JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 102, NO. B9, PAGES 20,123–20,132, SEPTEMBER 10, 1997

Fossil crust-to-mantle transition, Val Malenco (Italian Alps)

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Abstract. An exhumed, undisturbed fossil lower crust to upper mantle section is preserved in Val Malenco, Italian Alps, and is now exposed along the boundary between Penninic and Austroalpine nappes. Lower-crustal metapelitic rocks are welded to upper-mantle ultramafic rocks by a mid-Permian gabbro intrusion. The underplating of gabbro caused granulite metamorphism and partial melting of the metapelites. In the crust-to-mantle transition zone of at least 1 km thickness, gabbros, large xenoliths of restitic metapelites and ultramafic rocks occur, with densities of 2.95-3.14, 3.25 and 3.27 g/cm^3, respectively. The seismic Moho therefore did not coincide with the boundary between peridotites and crustal rocks but was situated above the upper limit of the peridotitic mantle. The whole complex underwent cooling with only moderate decompression within the kyanite field. This process started at 1 GPa and ~800°C and ended at 0.85 GPa and 600°C and is interpreted as thermal relaxation after the gabbro intrusion. Later, during Jurassic rifting, the crust-to-mantle section was exhumed at the Adria margin of the Tethys ocean.

Introduction

Petrologic analysis of exposed fossil crust-to-mantle transition zones is important for the interpretation of seismic data. However, many of the relatively few exposures interpreted as fossil continental crust-to-mantle transitions have been reinterpreted after rigorous investigations. For example, the Ivrea zone in the western Italian Alps has been cited repeatedly as a model of an exposed pre-Alpine crust-to-mantle transition [*Mehnert*, 1975; *Fountain*, 1976; *Voshage et al.*, 1990]. Recently, however, it has been proposed that the Ivrea lower crustal section represents a fossil accretionary wedge in which the ultramafic rocks were not located at the crust-to-mantle transition [*Quick et al.*, 1995]. PT histories have been shown to be one crucial parameter in determining if granulite terrains represent sections of lower crust [*Rudnick and Fountain*, 1995]. For example, the Valpelline series in the Western Alps [*Gardien et al.*, 1994] or the Sesia zone sensu strictu [*Lardeaux and Spalla*, 1991] have been interpreted as lower crust. The granulites in both these units show near isothermal decompression paths through the sillimanite stability field. Therefore they probably formed during extension of thickened Variscan continental crust, and these sections may not represent stable lower continental crust.

In this paper we describe an exhumed crust-to-mantle transition that has maintained its structural features since at least the latest Paleozoic, with the primary lithological contacts preserved. In contrast to other potential crust-to-mantle sections exhumed in the Alps, the Malenco granulites evolved along a PT path starting at greater depth and following a near isobaric cooling path (IBC granulites [*Harley*, 1989]) across the kyanite field. We will consider the questions of why these rocks have been exhumed and are now integrated in the chain of the Alps.

Paper number 97JB01510
0148-0227/97/97JB-01510$09.00

Geological Setting

The Penninic-Austroalpine boundary in Val Malenco is characterized by three tectonic units (Figure 1) which are from bottom to top (1) the Penninic nappes with their Mesozoic sedimentary cover and (2) the Penninic Malenco-Forno unit which is dominated by a huge body of serpentinized peridotites, the Malenco ultramafic rocks, with pieces of attached gabbros and granulites. Ophicarbonate rocks of assumed Jurassic age occur on top and within fracture zones of the Malenco ultramafic body. In their western part the Malenco ultramafic rocks are crosscut by mid-ocean ridge basaltic dikes belonging to the Forno "ophiolite" suite. The Forno unit itself consists of metamorphosed pillow basalts overlain by Jurassic to Cretaceous sediments [*Montrasio*, 1973; *Peretti*, 1985]. (3) The lower Austroalpine Margna nappe is composed of lower crustal and upper crustal rocks with their Mesozoic sedimentary cover. The Margna and the Malenco-Forno units represented the transition from the Adria continental margin to the Piemont ocean basin in Jurassic times. In this transition the Malenco ultramafic rocks constitute a denuded, ex-subcontinental mantle portion of the Adria lithosphere [*Trommsdorff et al.*, 1993]. The rocks of the Margna nappe formed the most distal part of the Adria continent [*Hermann and Müntener*, 1996]. Early Alpine convergence led to the formation of an Austroalpine nappe stack that was thrust over the Penninic units. Alpine metamorphism reached epidote-amphibolite facies conditions in the Val Malenco area. This

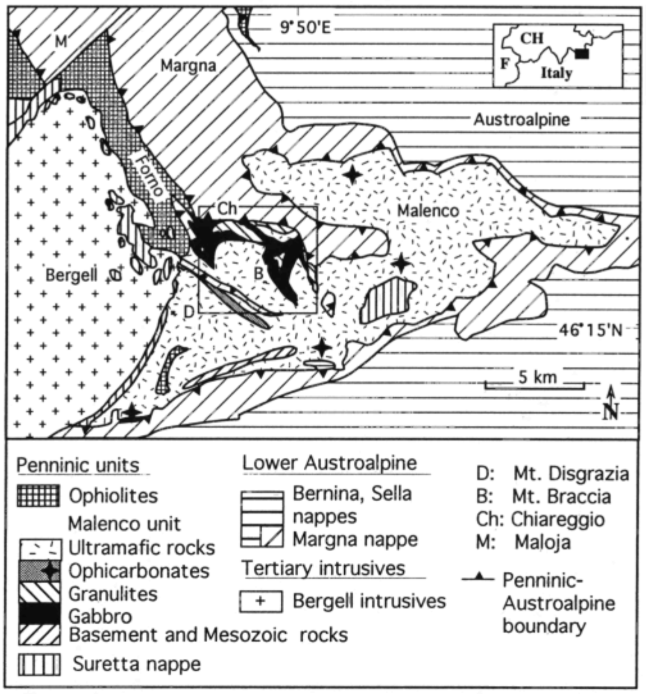

Figure 1. The Penninic-Austroalpine boundary region in Val Malenco (northern Italy). The frame outlines Figure 2 and contains the exposed lower crust-to-mantle transition.

metamorphism is of Cretaceous to Paleocene age (Frey et al., 1974). Peak metamorphism was followed by a polyphase deformational and metamorphic evolution [*Hermann and Müntener*, 1992]. This study is restricted to the Malenco unit in the Monte Braccia area (Figure 2) because (1) a crust-to-mantle section is preserved and (2) pre-Alpine high-grade metamorphic rocks with little or no Alpine metamorphic overprint predominate.

Malenco Rock Types

Rock types of the Malenco unit are (Table 1) (1) a predominant, basal, variably serpentinized spinel peridotite suite of great lithological heterogeneity. In the Monte Braccia area, fertile layered lherzolites, dunites and harzburgites occur. Several generations of pyroxenite dikes crosscut the lherzolite [*Müntener and Hermann*, 1996]. The Malenco peridotites are overlain by (2) granulites which are migmatitic, with granitoid partial melt segregations that crosscut the primary banding. The pelitic granulites are often garnet- and kyanite-rich restites (Figure 3). They are interlayered with minor calcsilicate rocks and marbles. The marbles are quartz-free and consist of calcite, clinopyroxene, olivine, phlogopite and rare spinel. In the calcsilicates wollastonite occurs occasionally. Malenco peridotites and the granulites are welded by (3) a gabbroic intrusion, with associated dikes that crosscut both rock types 1 and 2. The tholeiitic gabbro complex [*Gautschi*, 1980] evolved from magnesian gabbro (Mg-gabbro) to ferroan gabbro-norite (Fe-gabbro), quartz-diorite and highly differentiated pyroxene-amphibole gabbro. Pyroxenes often form cumulates indicating that they crystallized as first phases from the mafic melt. Olivine is minor and occurs interstitially in differentiated gabbros. Clinopyroxene has always a higher Mg/Mg+Fe ratio than olivine, and in the most primitive gabbro no olivine occurs. This indicates that clinopyroxene was the liquidus phase. The absence of olivine in the most primitive gabbros and the crystallization sequence pyroxenes–plagioclase–olivine in Fe-gabbros is consistent with crystallization at pressures of 1-1.2 GPa [*Green and Ringwood*, 1967; *Thompson*, 1972].

Determined and calculated densities of the granulites, gabbros and peridotites are given in Table 2, and representative whole rock compositions are shown in Table 3. The measured densities correspond to minimum values because both microcracks and small domains of retrograde hydration lead to a density decrease. The restitic metapelites have a high density of 3.25 g/cm^3 and low SiO_2 contents around 44 wt %. The densities for pelitic restites are comparable to those of the underlying mantle (3.27 g/cm^3). In restites containing more than 35 vol % garnet the density is higher than in mantle rocks and is calculated from normative mineral content (Table 2) to 3.52 g/cm^3. The densities of the pelitic restites are

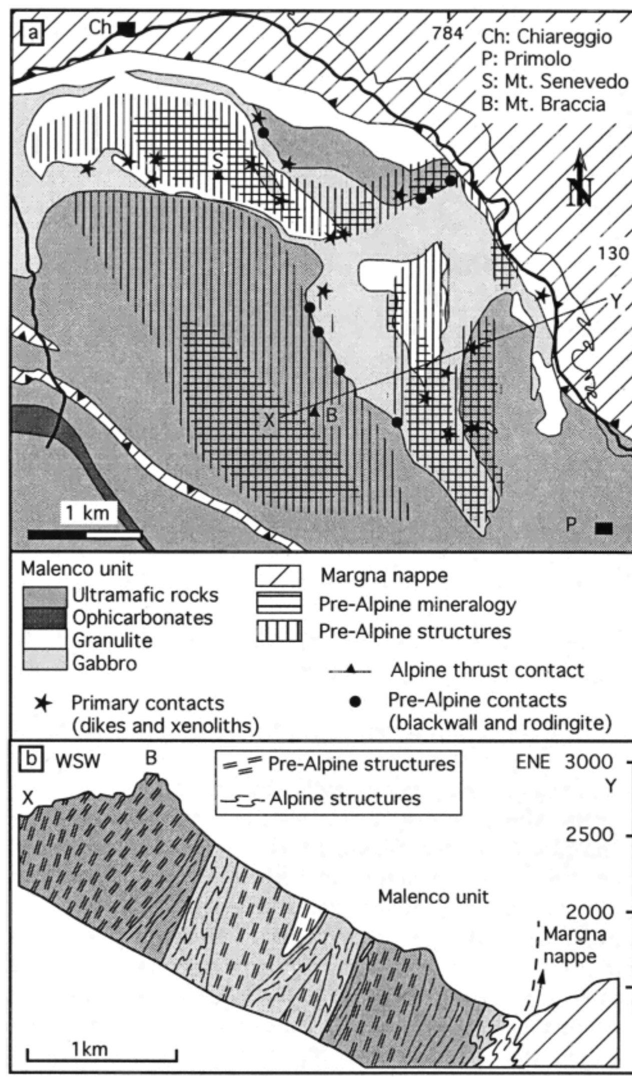

Figure 2. (a) Detailed map of the lower crust-to-mantle transition with location of intrusive contacts of gabbro with peridotites and granulites. Patterns for pre-Alpine structures and mineralogy refer to granulitic conditions. Line X to Y refers to profile below; 784/130 refers to Swiss grid coordinates. (b) The profile through the mapped area shows the distribution and orientation of pre-Alpine and Alpine structures. Note the different scale for map and profile.

Table 1. Parageneses in the Studied Rocks Formed During Pre-Alpine Retrograde Metamorphism

	Rock Types			
Stage	Peridotite	Contacts	Gabbro	Pelitic Granulites
Mantle/Igneous	Ol+Cpx+Opx+ Spl±Ti-Prg		Pl+Cpx+Opx+Ilm ±Spl±Ol±Ti-Prg	
Granulite	Ol+Cpx+Opx+ Spl±Ti-Prg		Cpx+Opx+Pl+Spl±Ol	Pl+Qtz+Grt_1+Ky_1 +Ilm±F
Granulite stage II			Cpx+Opx+Pl+Grt±Ol	Pl+Qtz+Grt_2+Grt_3+Bt +Ilm+Ky_2±Rt
Amphibolite	Ol±Opx+Chl +Cr-Spl+Tr±Tlc		Pl+Czo+Grt+Ts	Pl+Grt4+Pg+Ky_3+Rt+St +Ctd+Phe+Czo±Bt
Amphibolite stage II	Ol+Tr+Chl +Cr-Mag	Prg+Na-Di+Ep mafic blackwall	Pl+Czo+Hbl +Bt+Qtz±Grt	
Oceanic	Ctl±Tr±Chl	Grt+Di+Ep+Chl rodingite		

Mineral abbreviations are Bt, Biotite; Chl = Chlorite; Cpx, Clinopyroxene; Cr-Mag, Cr-Magnetite; Cr-Spl, Cr-Spinel; Ctd, Chloritoid; Ctl, Chrysotile; Czo, Clinozoisite; Di, Diopside; Ep, Epidote; Grt, Garnet; Hbl, Hornblende; Ilm, Ilmenite; Ky, Kyanite; Na-Di, Sodic Diopside; Opx, Orthopyroxene; Ol, Olivine; Pl, Plagioclase; Pg, Paragonite; Phe, Phengite; Prg, Pargasite; Qtz, Quartz; Rt, Rutile; Ti-Prg, Ti-Pargasite; Tlc, Talc; Tr, Tremolite; Ts, Tschermakite; Spl, Spinel; St, Staurolite.

above the upper limit for pelitic granulites compiled by *Rudnick and Fountain* [1995]. This may be explained by the restitic character of the granulites in the Val Malenco region.

The Crust-to-Mantle Transition

In the area of Monte Braccia (Figure 2a), features of the mid-Permian crust-to-mantle transition are well preserved. Gabbro dikes 30 cm to 3 m thick crosscut the Malenco mantle rocks at several localities (Figure 4a) and also occur within the pelitic granulites (Figure 4b). Further evidence for intrusive contacts is provided by granulite and peridotite xenoliths within the main gabbro intrusion. Such intrusive contacts were found over the whole area mapped (Figure 2a). This proves that the gabbro intruded the crust-to-mantle transition, and consequently, the Malenco ultramafic rocks represented subcontinental mantle in Permian times. The formation of blackwalls and rodingites during pre-Alpine hydration of contacts between mafic and ultramafic rocks (Table 1 and Figure 2a) provides further evidence that these rocks shared a common pre-Alpine history.

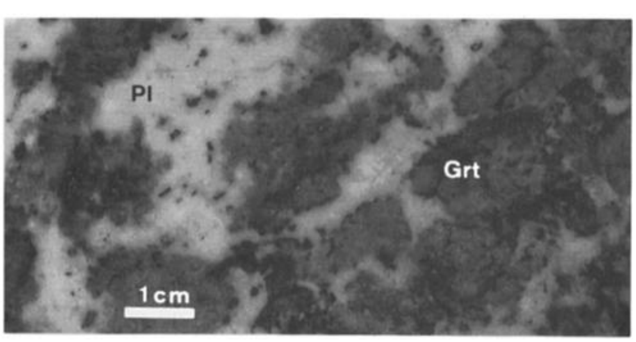

Figure 3. Hand specimen of a restitic pelitic granulite with more than 40% garnet (Grt) in a plagioclase rich matrix (Pl). The garnets reach up to 2 cm in diameter.

Areas in which the rocks show little or no Alpine deformation and have preserved their pre-Alpine mineralogy extend over several square kilometers (Figure 2a). Alpine deformation in this area was concentrated in narrow zones (Figure 2b) and caused no major rotation of the pre-Alpine structures, which preserve a constant direction of the foliation and lineation across the various rock types of the crust-to-mantle transition [*Hermann and Müntener*, 1996].

A reconstruction of the crust-to-mantle boundary eliminating Alpine structures (Figure 5) results in a transition zone of about 1 km thickness in which gabbros, pelitic granulites and peridotites are interlayered. The high density of the pelitic granulites may explain why these rocks were able to sink into the gabbro intrusion. A thickness of up to 2 km of the underlying ultramafic rocks is preserved, and these now cover an area of about 130 km^2. The overlying crustal section in the Malenco unit is only some hundreds of meters thick. The crystallization sequence in the gabbros is consistent with crystallization at 1-1.2 GPa. This would correspond to 35-42 km depth for the crust-to-mantle interface at the time of gabbro intrusion.

U/Pb Age Determinations on Zircons

Preliminary results of conventional U-Pb dating of single zircons from two rock types of the gabbroic unit have already been reported [*Hansmann et al.*, 1995, 1996]. The U-Pb data and age results together with new data of a leucogranitic mobilisate will be discussed in detail in a separate publication. Here the results are briefly summarized.

Zircons were separated from an Fe-gabbro and a highly differentiated Zr-P-Ti -rich gabbro. From the Fe-gabbro four single crystals and two fractions composed of a small number of grains were dated; 11 single crystals of the highly differentiated gabbro were analyzed. All these zircons showed low U contents ranging from 30 to 150 ppm and had accordingly low contents of radiogenic Pb resulting in relatively large analyti-

Table 2. Determined and Calculated Densities of the Malenco Rock Types

Sample	Rock Type	Determined[a]	Calculated (Norm)[b]		Mean Atomic Weight	Calculated (Mode)[c]	
T 64	Garnet granulite	3.25	3.52	(45 Grt, 14 Pl, 10 Qtz, 23 Ky, 7 Bt, 1 Ilm)	22.4	3.31	(35 Grt, 30 Pl, 15 Qtz, 15 Ky, 3 Bt, 2 Ilm)
B-F 217	Mg-gabbro	2.95	3.02	(58 Pl, 31 Opx, 10 Cpx, 1 Ilm)	21.9	2.99	(60 Pl, 20 Cpx, 20 Opx)
G-F 213	Fe-gabbro	3.14	3.19	(50 Pl, 19 Opx, 4 Ol 19 Cpx, 8 Ilm)	23.3	3.15	(50 Pl, 20 Cpx, 25 Opx, 5 Ilm)
L-UM 400	Peridotite	3.27	3.3	(66 Ol, 23 Opx, 7 Cpx, 4 Spl)	21.6	3.31	(55 Ol, 25 Opx, 15 Cpx, 5 Spl)

Units in grams per cubic centimeter; Abbreviations see Table 1.
[a]Buoyancy of handspecimens in water-aethanol mixture.
[b]Calculated on the basis of normative mineral content from whole rock analyses.
[c]Calculated on the basis of estimated mineral mode from representative rock types. Compositions of minerals: 1, garnet granulite; Grt = 55 Alm, 38 Py, 5 Gro, 2 Spe; Pl = An (45); 2, Mg-gabbro; Pl = An (50), Cpx = Di (80), Opx = En (70); 3, Fe-gabbro; Pl = An (50), Cpx = Di (65), Opx = En (60); 4, peridotite; Ol, Opx, Cpx: XMg = 0.9; Spi = XMg = 0.7, YAl = 0.85.

cal errors. On a concordia diagram, 15 out of 17 zircon data points define a linear array showing little to moderate discordance with respect to an upper concordia intercept. Best fit regression [*York*, 1969; *Ludwig*, 1994] yields concordia intercept ages of 269±22 Ma and 131±88 Ma (95% confidence limit).

From a leucogranitic dike, nine single zircons were dated. These zircons were relatively U-rich (650 - 1750 ppm, with an exceptional crystal having about 4000 ppm), resulting in higher contents of radiogenic Pb and yielding smaller analytical errors than the gabbroic zircons. Eight out of nine zircons define a linear array. They are only slightly discordant with respect to an upper concordia intercept, except for the U-rich zircon which is strongly discordant. A best fit regression through these 8 data points yields concordia intercept ages of 274.2±4.7 Ma and 96±11 Ma (95% confidence limit). One data point strongly deviates from this line, suggesting the presence of inherited lead.

The upper concordia intercepts yield Permian ages and are interpreted as the intrusion age of the gabbro and as the formation age of anatectic melts, respectively. Lead loss from the zircons was most likely caused by Cretaceous Alpine metamorphism as indicated by the lower intercept age of 96±11 Ma of the leucogranitic dike.

Granulite Facies Metamorphism

The pelitic granulites are migmatites with a garnet- and kyanite-rich restite that was in equilibrium with partial melts (Figure 6a). These partial melts coalesced and formed leucogranitic dikes that locally intrude the Permian gabbros (Figure 6b). The U-Pb zircon data from the anatectic leucogranite at the gabbro contact yield an age that overlaps within error limits the zircon age obtained from the gabbros. Partial melting and granulite facies metamorphism are therefore considered to be concomitant with the gabbro intrusion. The granulite facies paragenesis in the pelitic restites consists of garnet, kyanite, plagioclase, quartz, ilmenite and minor biotite (Table 1 and mineral composition in Table 4). Garnet-ilmenite thermometry yields temperatures of ~760°C (Figure 7). The presence of kyanite in the granulite facies paragenesis indicates a minimum pressure of 0.9 GPa. The garnets are characterized by high pyrope content (37%) and by very low grossularite content (~2%). Biotite occurs as inclusions and as flakes in textural equilibrium with the granulite facies garnets.

Table 3. Whole Rock Compositions

Major Elements wt %	Peridotite L-UM 400	Mg-Gabbro B-F 217	Fe-Gabbro G-F 213	Granulite T 64	2σ
SiO_2	43.5	52.9	45.9	43.6	0.71
TiO_2	0.05	0.46	5.11	0.89	0.01
Al_2O_3	2.27	16.2	12.6	26.8	0.27
Fe_2O_3 [a]	8.63	7.99	16.8	15.6	0.06
MnO	0.12	0.16	0.28	0 30	0.02
MgO	42.3	10.2	6.88	6.16	0.14
CaO	1.71	9.01	9.26	1.65	0.16
Na_2O	<0.21	2.53	2.34	0.78	0.2
K_2O	<0.02	0.18	0.32	0.77	0.1
P_2O_5	0.01	0.02	0.03	<0.01	0.02
Cr_2O_3	0.39	0.05	0.02	<0.01	0.01
NiO	0.36	<0.01	<0.01	<0.01	0.01
LOI [b]	0.53	0.18	0.33	1.85	
Σ	99.1	99.9	99.8	98.4	

Trace Elements (ppm)	Peridotite L-UM 400	Mg-Gabbro B-F 217	Fe-Gabbro G-F 213	Granulite T 64	Detection Limit
F	<50	117	<50	337	50
Ba	<10	47	122	792	10
Rb	<3	<3	<3	73	3
Sr	<10	273	225	70	10
Pb	<5	<5	<5	<5	5
Nb	<5	<5	<5	<5	5
La	<17	<17	82	23	17
Ce	<17	<17	<17	51	17
Nd	<11	<11	<11	<11	11
Y	<3	<3	12	32	3
Zr	<4	<4	13	171	4
V	53	152	556	261	16
Cr	2682	360	95	242	18
Ni	2205	68	69	120	11
Co	134	21	92	33	11
Cu	18	<8	32	75	8
Zn	47	48	123	278	6
Ga	<4	10	20	35	4
Sc	9	31	65	41	2
S	<50	<50	2217	2964	50

[a] Fe_2O_3 is total iron.
[b] LOI, Loss on ignition.

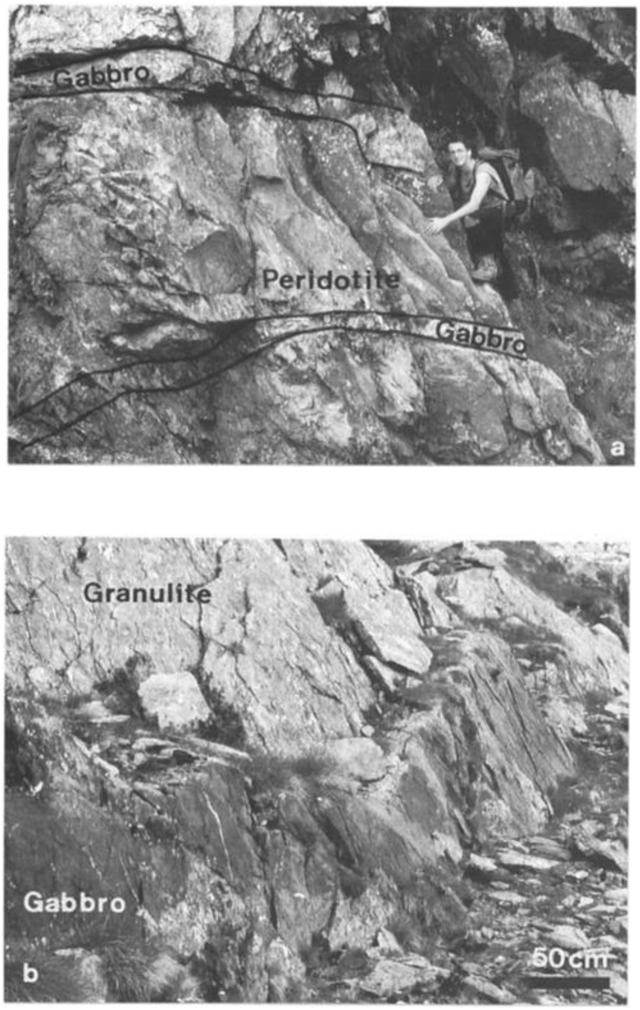

Figure 4. (a) Several gabbro dikes intrude the peridotites (Swiss grid coordinates: 784'200 / 128'360). (b) A highly differentiated Fe-gabbro dike crosscuts the pelitic granulites (Swiss grid coordinates: 781'350 / 130'600).

This permits the application of the petrogenetic grid (KFMASH) with contour lines for garnet composition coexisting with biotite reported by *Spear and Cheney* [1989]. The Fe/Fe+Mg of 0.6 in Grt_1 (Table 4) indicates a pressure of about 1 GPa for temperatures of 760°C as given by garnet-ilmenite thermometry (Figure 7). This pressure overlaps with the pressure estimated for the intrusion of the gabbro. Subsequent to the intrusion the gabbros recrystallized to a granular spinel-bearing assemblage. The presence of plagioclase+olivine+two pyroxenes+spinel (Table 1) and the absence of garnet indicates that the gabbros recrystallized at moderate pressures, which is consistent with the determined 1 GPa. Small neoblasts formed around the large, preexisting mantle minerals, indicating a granulite facies equilibration in the ultramafic rocks (see Table 1).

Retrograde Metamorphism

Retrograde metamorphism is best documented by garnet recrystallization in the pelitic granulites (Figure 8 and Table 4). The pyrope-rich garnet cores (Grt_1) have composite rims consisting of Grt_2 and Grt_3 (Figure 8a). Grt_2 is characterized by a decrease in Mg at constant Ca content and occasionally coexists with recrystallized biotite. The transition to Grt_3 is marked by a significant increase in Ca content. Small, newly formed idiomorphic garnets in the metapelites have Grt_3 composition and are also zoned, displaying a Ca increase from the core (Grt_3) to the rim (Grt_4; see Figure 8b). During this retrograde evolution kyanite is stable and plagioclase is present. Ilmenite is rimmed by rutile, indicating near isobaric cooling subsequent to granulite facies metamorphism [e.g. *Bohlen and Liotta*, 1986]. The application of several thermobarometers indicates that the pelitic granulites cooled from conditions of 750°C and 1 GPa to 600°C and 0.85 GPa (Figure 7). The last stage of this near isobaric cooling is recorded by replacement of plagioclase and kyanite with clinozoisite, paragonite and rare phengite. Between garnet and kyanite occasionally a corona consisting of staurolite and chloritoid formed. Calculated PT conditions for the formation of these minerals are consistent with the applied thermobarometers (Figure 7).

In the gabbros a multistage corona between plagioclase and olivine formed subsequent to the granulite facies equilibration. A spinel-clinopyroxene-orthopyroxene corona is overprinted by a garnet-clinopyroxene orthopyroxene corona (Table 1). The transition from spinel- to garnet-granulite is consistent with isobaric cooling within the gabbros and indicates that gabbros and pelitic granulites shared a common retrograde evolution. The ultramafic rocks recrystallized from spinel to chlorite-amphibole peridotites. The fact that no plagioclase formed in the peridotites is also consistent with cooling at only moderate pressure decrease.

The subsequent, retrograde, exhumational metamorphic path started under amphibolite facies conditions and began with influx of H_2O. Hydration reactions in all the rocks were accompanied by blackwall formation along contacts of mafic to ultramafic rocks. Jurassic formation ages of blackwall amphiboles indicate that hydration and exhumation is related to Jurassic rifting [*Müntener et al.*, 1997]. Further exhumation along a PT path through greenschist facies conditions to the ocean floor is obscured by the Alpine greenschist metamorphic overprint. However, the margins of gabbros are rodingitized when in contact with serpentinized ultramafic rocks (Table 1) providing evidence for metamorphism and metasomatism in an oceanic environment. This is supported by the occurrence of chrysotile relics in the serpentinites [*Mellini et al.*, 1987] and by sedimentary ophicarbonates with marine isotopic signatures [*Pozzorini and Früh-Green*, 1996] associated with the ultramafic rocks (Figure 1).

Discussion

Field data demonstrate that the lower crustal rocks encountered in the Malenco profile were attached to their underlying mantle during gabbro intrusion. The gabbro intruded in the

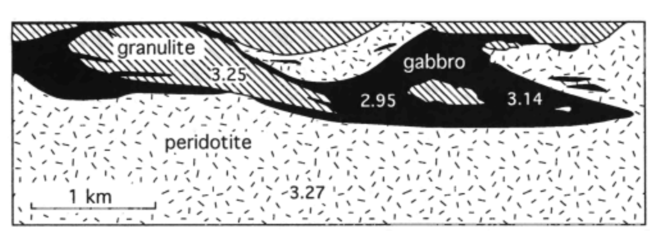

Figure 5. Reconstruction of the crust-to-mantle transition. Measured densities (grams per cubic centimeter) are indicated.

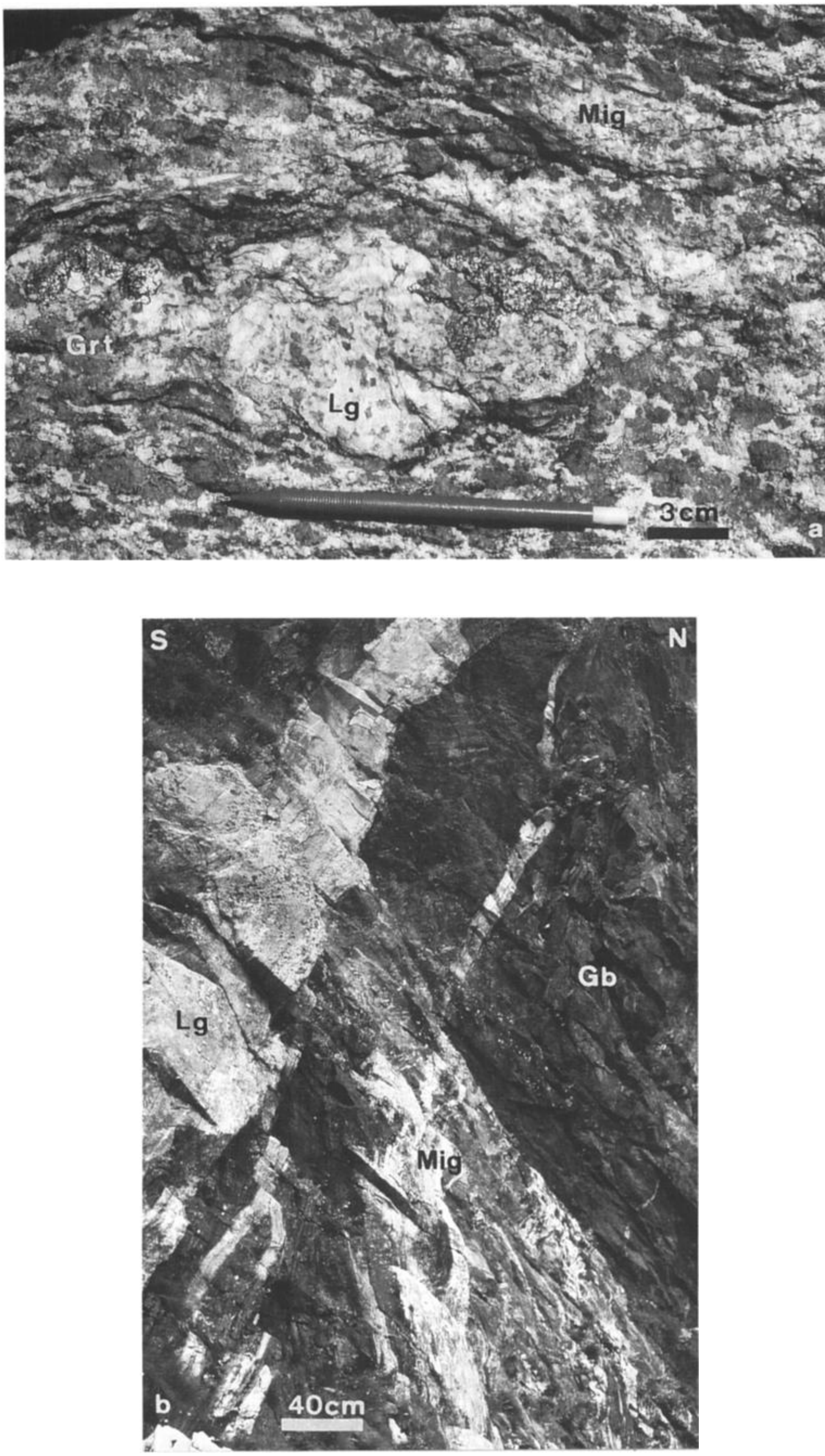

Figure 6. (a) Pockets of leucogranites (Lg) formed in the migmatitic (Mig) pelitic granulites during partial melting. The restitic granulites are rich in garnet (Grt; Swiss grid coordinates: 781'500 / 130'700). (b) The leucogranites (Lg) which result from partial melting occasionally intrude the gabbro (Gb; Swiss grid coordinates: 782'100 / 130'720).

Table 4. Representative Mineral Analyses From the Metapelites

	Granulite Facies G-FS 207			Stage II		Amphibolite		Granulite Stage II G-FS 205			Amphibolite	
	Grt_1	Ilm	Pl	Grt_2	Bt	St	Ctd	Grt_3	Grt_4	Pl	Pg	Average Relative Error (2σ), %
SiO_2	39.2	<0.06	57.3	38.6	34.6	28.6	25.2	37.9	37.7	56.1	50.2	0.6 (at 40% level)
TiO_2	0.04	52.8	-	0.15	1.15	-	-	-	-	-	0.07	6.2 (at 0.2% level)
Cr_2O_3	0.10	0.05	-	0.09	0.07	-	0.19	-	-	-	-	4.6 (at 0.1% level)
Al_2O_3	22.1	-	27.7	21.1	20.8	55.1	42.1	21.8	21.6	26.9	39.4	1.0 (at 20% level)
Fe_2O_3 [a]	0.96	-	0.08	0.29	-	-	0.08	0.89	1.71	-	0.26	
FeO	26.1	45.7	-	30.6	14.9	12.0	16.4	33.3	26.0	-	-	2.8 (at 10% level)
MnO	0.99	0.41	-	1.49	0.04	0.10	0.05	0.45	0.78	-	-	20.4 (at 0.2% level)
MgO	9.68	0.52	-	5.97	12.8	2.12	7.61	2.60	3.26	-	0.08	1.2 (at 10% level)
CaO	1.84	-	9.22	2.06	0.07	0.02	-	5.37	9.64	9.34	0.27	1.2 (at 10% level)
Na_2O	-	-	6.65	-	0.18	-	-	-	-	6.38	6.33	4.2 (at 1% level)
K_2O	-	-	0.05	-	9.36	-	-	-	-	0.04	0.83	10.0 (at 0.2% level)
H_2O calc					3.96	2.19	7.51				4.85	
Σ	101.0	99.5	101.0	100.1	98.0	100.2	99.19	102.4	100.8	98.9	102.3	
Si	2.98	0.00	2.54	2.99	2.62	7.82	2.01	2.97	2.95	2.54	3.01	
Ti	0.00	1.00	0.00	0.00	0.07	0.01	0.00	0.00	0.00	0.00	0.00	
Cr	0.01	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	
Al	1.98	0.00	1.45	1.99	1.85	17.80	3.96	2.01	2.00	1.44	2.87	
Fe3	0.06	0.00	0.00	0.02	0.00	0.00	0.01	0.05	0.10	0.00	0.01	
Fe2	1.66	0.97	0.00	2.01	0.95	2.74	1.10	2.18	1.70	0.00	0.00	
Mn	0.06	0.01	0.00	0.10	0.00	0.02	0.00	0.03	0.05	0.00	0.00	
Mg	1.10	0.02	0.00	0.70	1.45	0.87	0.91	0.30	0.38	0.00	0.01	
Ca	0.15	0.00	0.44	0.17	0.01	0.01	0.00	0.45	0.81	0.45	0.02	
Na	0.00	0.00	0.57	0.00	0.03	0.00	0.00	0.00	0.00	0.56	0.76	
K	0.00	0.00	0.00	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.07	
H					2.00	4.00	4.00				2.00	
X Mg	0.37	0.02		0.25	0.61	0.24	0.45	0.12	0.17			

[a] calculated assuming stoichiometry.

Cations are calculated on the basis of eight cations (cat), 12 oxygens (oxy) (Grt); 2 cat, 3 oxy (Ilm); 5 cat, 8 oxy (Pl); 48 oxy (St); 8 cat, 14 oxy (Ctd); 11 oxy, Σ cat-Na-K=7-Ti (Bt); 11 oxy, Σ cat-Na-K=6 (Pg).

Units in weight percent.

mid Permian [*Hansmann et al.*, 1995]. The crust-to-mantle interface was located at this time at 35 km depth as indicated by the crystallization sequence in the gabbro and the pressure documented in the country rocks. In the ~1 km thick crust-to-mantle transition zone, peridotites, gabbros and lower crustal rocks are mixed (Figure 5).

Field evidence and U-Pb zircon data indicate that partial melting and granulite facies metamorphism in the metapelites represent a deep-seated contact metamorphism that was caused by the gabbro intrusion. This is supported by the similar pressure of 1 GPa recorded in the gabbro and the metapelites. The subsequent metamorphic evolution is characterized by a near-isobaric cooling. *Harley* [1989) proposed that the tectonic origin of granulites can be interpreted on the basis of their PT paths. He distinguished between granulites which follow an isothermal decompression path (ITD) and isobarically cooled (IBC) granulites. ITD granulites form in crust thickened by collision and are subsequently tectonically exhumed. *Rudnick and Fountain* [1995] pointed out that ITD granulites do not represent the stable lower continental crust: they are rather upper crustal rocks that went through an orogenic cycle starting and ending near the surface. IBC granulites are regarded as products of mafic underplating [*Bohlen*, 1991] and are interpreted as true lower crust [*Rudnick and Fountain*, 1995]. These statements are valid for the Malenco rocks which are IBC granulites (Figure 7).

At the end of the near isobaric cooling path the metamorphic conditions were about 600°C and 0.85 GPa, indicating that the rocks resided at the base of a 30 km thick continental crust. These are conditions that would result in a surface heat flow of about 70 mW/m^2 (Figure 7b), applying the model of *Chapman* [1986]. Such a heat flow is slightly higher than the present average heat flow of 60 mW/m^2 [*Pollack and Chapman*, 1977] but may be typical for young continental crust.

The determined high density of restitic pelitic granulites of 3.25 g/cm^3 explains why these rocks were able to sink into the gabbro intrusion (Figure 5) which has measured densites between 2.95 g/cm^3 and 3.16 g/cm^3 (Table 2). The pelitic granulites nearly reach the densities of the mantle rocks which are determined as 3.27 g/cm^3. According to the empirical correlation between seismic P wave velocity and density by *Rudnick and Fountain* [1995], the measured densities correspond to about 7-7.3 km/s for gabbros, 7.7 km/s for pelitic granulites and 8 km/s for peridotites. However, rock composition also influences seismic velocity. Iron-rich rocks have a higher mean atomic weight and a lower seismic velocity for a given density (see Figure 5 of Rudnick and Fountain). The mean atomic weight for the Mg-gabbro (21.9) is significantly lower than that of the denser Fe-gabbro (23.3; see Table 2). The corresponding P wave velocity is around 7 km/s for both rock types, indicating that the higher density of

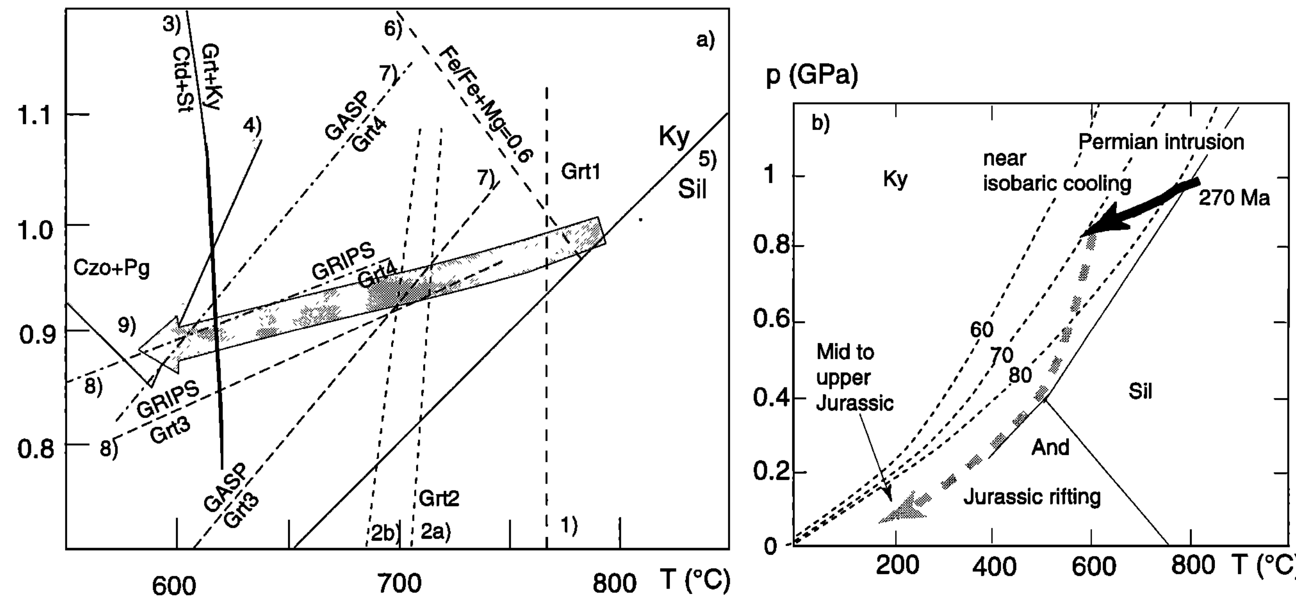

Figure 7. (a) Compiled PT diagram for the pelitic granulites. Temperatures: 1, Grt-Ilm [*Pownceby et al.*, 1987]; 2a, Grt-Bt [*Hodges and Spear*, 1982]; 2b, Grt-Bt [*Ferry and Spear*, 1978]; 3, net transfer reaction Grt+Ky+H_2O -> Ctd+St+Qtz; 4, Pl+Ky+H_2O -> Para+ Czo+Qtz; both calculated with VERTEX (*Connolly* [1990] using the database of *Holland and Powell* [1990])- Pressures: 5, Sil-Ky [*Holdaway*, 1971]; 6, Fe-Mg in Grt [*Spear and Cheney*, 1989]; 7, garnet-alumosilicate-plagioclase-quartz (GASP) [*Ghent*, 1976] with parameters of *Newton and Haselton* [1981]; 8, garnet-rutile-ilmenite-plagioclase-quartz (GRIPS) (*Bohlen and Liotta* [1986] with parameters of *Hodges and Spear* [1982] for Grt and *Hodges and Royden* [1984] for Pl); 9, minimum pressure of paragenesis Pg+Czo calculated with VERTEX (*Connolly* [1990] using the database of *Holland and Powell* [1990]). Estimated errors of ±50°C and of minimum ±0.1 GPa must be considered for the exchange thermometers and barometers and of ±25°C for the net transfer reactions. Grt_{1-4} refers to the representative compositions given in Table 4 and provides evidence for an isobaric cooling of the pelitic granulites shown by the grey arrow. (b) Pre-Alpine PT evolution of the crust-to-mantle transition after the intrusion of the Permian gabbro. The common isobaric cooling of all rock types is indicated by the black arrow. In the Mid to Upper Jurassic times, the whole crust-to-mantle transition was exhumed (see Figure 9). The grey dashed arrow shows the probable exhumation path during Jurassic rifting. Geotherms (dashed lines) corresponding to different surface heat flows (in milliwatts per square meter) are taken from *Chapman* [1986]. And, Andalusite; Ky, Kyanite; Sil, Sillimanite.

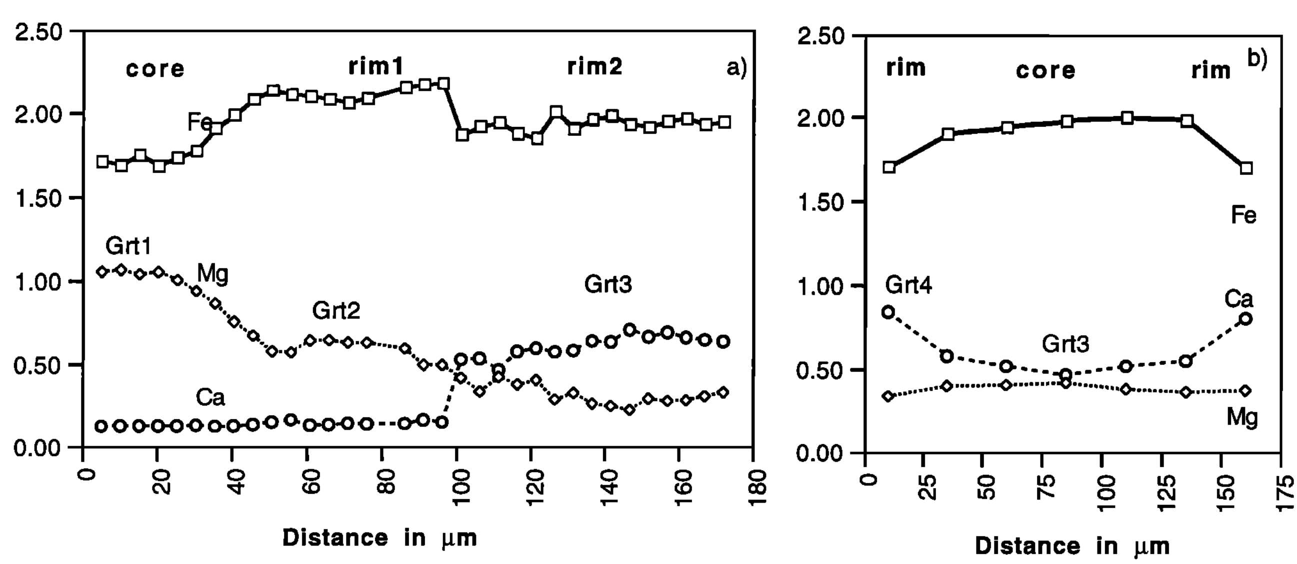

Figure 8. Electron microprobe traverses through garnets in the pelitic granulites. (a) The up to 2 cm large garnet cores are bordered by two generations of rims. The decrease of the Mg and the increase of Ca from the core to the rims reflects a retrograde evolution without significant pressure decrease. (b) Small idiomorphic garnets formed during cooling with an increase of the grossularite content from core to rim. Grt_{1-4} refer to the representative compositions given in Table 4.

the Fe-gabbro is compensated by the higher mean atomic weight [e.g. *Rudnick and Fountain*, 1995]. The garnet-rich restitic granulite has a mean atomic weight of 22.4. The calculated density of 3.52 g/cm^3 clearly exceeds mantle values and the P wave velocity of such a rock corresponds to 8.1 km/s. This is slightly higher than the 8 km/s for the peridotites (mean atomic weight 21.6). Therefore in the studied crust-to-mantle transition the Moho (change in P wave velocity from 6-7 to 8 km/s) did not coincide with the petrologic crust-to-mantle boundary but was most probably situated within the lowermost continental crust.

The reason that the Malenco crust-to-mantle section became integrated in the Alpine edifice is closely related to the formation of the Tethys continental margin. This process started in the Late Triassic to Early Jurassic [*Bertotti et al.*, 1993], long after the thermal relaxation of the Variscan lithosphere. In the Austroalpine region, the Jurassic rifting is well documented [*Froitzheim and Manatschal*, 1996]. For the Malenco margin, evidence for Jurassic exhumation has been compiled by *Trommsdorff et al.* [1993] and *Hermann and Müntener* [1996]. Along a low angle normal fault, pieces of lower crust together with their substratum, the subcontinental upper mantle, were exhumed, leading to a Jurassic configuration as shown in Figure 9. In this scenario the subcontinental mantle with the lower crust partially attached was tectonically denuded. Local ophicarbonate formation indicates seafloor exposure of the entire sequence subsequent to Jurassic rifting. Based on geological constraints, the exhumed crust-to-mantle section is situated between the continental margin and the more distal Forno ophiolites with crosscutting MORB dikes and pillow lavas overlying the Malenco mantle. During later Alpine convergence the section of Figure 5 was situated above the zone of subduction and therefore was not affected by deep burial. It then became integrated into the Alpine nappe pile.

Conclusions

Three lines of evidence lead to the conclusion that the granulites, gabbros and peridotites of Val Malenco represent a fossil, undisturbed crust-to-mantle transition: (1) Crust and mantle are welded by a Permian gabbro intrusion and these relationships have been preserved despite Jurassic rifting and Alpine nappe tectonics. (2) The paleodepth of the crust-to-mantle transition is 35 km. (3) The near isobaric cooling path indicates a period of crustal relaxation toward a stable situation in pre-Jurassic times.

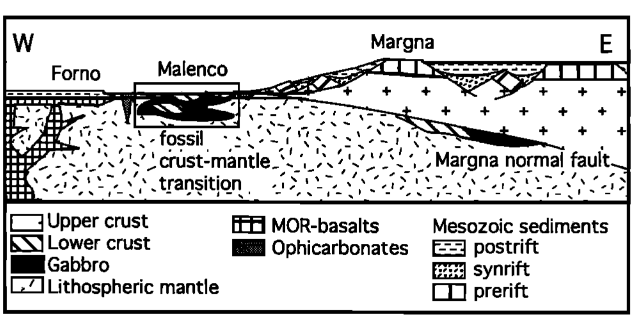

Figure 9. Reconstruction of the Jurassic Adria continental margin in the Val Malenco region. The exhumed crust-to-mantle transition is positioned between the Margna continental crust and the Forno ophiolite suite. The proposed Margna normal fault [*Hermann and Müntener*, 1996], separating upper crust from mantle rocks, led to exhumation and denudation of subcontinental mantle with attached gabbros and lower crust. The synrift and the oldest postrift sediments are of Jurassic age, indicating that the whole crust-to-mantle transition was exhumed in Jurassic times.

It has been shown that the Moho, based upon seismic velocities and thus densities, does not necessarily coincide with the petrologic crust-to-mantle transition. Density values of the different rock types explain why restitic pelitic granulites were able to sink into underlying mafic intrusives. From a petrologic point of view, the Malenco crust-to-mantle transition is represented by a rather heterogeneous suite of pelitic restites, gabbroic and peridotitic rocks of at least 1 km of thickness.

Acknowledgments. V.T. acknowledges financial support provided by Swiss National Science Foundation grants 2000-037388.93/1 and 21-36113.92. We thank J. Ridley, D. Bernoulli, B.W. Evans, N. Mancktelow and P. Nievergelt for helpful comments. Constructive and thorough rewiews by J. Beard, G. Bergantz and P. Kelemen helped to improve this paper.

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(Received October 24, 1996; revised May 12, 1997;
accepted May 20, 1997)