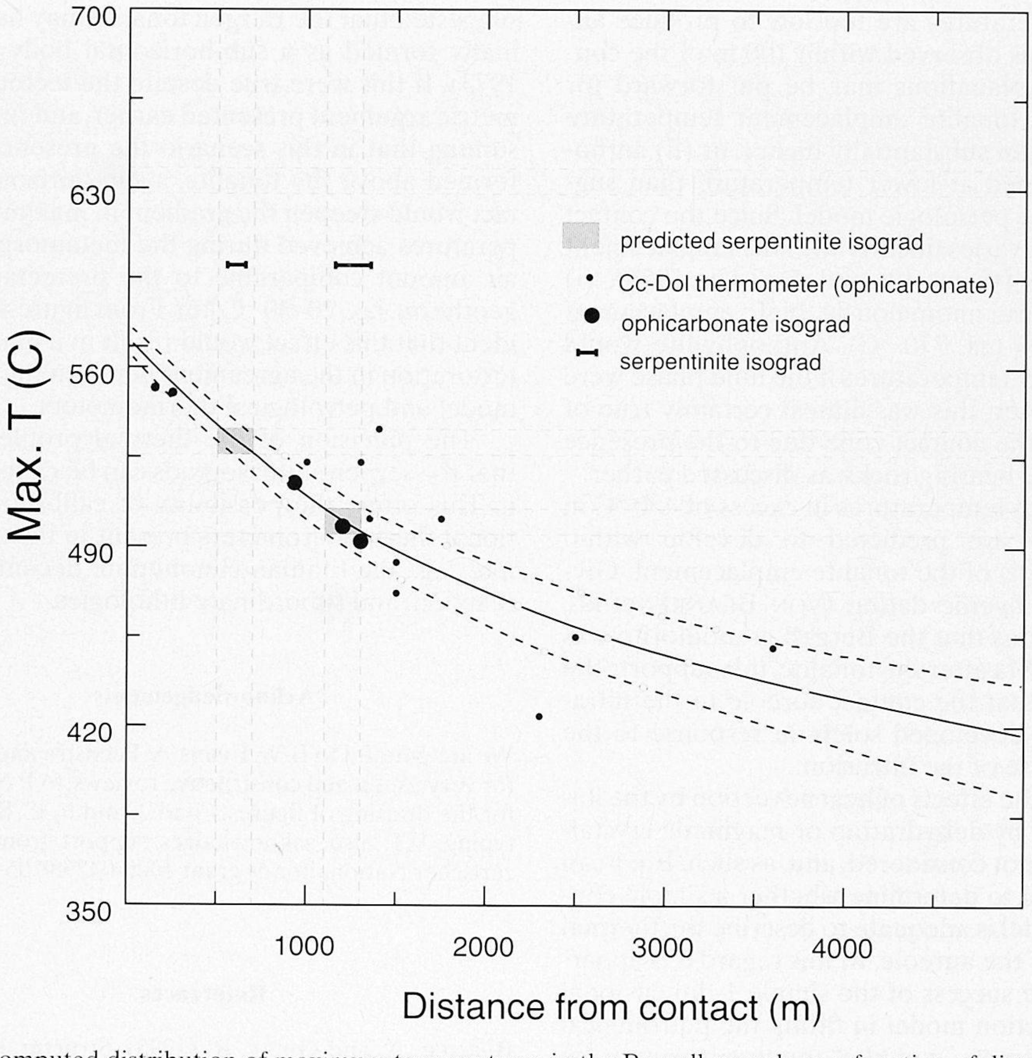

Fig. 4 Computed distribution of maximum temperatures in the Bergell aureole as a function of distance from the tonalite contact. Solid curve is the profile obtained for an initial country rock temperature (T_0) of 350 °C, dashed curves indicate profiles for T_0 = 330–370 °C. Horizontal dashed lines indicate the T intervals predicted from the serpentinite model for the Tr-, Ta-, and Ap-isograds. Vertical dashed lines locate the distance intervals over which the Ta- and Tr-isograds are predicted to occur from the combined thermal and petrological modeling, these compare well with the observed isograd locations, indicated by horizontal bars, in the NE and SE portions of the contact zone. The predicted thermal profile also compares well with thermometric determinations in the ophicarbonate rocks, in particular the isograd reactions (as indicated by large filled circles, TROMMSDORFF and EVANS, 1977; TROMMSDORFF and CONNOLLY, 1990). Small filled circles indicate temperatures determined by Cc-Do thermometry (TROMMSDORFF and EVANS, 1977), these are subject to greater uncertainty due to retrograde equilibration. Small open circles along thermal profiles indicate the interval within the aureole over which the rocks have begun cooling at 0.1 Ma time intervals commencing with emplacement. For example, by 0.6 Ma after emplacement rocks within 3750 m of the contact have achieved maximum contact metamorphic temperatures and begun cooling for the T_0 = 350 °C model.

able to optimize the agreement of the temperatures inferred from metamorphic phase equilibria with the maximum temperatures computed from Eq. 1. The only constraint on T_0 is that it must have been below the peak metamorphic temperature of the regional metamorphism, ca 440 °C (MELLINI et al., 1987), which was waning at the time of the tonalite emplacement (JAEGER, 1973).

Figure 4 shows that excellent agreement can be obtained between the maximum temperatures computed from Eq. 1 and those inferred for the metamorphic isograds, taking T_0 = 350 °C. The only notable inconsistency is the fact that the model temperatures are too low to produce anthophyllite, as observed within 100 m of the contact. Two explanations may be put forward for this: (i) the tonalite emplacement temperature may have been substantially higher, or (ii) anthophyllite formed at lower temperature than suggested by the petrologic model. Since the contact temperature varies linearly with the emplacement temperature (CARSLAW and JAEGER, 1959), (i) would require anomalously high emplacement temperatures (ca. 770 °C). Anthophyllite would form at lower temperatures if the fluid phase were not pure water; this was almost certainly true of the fluid in the contact zone due to the presence of carbonate-bearing rocks, as discussed earlier.

Maximum temperatures in excess of 450 °C in the aureole are predicted to develop within 0.5 Ma (Fig. 4) of the tonalite emplacement. Given that radiogenic dating (VON BLANKENBURG, 1990) indicates that the Bergell granodiorite was emplaced 2 Ma after the tonalite, this supports the contention that the contact aureole in the ultramafic rocks developed solely in response to the tonalite phase of the intrusion.

In Eq. 1 the effects of heat advection by the fluids released by dehydration or magmatic crystallization are not considered, and, as such, Eq. 1 can only be used to determine whether a simple conduction model is adequate to describe the thermal evolution of the aureole. In this regard it is apparent from the success of the simple 1-dimensional heat-conduction model in fitting the petrological data, that a more complex treatment cannot be justified. In general, heat advection will result in a broadening of the thermal anomaly associated with the intrusion, and a lowering of temperatures in the vicinity of the contact. Both these effects would reduce the quality of the fit obtained here with a pure conduction model; thus it may be concluded that heat advection did not play a significant role in the development of the aureole. It has been argued that fluid advection of heat will be unimportant unless free convection occurs, or fluid flow is highly focused (e.g., CONNOLLY and THOMPSON, 1989; CONNOLLY, 1996). That neither of these effects is important in many contact metamorphic aureoles is suggested by the success of simple heat conduction models (e.g., FURLONG et al., 1991).

Thermal profiles computed for T_0 = 330 and 370 °C (Fig. 4) are sensibly poorer fits to the metamorphic isograds, than those obtained for T_0 = 350 °C. This suggests 350 °C can be taken as the pre-intrusive ambient temperature with an accuracy comparable to this temperature range, implying a geothermal gradient of 28 ± 2 °C/km at the time of the tonalite emplacement. It has been suggested that the Bergell tonalite may have originally formed as a sub-horizontal body (WENK, 1973). If this were true despite the tectono-barometric argument presented earlier, and further assuming that in this scenario the present aureole formed above the tonalite, a sub-horizontal contact would steepen the gradient in maximum temperatures achieved during the metamorphism by an amount comparable to the premetamorphic geotherm, i.e., 20–30 °C/km. From figure 4, it is evident that this effect would result in a marked deterioration in the agreement between the thermal model and petrological thermometers.

The precision of the thermal profile is such that the serpentinite isograds can be calibrated by it. This offers the possibility of calibrating additional thermobarometers present in the serpentinite, e.g., the titanian-clinohumite decomposition reaction, and subordinate lithologies.

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References

BERGER, A. and GIERÉ, R. (1995): Structural observations at the eastern contact of the Bergell pluton. Schweiz. Mineral. Petrogr. Mitt., 75, 241–258.

BUCHER-NURMINEN, K. (1977): Die Beziehungen zwischen Deformation, Metamorphose und Magmatimus im Gebiet der Bergeller Alpen. Schweiz. Mineral. Petrogr. Mitt., 57, 413–434.

BURNHAM, C.W. and NEVASKIL, H. (1986): Granite pegmatite magmas. Am. Mineral. 71, 239–264.

CARSLAW, H.S. and JAEGER, J.C. (1969): Conduction of heat in solids. Oxford University Press, 510 pp.

CHAPMAN, D.S. and FURLONG, K.P. (1992): Thermal state of the lower continental crust. In: FOUNTAIN, D.M., ARCULUS, A. and KAY, R.W. (eds.): Continental Lower Crust, Elsevier, 408 pp.

CLARK, S.P. (1966): Handbook of physical constants. Geol. Soc. Mem. 97, 587 pp.
CLEMENS, J.C. and NAVROTSKY, A. (1987): Mixing properties of $NaAlSiO_8$ melt-H_2O: new calorimetric data and some geologic implications. J. Geol. 95, 173–186.
CONNOLLY, J.A.D. (1990): Calculation of multivariable phase diagrams: an algorithm based on generalized thermodynamics. Am. J. Sci. 290, 666–718.
CONNOLLY, J.A.D. (1995): Phase diagram methods for graphitic rocks. In: "Quantitative Phase Diagram Applications in Earth Material Sciences", Proceedings of the VII Siena Summer School, University of Siena, 35–66.
CONNOLLY, J.A.D. (1996): Mid-crustal focused fluid movement: thermal consequences and silica transport. In: JAMTVEIT, B. and YARDLEY, B. (eds): Fluid flow and transport in rocks, 233–249. Chapman Hall, 430 pp.
CONNOLLY, J.A.D. and THOMPSON, A.B. (1989): Fluid and enthalpy production during regional metamorphism. Contrib. Mineral. Petrol. 102, 346–366.
CONNOLLY, J.A.D. and TROMMSDORFF, V. (1991): Petrogenetic grids for metacarbonate rocks: pressure-temperature phase-diagram projection for mixed-volatile systems. Contrib. Mineral. Petrol. 108, 93–105.
CORNELIUS, H.P. (1928): Zur Altersbestimmung der Adamello- und Bergeller Intrusion. Sitzungsberichte der Akademie der Wissenschaften in Wien, Mathem.-naturw. Klasse, Abt. I, 137/8, 541–562.
EVANS, B.W. and GHIORSO, M.S. (1995): Thermodynamics and petrology of cummingtonite. Am. Mineral. 80, 949–963.
FERRY, J.M. (1995): Fluid flow during contact metamorphism of ophicarbonate rocks in the Bergell aureole, Val Malenco, Italian Alps. J. Petrol. 36, 1039–1053.
FURLONG, K.P. and CHAPMAN, D.S. (1987): Crustal heterogeneities and the thermal structure of the continental crust. Geophys. Res. Lett. 14, 314–317.
FURLONG, K.P., HANSON, R.B. and BOWERS, J.R. (1991): Modeling thermal regimes. Rev. Mineral. 26, 437–505.
GIERÉ, R. (1985): Metasedimente der Suretta-Decke am Ost- und Südostrand der Bergeller Intrusion: Lithostratigraphische Korrelation and Metamorphose. Schweiz. Mineral. Petrogr. Mitt. 65, 57–78.
GUNTLI, P. and LINIGER, M. (1989): Metamorphose in der Margnadecke im Bereich Piz de la Margna und Piz Fedoz (Oberengadin). Schweiz. Mineral. Petrogr. Mitt. 69, 289–301.
HOLLAND, T.J.B. and POWELL, R. (1990): An enlarged and updated internally consistent dataset with uncertainties and correlations. J. Met. Geol. 8, 89–124.
HOLLAND, T.J.B. and POWELL, R. (1991): A compensated-redlich-kwong (CORK) equation for volumes and fugacities of CO_2 and H_2O in the range 1 bar to 50 kbar and 100–1600 °C. Contrib. Mineral. Petrol. 109, 265–273.
JAEGER, E. (1973): Die alpine Orogenese im Lichte der radiometrischen Altersbestimmung. Eclogae geol. Helv. 66/1, 11–21.
MELLINI, M., TROMMSDORFF, V. and COMPAGNONI, R. (1987): Antigorite polysomatism: behaviour during progressive metamorphism. Contr. Mineral. Petrol. 97, 147–155.
PERETTI, A. (1985): Der Monte-del-Forno-Komplex am Bergell-Ostrand: Seine Lithostratigraphie, alpine Tektonik and Metamorphose. Eclogae geol. Helv. 78, 23–48.
PFIFFNER, M. and WEISS, M. (1994): Strukturelle und petrographische Untersuchungen im Grenzbereich Penninikum-Unterostalpin am Südostrand des Bergell-Plutons (Val Masino, Italien). Schweiz. Mineral. Petrogr. Mitt., 74, 245–264.
PIWINSKII, A.J. (1968): Experimental studies of igneous rock series: central Sierra batholith, California. J. Geol. 76, 548–570.
POZZORINI, D. (1996): Stable isotope investigations of ophicarbonate rocks Bergell aureole, Malenco: Constraints on fluid-rock interaction. Ph. D. Thesis ETH Zürich, 198 pp.
PRICE, R.H. and SLACK, M.R. (1954): The effect of latent heat on numerical solutions of the heat flow equation. British J. Appl. Phys. 5, 285–287.
REBER, D. (1995): Strukturelle and petrographische Untersuchungen im oberen Val Malenco (Prov. Sondrio, N-Italia). Diplomarbeit Univ. Zürich, 109 pp. (unpubl.).
REUSSER, C.E. (1987): Phasenbeziehungen im Tonalit der Bergeller Intrusion (Graubünden, Schweiz/ Provinz Sondrio, Italien). Ph. D. Thesis ETH Zürich, 220 pp.
RIKLIN, K. (1978): Strukturen und Metamorphose im Bereich der südlichen Murettolinie. Schweiz. Mineral. Petrogr. Mitt., 58, 345–356.
SCHATZ, J.F. and SIMMONS, G. (1972): Thermal conductivity of earth materials at high temperatures. J. Geophys. Res. 77, 6966–6983.
SCHMUTZ, H.V. (1976): Der Mafitit-Ultramafitit-Komplex zwischen Chiavenna und Val Bondasca. Beitr. Geol. Karte Schweiz Neue Folge 149, 73 pp.
TROMMSDORFF, V. and CONNOLLY, J.A.D. (1990): Constraints on phase diagram topology for the system $CaO–MgO–SiO_2–CO_2–H_2O$. Contr. Mineral. Petrogr. 104/1, 1–7.
TROMMSDORFF, V. and EVANS, B.W. (1972): Progressive metamorphism of antigorite schist in the Bergell tonalite aureole (Italy). Am. J. Sci. 272, 423–437.
TROMMSDORFF, V. and EVANS, B.W. (1974): Alpine metamorphism of peridotitic rocks. Schweiz. Mineral. Petrogr. Mitt. 54, 333–352.
TROMMSDORFF, V. and EVANS, B.W. (1977): Antigorite-ophicarbonates: contact metamorphism in Val Malenco, Italy. Contrib. Mineral. Petrol. 62, 310–312.
TROMMSDORFF, V. and NIEVERGELT, P. (1983): The Bregaglia (Bergell) Iorio intrusive and its field relations. Mem. Soc. Geol. It. 26, 55–68.
TURCOTTE, D.L. and SCHUBERT, G. (1992): Geodynamics. Wyllie, 447 pp.
VON BLANKENBURG, F. (1990): Isotope geochemical and geochronological case studies of Alpine magmatism and metamorphism: the Bergell intrusion and Tauern window. Ph. D. Thesis ETH Zürich, 186 pp.
WENK, H.R. (1973): The structure of the Bergell Alps. Eclogae geol. Helv. 66, 255–291.
WENK, H.R. and WENK, E. (1969): Physical constants of alpine rocks. Schweiz. Mineral. Petrogr. Mitt. 49, 343–358.
WICKHAM, S.M. (1987): The segregation and emplacement of granitic magmas. J. Geol. Soc. Lond. 144, 281–297.

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