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Zermatt-Saas and Antrona Zone: A petrographic and geochemical comparison of polyphase metamorphic ophiolites of the West-Central Alps.

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Abstract

Despite the polyphase metamorphic history and an intense deformation of the different Mesozoic mafic-ultramafic zones of the West-Central Alps, all typical members of ophiolites, that is ultramafic and mafic plutonic rocks, mafic dikes and volcanic rocks and deep sea sediments can be recognized. The petrographic-geochemical comparison focuses on two zones of the large Piemonte- Ligurian domain: (1) the Zermatt-Saas zone with its abundant relics of Cretaceous high pressure metamorphism and (2) the Antrona zone, which lies essentially in the Tertiary amphibolite facies zone. The special interest of a comparison derives from the fact that the two zones form an incomplete envelope around the continental basement nappe of the Monte Rosa, however without displaying a direct connection. Based on detailed field and laboratory studies we compare the two zones in terms of their sediments (detrital calcschists, manganiferous quartzites), their volcanic suite (today fine grained eclogites, amphibolites and greenschists), their mafic plutonic suite (coarse grained eclogites, amphibolites and greenschists) and their mantle rocks (serpentinites and olivine-dominated schists). Although the lithologies of the two zones are quite similar and comparable to the Western Alps meta-ophiolites (mid ocean ridge basalt volcanics of "transitional" type, predominance of poorly depleted lherzolites among the ultramafic rocks), there are some minor, but systematic differences which exclude a close genetic connection of the two zones. The volcanic rocks of Antrona zone show a very limited chemical variation, suggesting a rapid extrusion in a fast spreading environment. In contrast, in the Zermatt-Saas zone volcanic rocks display a much greater compositional variability and often spilitic compositions related to pillow lavas, suggesting a relatively slowly spreading environment with occasional interaction with seawater.

Keywords: Ophiolites, geochemistry, metamorphism, Zermatt-Saas zone, Antrona zone, West-Central Alps.

1. Introduction

Both the Zermatt-Saas and the Antrona zone belong to the Piemonte-Ligurian ophiolite zone, forming the internal Pennine domain of the Central Alps (Fig. 1). The Zermatt-Saas zone is famous for its numerous relics of the Cretaceous ("eo-Alpine") high pressure metamorphism that survived the Tertiary ("meso-Alpine") greenschist grade metamorphism. It has been described in numerous publications mainly dealing with metamorphic phase relations (see references in BEARTH and SCHWANDER, 1981 and BARNICOAT and FRY 1986). The Antrona zone is smaller in extent and is dominated by a Tertiary amphibolite facies metamorphism. Although an increasing number of studies with emphasis on structural geology (LADURON, 1976; MÜLLER, 1976; MERLIN, 1977; BAUMANN, 1979; KLEIN, 1978; MILNES et al. 1981; MARTIN, 1982; VINARD, 1986; CORNAZ, 1988; JABOYEDOFF, BÉGLÉ and LOBRINUS,1989) and on geochemical-petrological aspects are available (BECCALUVA et al., 1984a; COLOMBI and PFEIFER, 1986; MASSON, 1986; LADEUZE, 1988, COLOMBI, 1988), the Antrona zone is often neglected or not explicitely considered in paleogeographic reconstructions of the Western Tethys (e.g. LAGABRIELLE, 1987). Today, the two zones are separated by the continental basement nappe of the Monte Rosa, the Zermatt-Saas zone

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is situated on top of it and the Antrona zone below. However in the Furggtal, E of Saas Fee, the two zones are only 3 km apart (BEARTH, 1954; WETZEL, 1972; BRUTTIN, 1985; WAHLI-WENGER, 1985; CORNAZ, 1988; JABOYEDOFF, BÉGLÉ and LOBRINUS, 1989) and in the southern steep belt (former "root zone"), E of Domodossola, the two zones are only separated by a 500m wide antiform of the Monte Rosa nappe and are very much thinned out (REINHARDT, 1966; COLOMBI and PFEIFER, 1986; COLOMBI, 1988). Both zones can be followed as 50 to 200m thick fragments of an ophiolite series along a west-east geotraverse of about 100km from Zermatt to Locarno (Fig.1).

In the southern and the eastern parts of the studied region, some tectonic complications occur. First, in the southeastern, strongly thinned out continuation of the Piemonte zone, i.e. in the upper Val Sesia and Val Anzasca south of the Monte Rosa region, the Zermatt-Saas zone cannot be distinguished from the Combin zone sensu stricto of DAL PIAZ et al. (1979; mainly Tsaté-nappe according to the new terminology proposed by SARTORI, 1987, ALLIMANN, 1987 and ESCHER, 1988; see section 2.1). However, as the Tsaté nappe contains much less ophiolitic material than the Zermatt- Saas zone and considering the very reduced overall thickness of the two zones in this region (50 to 200m), most of the mafic- ultramafic rocks seem to belong to the latter zone. Second, in the eastern part of the geotraverse, the Antrona zone can only be followed until Druogno/Valle Vigezzo. Farther east, in the Centovalli E of Locarno, the mafic-ultramafic rocks of the complex Orselina zone (of yet un-

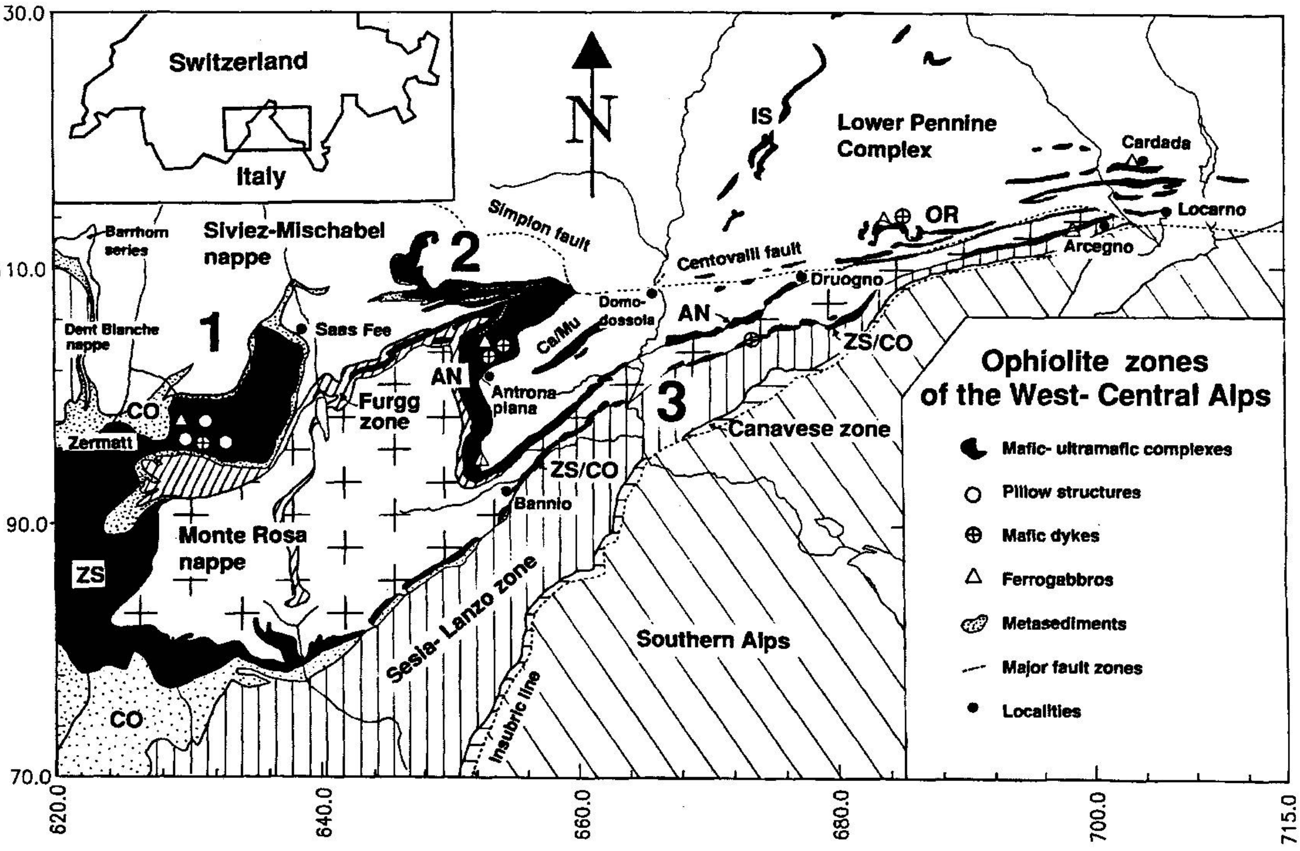

Fig. 1 A Tectonic map of the West-Central Alps with major mafic-ultramafic complexes outlined in black (area around Zermatt and Saas Fee based on SARTORI, 1987; ESCHER, MASSON and STECK, 1988; STECK, 1989). For clarity some of the continental basement nappes directly touching the ophiolite zones of Zermatt- Saas and of Antrona are indicated as well. Symbols indicate the distribution of the rarer members of the ophiolite suites. Continental units are labeled in lower case letters, the oceanic (ophiolitic) units in capital letters, abbreviated as follows: ZS: Zermatt-Saas, CO: Combin sensu stricto (mainly sedimentary, only few mafic-ultramafic intercalations), ZS/CO: the former two zones indistinguishable, AN: Antrona. The following two zones lie in a tectonically poorly known area, therefore exact tectonic limits are omitted: OR: Orselina, IS: Isorno. Other abbreviations: Ca/Mo: Camughera-Moncucco zone. 1, 2, 3: the three regions distinguished in the discussions of this paper. Numbers at the margins correspond to the Swiss coordinate system in kilometers.

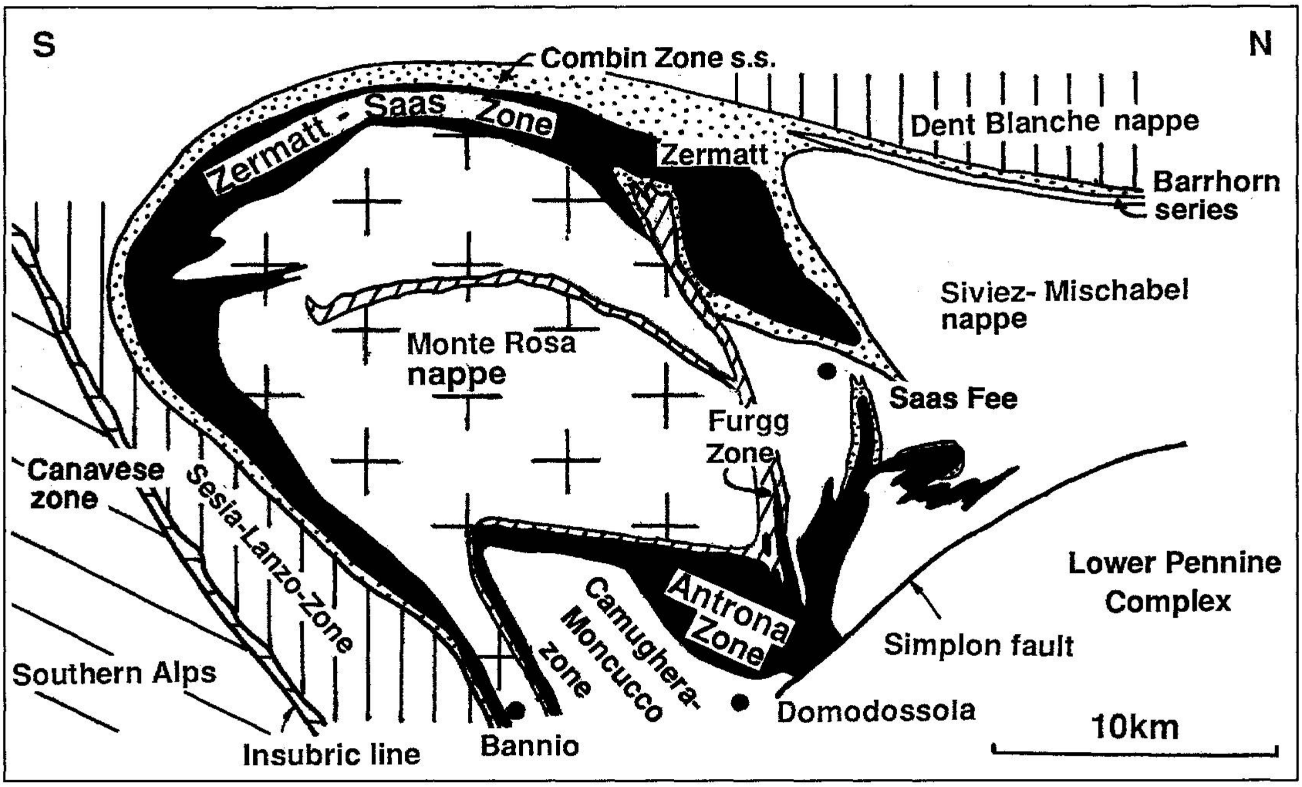

Fig. 1 B Synthetic cross section through the area shown on figure 1A (modified from MILNES et al., 1981).

known, but presumably pre-mesozoic age) cannot be distinguished from a possible eastern continuation of the Antrona-zone (see Fig. 1).

The diversity of metamorphic grade in the west and in the east of this geotraverse offers a unique opportunity to study the effect of metamorphism on the original ophiolitic rock compositions beyond the alpine greenschist facies. In this paper we summarize the petrographic and geochemical results of an intensive study of the mafic-ultramafic rocks of the geotraverse presented above. Details on mineral equilibria and metamorphic conditions can be found in COLOMBI and PFEIFER (1986), COLOMBI (1987, 1988), GANGUIN (1986, 1987, 1988 and this volume). As we will show, metamorphism had little effect on the original bulk rock compositions. This allows us to reconstruct the general paleotectonic situation of the ophiolites and contribute to the discussion about a common origin of the two zones, a hypothesis suggested by many structural geologists (MILNES et al. 1981; ESCHER, MASSON and STECK, 1988).

2. Rock Types

Most of the common members of Western Tethys ophiolite suites have been identified along the whole geotraverse explored here, independently of the metamorphic grade. Table 1 summarizes the different rock types encountered. In the following discussion we will distinguish three different regions: (1) a western region in the neighbourhood of Zermatt (including Täsch Valley), dominated by the zone of Zermatt-Saas, characterized by a meso-Alpine greenschist facies with abundant relics of an eo-Alpine eclogite facies (labeled " Zermatt-Saas (W)" on the figures that follow), (2) a northeastern region dominated by the Antrona zone, characterized by a meso-Alpine amphibolite facies grading from the first appearance of oligoclase in mafic rocks in the W up to sillimanite grade (in metapelitic rocks) in the E, with very few relics of an earlier high pressure phase and (3) a southeastern part, were the Zermatt-Saas and the Combin sensu stricto zone are indistinguishable and the metamorphism has the same grade as in region no.2 (labeled "Zermatt- Saas / Combin (E)" on the figures). Therefore the regions 2 and 3 are not differentiated on table 1.

2.1. SEDIMENTS

In the western region (no.1) thick piles of calcschists ("schistes lustrés", "Bündnerschiefer"), marbles and Mn-rich quartzites occur. A

Tab. 1 Metamorphic analogues of the different series of an ophiolite suite: rock types as a function of metamorphic grade (greenschist facies with eclogite relics in the western region, amphibolite facies in the eastern regions).

ORIGINAL OPHIOLITE MEMBER	METAMORPHIC EQUIVALENT western region (no.1)	eastern regions (no. 2,3)
sediments - calcareous sed. - siliceous sed. - metalliferous sed.	- calcschists, tremolite- marbles - quarzites - Mn-rich phengite-quartzites	- rare marbles and micaschists
volcanic rocks - hyaloclastite (mainly pillows) - basalts s.l.	- glaucophanites, barroisit.-amphibole and chlorite rich greenschists - kyanite-and parag.-bearing eclogites, Ca-amphibole-chlorite-albite-amphibolites +- talc-phlogopite intergrowths (fine- grained)	- no equivalent found - hornblende oligoclase/ andesine amphibolites +- chlorite,Ca-pyroxene (fine- grained)
dykes	- Eclogites, amphibolites (fine grained) usually cutting meta- gabbros	- dark amphibolites in light meta-magnesio-gabbros
mafic plutonites - magnesiogabbros (plag-cpx-gabbro olivine- gabbro, troctolites) - ferrogabbros	- light talc- and omphacite-rich eclogites (coarse- grained), epidote-tremolite-albite-amphibolites (coarse- grained) - dark rutile- and garnet-rich eclogites (coarse grained)	- Mg-hornblende-epidote-anorthite-amphibollites +-chlorite,diopside (coarse-grained) - garnet-cummingt.-amphibolites, often symplect. with Ca-cpx
ultramafic rocks - dunites/ harzburgites - lherzolites - pyroxenites - metasomatic ultramafic rocks	- olivine-rich serpentinites - antigorite- serpentinites - diopside- Ti-clinohumite-bearing serpentinites - diopside-chlorite rocks - carbonate-talc-bearing serpeninites, chlorite-tremolite-schists	- olivine-chlorite rocks - enstatite/Mg-amphib.-olivine-schists - tremolite-enstatite/ Mg-amphib.-oliv.-schist - Tremolite/Mg-amphib.-chlorite rocks - carbonate- bear. talc-Mg-amphib.-rocks, tremol.-Mg-amph.-chlorite-rocks
Ca-rich mafic rocks (rodingites)	- garnet- diopside-epidote-vesuvianite- rocks +- prehnite	- garnet- diops.- epidote vesuvian.-Fe-Ti-spinel

large part of the calcschists seems to be Cretaceous in age (MARTHALER, 1984), whereas thin manganiferous quartzites are considered to represent radiolarian cherts showing traces of hydrothermal activity of the Upper Jurassic (BEARTH, 1976; BEARTH and SCHWANDER, 1981; GANGUIN, 1983). Recent stratigraphic and structural studies allowed to subdivide apparently continuous sediment packages and attribute them to several new independent nappes of different origin (SARTORI, 1987; 1988; ALLIMANN, 1987; ESCHER, 1988): an oceanic unit ("Tsaté nappe") and two continental units (1: "Mont Fort nappe", 2: Mte Rosa nappe). According to this new model, the Combin zone sensu stricto of DAL PIAZ et al. (1979) contains elements of both the Tsaté and the Mont Fort nappe (cf. VANNAY and ALLEMANN, 1989). Only a thin part of all these sediments can be attributed to the underlying Zermatt-Saas zone (SARTORI, 1987, fig. 4; STECK, 1989, this volume). In the eastern regions (no. 2 and 3), metasediments occur as thin marble and calcschist packages (Fig. 1; BEARTH, 1939; REINHARDT, 1966; MÜLLER, 1976; MARTIN, 1982; VINARD, 1986; JABOYEDOFF et al. 1989, CORNAZ, 1988). Quartzites and micaschists are rare and metalliferous sediments seem to be completely absent.

2.2. VOLCANIC ROCKS

The original small grain size of volcanic rocks has been well preserved during the different stages of metamorphism. This feature and their darker green color allows to distinguish them from metagabbros in the field. In the western region (no.1) original pillow structures are well preserved, even in eclogite facies (BEARTH, 1959; 1973; OBERHÄNSLI, 1980; 1982; BARNICOAT, 1988). BEARTH and STERN (1979) found that pillow rims were relatively rich in Al and poor in Mg compared to pillow cores and that the interstitial pillow matrix was enriched in carbonate. However, in the east (regions no. 2 and 3), where considerable stretching has oblitterated most original structures, neither structural nor chemical indication of pillow lavas (as described above) has yet been found. Spilitic enrichment in sodium and sulfur is very common in the Zermatt-Saas zone, leading to in part sulfide-bearing glaucophanites or greenschists rich in barroisitic amphibole and chlorite. In the Antrona zone equivalents of such rocks have not been found.

In the west, former basalts and their hyaloclastic equivalents occur either as fine-grained eclogites or as lower grade albite-bearing mafic schists. In both eastern regions, volcanic rocks mainly occur as fine grained dark green amphibolites (table 1).

2.3. DIKES

Outcrops of subvolcanic rocks are rare and are usually found as 10 to 50 cm thick dikes crosscutting the plutonic sequence (gabbros and more rarely ultramafics). In some outcrops of the western region up to 90% can be made up of zoned dikes, which often exhibit cm-size deformed pseudomorphs of magmatic phenocrysts in the center and finer grained rims towards the gabbroic wall rock. Typical examples occur in the Täsch Valley NE of Zermatt and in the gabbro of the Allalinhorn SW of Saas Fee (BEARTH, 1967; FRY, 1972; MEYER, 1983; GANGUIN, 1988). In the eastern regions, fine-grained dark-green layers, parallel to the schistosity of the adjacent light-green metagabbro are interpreted as metadikes. In one instance well preserved dikes crossing ultramafics have been found (at Antronapiana, see sample localities on fig. 1). Part of the zoned and boudinaged rodingites (see section 2.6.) probably were dikes. In summary, a proper sheeted dike complex originally situated between the plutonic and the volcanic suite cannot be found in either region. However, the features found are remarkably similar to those described by BONATTI et al. (1975) from the Mid Atlantic Ridge and from the Apennine and seem to be typical for the Western Alps ophiolites (DIETRICH, 1980; LOMBARDO and POGNANTE, 1982).

2.4. MAFIC PLUTONIC ROCKS

In this group rare relics of the magmatic stage have survived the polyphase metamorphism, especially in the western region (chromian spinel, clinopyroxenes of diopsidic and endiopsidic composition). However, the relative abundance of such relics as described by MEYER (1983) from the gabbro of the Allalinhorn W of Saas Fee, is a rare exception. Usually, the macroscopic distinction from meta-basalts is based on texture and color index: former gabbros are systematically coarser grained (flaser structure at cm-scale). Former magnesiogabbros are usually lighter green than former basalts. In the western region the high pressure equivalents of these rocks contain an amazing variety of mineral assemblages including talc, kyanite, omphacite and chloritoid (Täschtal: BEARTH, 1973; BARNICOAT and FRY, 1986; GANGUIN, 1988; Allalinhorn: BEARTH, 1967; MEYER, 1983). The amphibolite facies equivalents of the eastern regions show, aside from a varying An-content, an uniform assemblage all along the geotraverse looked at: epidote, zoned magnesio-hornblende +/- chlorite or calcic clinopyroxene.

In all three regions, dark black-green rocks, frequently showing eclogite assemblages, can be found, which upon analysis, turn out to be very rich in Ti and Fe (see below). We interprete them as ferrogabbroic plutonic rocks comparable to cumulate type rocks from other Western Alps occurrences (LOMBARDO and POGNANTE, 1982; POGNANTE, LOMBARDO and VENTURELLI, 1983; BECCALUVA et al. 1984a; BERTRAND et al., 1987) or from the Appenine (SERRI, 1980, SERRI et al. 1985). In the western region and at some localities in the eastern regions these rocks usually are rutile- and garnet-rich eclogites (GANGUIN, 1988; COLOMBI and PFEIFER, 1986). In the eastern regions cummingtonite- or diopside-bearing, often symplectic amphibolites are found as equivalents. The presence of diopside is interpreted as an intermediate relic of the meso-Alpine decompression event (COLOMBI, 1988).

2.5. ULTRAMAFIC ROCKS

These rocks typically occur as megaboudins of some tenths of meters (max. 500m) within the mafic rocks. Due to this intense deformation (dismembering and folding) the exact origin of the rocks (tectonic mantle peridotites or cumulate series at the base of the crustal mafic plutonic suite) cannot be determined. All ultramafic rocks are metamorphic and reflect the Tertiary metamorphism (cf. section 3.4). In the western region one finds antigorite-olivine-serpentinites, whereas in the eastern regions olivine-dominated schists occur. About 60% in volume are metalherzolites and 20% meta-pyroxenites (former olivine-clinopyroxenites, websterites and possibly wherlites), containing tremolite or diopside. The latter mineral occurs as pseudomorphs after a presumably mantle clinopyroxene and as fine grained newly formed crystals. About 20% are Ca- silicate poor serpentinites or olivine-dominated schists that correspond to former harzburgites and dunites. Original layering, marked by an enrichment of spinel, diopside/tremolite or olivine is preserved in lenses thicker than 100 meters. In the marginal parts of ultramafic masses, pseudomorphs of antigorite after clinopyroxene indicate a metasomatic calcium depletion, often responsable for almost pure antigorite schists of Ca-poor (pseudoharzburgitic) composition.

2.6. Ca-RICH MAFIC ROCKS (META-RODINGITES)

In all three regions, in close relationship to ultramafic rocks, zoned garnet- diopside-inclusions of meter-scale with rims of chlorite-amphibole rocks occur. They correspond to former mafic rocks which formed through Ca-Al-metasomatism during oceanic serpentinization (COLEMAN, 1977). They are usually strongly boudinaged, but in some cases of the western region, their original gabbroic context can still be recognized (BEARTH, 1967; DAL PIAZ et al., 1980; GANGUIN, 1988). Rodingitic contacts of ultramafic rocks with accompanying metasediments also occur (BEARTH, 1967). However, the majority of rodingite occurrences seems to correspond to former dikes and sills.

3. Metamorphism

3.1 CRETACEOUS (EO-ALPINE) ECLOGITE FACIES

Around Zermatt and Saas Fee (region no.1) outcrops with rocks that have preserved their high pressure mineral assemblage are relatively abundant (table 1). The eo-Alpine event is polystadial with an early blueschist facies, followed by an eclogite facies for which maximum conditions of 550-600°C and 18-24 kbar have been estimated, based on mafic and carbonate mineral assemblages (OBERHÄNSLI, 1980; 1986; MEYER, 1983; BARNICOAT and FRY 1986; GANGUIN, 1986,1988). Eclogites of region no. 2 (Antrona zone) indicate almost similar conditions, however with considerable spread in temperature (500- 800°C ; COLOMBI and PFEIFER, 1986; LADEUZE, 1988).

3.2. TERTIARY (MESO-ALPINE) GREENSCHIST FACIES IN THE WESTERN REGION

The first retrograde overprint of eo-Alpine parageneses occurred at about 450-500° C and 6-10kbar. This estimation is based on phengite composition and the typical mineral pair barroisitic blue-green amphibole-albite (GANGUIN, 1988). Similar conditions have been estimated for the symplectites of the gabbros of the Allalinhorn W of Saas Fee, which contain blue-green hornblende (mainly barroisite), pargasitic amphiboles and, in the vicinity of Mg- chloritoid, corundum, diaspor, margarite and sphene (MEYER, 1983). The second retrograde overprint produced tremolite-albite-biotite, together with albite veins, which indicates ordinary upper greenschist facies conditions, estimated approximately at 450-500 °C and 3- 5kbar.

3.3. MESO-ALPINE AMPHIBOLITE FACIES IN THE EASTERN REGION

At this metamorphic grade care has to be taken to distinguish parageneses in metavolcanic rocks from those in metagabbros (cf. table 1). In the northeastern region (no. 2), temperature estimations based on the Ti-content of amphiboles, the plagioclase composition and the garnet-biotite thermometer in adjacent metapelites range from 550°C at Antronapiana to 700°C at Locarno-Cardada. In the southeastern region (no.3) the same methods indicate 500°C at Bannio/Valle Anzasca and 600°C at Arcegno-Locarno (COLOMBI, 1988). Pressures are more difficult to estimate. In the adjacent metapelites, going from W to E, the transition from kyanite to sillimanite can be observed, indicating at least pressures of about 5kbar.

3.4. METAMORPHISM OF ULTRAMAFIC ROCKS

Because ultramafic rocks are little sensitive to high pressure, the eo-Alpine and meso-Alpine mineral associations are difficult to distinguish. West of Druogno/Valle Vigezzo (fig. 1), antigorite-tremolite-chlorite-magnetite +/- diopside associations dominate, whereas farther east olivine-talc-tremolite-chlorite-Fe-Cr-spinel+/Mg-amphibole, enstatite is found. In the southeastern (no. 2) and the eastern region W of Druogno serpentine-poor, olivine-rich and serpentine-rich fragments of some 100m can be found adjacent to each other. This feature probably indicates that only part of the ultramafic rocks were already serpentinized (in the ocean) at the onset of the Alpine orogeny. They seem to have metastably survived the subsequent metamorphism as olivine-dominated rocks, because the deformation was not pervasive enough to allow hydration. One of the best preserved examples can be observed at Alpe di Cama, E of Antronapiana (fig. 1). However, fragments already serpentinized in the oceanic environment recrystallize more easily to metamorphic serpentinites.

4. Bulk rock composition

4.1. INTRODUCTION

In a systematic survey of the mentioned W-E geotraverse around 150 mafic and about 50 ultramafic samples have been analyzed from the three ophiolite regions. Bulk rock analyses have been obtained by classical XRF methods on glass beads for major and minor elements and on powder pellets for common trace elements (table 2). Rare earth elements of 15 samples have been analyzed with ICP-methods and/or neutron activation (table 3 and 4). In contrast to earlier studies of the Zermatt-Saas zone (BEARTH and STERN, 1971; 1979), we tried to avoid rocks with pillow structures. Another 90 unpublished analyses from local studies were at our disposition for comparison (WAHLI-WENGER, 1985; VINARD, 1986; MASSON, 1986; CORNAZ, 1988; JABOYEDOFF et al., 1989); they are in excellent agreement with the data cited above.

4.2. SEDIMENTS

The only data available concern metalliferous sediments from Mn-deposits (DAL PIAZ et al.,1979; MARTIN et KIENAST, 1987; GANGUIN, 1983) of the Zermatt-Saas and the Combin-zone sensu stricto. They display typical trace- element patterns of submarine hydrothermal deposits, i.e. low in Cu, Ni, Co, U, Th, Ce and La (GANGUIN, in prep.; cf. BONATTI, 1975, TOTH, 1980; CRERAR et al. 1982).

4.3. GENERAL CHEMICAL FEATURES OF MAFIC ROCKS

Mafic volcanic and plutonic rocks are in general well discriminated on a number of major and trace element diagrams (Fig. 2,3,4). Meta-magnesiogabbros show typically lower TiO_2-, Fe/Mg-, V- and REE- contents but often higher Al_2O_3-, Ni- and Cr- values than the meta-volcanic rocks (table 2). Comparing the Zermatt-Saas zone with the Antrona zone, a slight tendency towards higher Na_2O+ K_2O values of the former is observed in the igneous AFM-diagram (fig. 2). For the Zermatt-Saas zone some trace elements show little correlation with Zr (Y, cf. fig. 3, and Rb, Sr), suggesting a metasomatic change in connection with a hydration event, which could have taken place either during oceanic spilitization (cf. SEYFRIED et al., 1978 and section 4.4.) or during the meso-Alpine overprint of the eo-Alpine eclogitic rocks. Among the major elements, only K_2O, Na_2O and in one case MgO (Zermatt- Saas zone) are not correlated with relatively stable elements like Zr or Ti, which indicates an amazing preservation of original composition despite at least two metamorphic events. Apart from Nd, which

Tab. 2 Bulk rock analyses of representative samples of all rock types. A: meta-basalts, B: meta-gabbros, C: ultramafic rocks. The first analysis of each of the mafic rock groups corresponds to a representative analysis close to the mean, the other two are representative analyses with very low and very high zirconium values respectively. Analytical methods: major and common trace elements : mainly XRF with a Cr-tube (Philips PW 1400). Major element correction after De Jongh (1973), most traces measured and corrected after Nisbet et al. (1979) and Reusser (1987). La, Ce, Nd: measured with a Mo-tube. FeO: colorimetry modified after Wilson (1960). CO_2: coulometry (Hermann and Knacke, 1973). H_2O: calculated from loss on ignition, FeO, CO_2 and S. Analyst: J.-C. Lavanchy, Lausanne. Uncertainties (2 sigma): major elements max. 5% rel. (SiO_2: 1% abs.), traces: max. 20% rel. below 100ppm, max. 10% rel. above 100ppm.

A

META-BASALTS									
	ANTRONA			ZERMATT-SAAS /COMBIN (EAST)			ZERMATT-SAAS (WEST)		
sample	7-5[1)]	25-26[1)]	7-1[1)]	21-15[1)]	21-10[1)]	12-53A[1)]	30-22[2)]	ZS69[3)]	ZS95[4)]
major elements [wt. %]									
SiO2	48.04	49.10	48.63	50.54	49.86	47.45	49.04	44.40	49.11
TiO2	1.92	0.94	2.04	1.59	1.03	1.65	0.94	2.90	1.83
Al2O3	15.66	17.53	15.89	16.08	17.49	16.78	20.68	21.10	16.31
Fe2O3	3.52	3.21	4.06	3.02	4.39	4.07	1.50	4.20	3.71
FeO	6.65	4.30	5.95	5.18	3.20	4.76	4.64	7.10	5.66
MnO	0.19	0.13	0.17	0.16	0.14	0.17	0.11	0.00	0.21
MgO	5.57	8.88	6.85	6.90	8.06	9.26	6.15	8.90	5.88
CaO	12.10	9.70	9.10	10.39	9.13	11.67	9.98	2.10	9.55
Na2O	3.45	3.10	4.03	4.42	3.52	2.78	4.04	3.90	5.52
K2O	0.59	0.07	0.69	0.17	0.53	0.11	0.34	0.40	0.02
P2O5	0.30	0.08	0.27	0.22	0.13	0.12	0.13	0.30	0.21
H2O	1.33	2.12	1.79	1.65	2.54	1.06	2.47	3.10	1.01
CO2	0.03	0.05	0.34	0.02	0.11	0.07	0.09	0.00	0.70
Total	99.35	99.21	99.81	100.34	100.15	99.95	100.11	98.40	99.72
trace elements [ppm]									
Ba	51	25	72	30	82	44	71	39	47
Rb	10	<4	14	<4	22	4	7	<4	4
Sr	175	172	166	299	304	161	300	38	267
Pb	<7	<7	<7	<7	<7	<7	<7	<7	15
Th	<2	<2	<2	<2	<2	<2	<2	3	3
U	<8	<8	<8	<8	<8	<8	<8	38	<8
Nb	<4	<4	<4	<4	<4	4	8	<4	8
La	7	<4	9	4	9	10	<4	<4	17
Ce	20	8	23	22	24	<6	6	147	<6
Nd	10	6	18	10	9	24	13	41	57
Y	22	8	43	30	15	35	18	<5	53
Zr	159	60	182	151	58	132	91	<4	183
V	237	142	233	176	121	175	115	59	199
Cr	183	372	208	252	206	341	169	<14	164
Ni	65	145	92	74	67	112	90	11	81
Co	30	28	40	36	37	35	39	<4	34
Cu	19	18	43	<5	<5	54	29	<5	38
Zn	82	49	95	54	80	33	47	<4	92
Ga	8	4	18	15	16	12	15	<3	22
Sc	33	29	37	37	27	36	18	<1	34
S	<6	<6	118	<6	14	608	<6	<6	<6

Rock type : 1) normal amphibolite, 2) garnet-amphibolite, 3) glaucophane-schist, 4) amphibolitic eclogite

B

META-GABBROS									
	ANTRONA			ZERMATT-SAAS /COMBIN (EAST)			ZERMATT-SAAS (WEST)		
sample	7-3[1)]	17-4[1)]	26-10[1)]	85/25[2)]	14-6[1)]	12-52[1)]	ZS353[3)]	ZS249[1)]	ZS299[1)]
major elements [wt. %]									
SiO2	48.03	49.28	47.63	46.39	48.75	46.98	42.19	45.50	49.70
TiO2	0.23	0.25	0.49	0.14	0.23	0.86	5.58	5.50	3.70
Al2O3	20.41	17.20	17.05	19.07	17.22	15.56	11.83	13.30	9.80
Fe2O3	1.43	1.38	1.20	2.34	1.02	1.00	7.25	1.90	10.40
FeO	2.69	3.06	3.80	2.35	3.51	4.51	8.97	11.70	1.20
MnO	0.08	0.09	0.10	0.08	0.10	0.14	0.33	0.20	0.10
MgO	8.94	9.79	9.81	12.67	11.61	13.50	6.07	5.50	7.20
CaO	14.36	14.43	14.60	8.86	12.94	12.33	9.86	10.50	12.30
Na2O	1.96	2.07	1.81	3.00	1.48	1.07	3.87	3.50	4.40
K2O	0.11	0.03	0.05	0.00	0.23	0.83	0.00	0.00	0.00
P2O5	0.02	0.01	0.04	0.08	0.01	0.04	2.64	0.20	0.00
H2O	1.50	1.46	2.01	4.44	1.82	2.30	0.87	1.30	0.20
CO2	0.03	0.06	0.03	0.15	0.04	0.15	0.11	0.00	0.00
Total	99.79	99.11	98.62	99.57	98.96	99.27	99.57	99.10	99.00
trace elements [ppm]									
Ba	6	9	17	3	9	60	104	78	56
Rb	8	<4	<4	<4	12	64	<4	5	<4
Sr	235	225	211	156	172	153	266	30	15
Pb	<7	<7	<7	<7	<7	21	67	7	29
Th	<2	<2	<2	<2	<2	2	<2	2	5
U	<8	<8	<8	<8	<8	<8	<8	50	38
Nb	4	<4	4	4	<4	4	19	<4	<4
La	<4	<4	<4	<4	<4	<4	68	<4	<4
Ce	<6	<6	<6	15	<6	25	96	575	547
Nd	<3	<3	<3	3	<3	4	135	21	<3
Y	12	8	17	14	6	31	133	<5	9
Zr	19	8	34	17	11	33	126	<4	<4
V	62	71	109	26	64	100	335	<3	5
Cr	866	949	534	279	3192	905	65	<14	<14
Ni	148	184	136	319	289	291	63	<7	20
Co	27	26	33	29	31	33	58	<4	<4
Cu	29	48	35	30	<5	27	75	<5	<5
Zn	29	26	38	43	42	57	174	<4	<4
Ga	13	9	12	7	10	14	35	<3	<3
Sc	25	32	41	<1	27	35	37	<1	<1
S	<6	<6	<6	<6	<6	<6	1855	<6	8

rock types: 1) meta-magnesiogabbro, 2) meta-troctolite, 3) meta-ferrogabbro

C

ULTRAMAFICS									
	ANTRONA			ZERMATT-SAAS /COMBIN (EAST)			ZERMATT-SAAS (WEST)		
sample	97-10[4)]	62-3[3)]	49-7B[2)]	92-2[5)]	92-12[3)]	78-51[4)]	73-22[4)]	44-14[1)]	48-26[2)]
major elements [wt. %]									
SiO2	41.31	39.35	39.05	41.26	41.13	40.86	38.44	42.97	41.06
TiO2	0.07	0.02	0.04	0.10	0.02	0.16	0.10	0.09	0.11
Al2O3	1.72	1.61	3.06	2.65	1.09	4.50	1.77	2.89	3.44
Fe2O3	2.28	3.75	5.88	2.03	6.29	2.52	7.17	6.13	3.68
FeO	5.96	3.21	2.64	5.94	2.46	8.83	6.01	2.99	3.85
MnO	0.15	0.08	0.12	0.13	0.11	0.15	0.15	0.12	0.13
MgO	38.41	37.23	35.68	38.77	38.72	34.89	37.18	24.84	33.11
CaO	3.76	0.68	1.76	0.68	0.02	0.79	0.02	13.63	3.79
Na2O	0.11	0.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K2O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P2O5	0.01	0.01	0.00	0.03	0.02	0.07	0.04	0.02	0.02
H2O	2.78	12.83	10.83	4.36	9.29	6.38	8.02	4.56	10.05
CO2	1.17	0.00	0.00	3.37	0.11	0.00	0.00	0.00	0.00
Cr2O3	0.26	0.28	0.33	0.43	0.37	0.27	0.32	0.95	0.34
NiO	0.17	0.40	0.27	0.30	0.30	0.18	0.11	0.21	0.22
Total	98.16	99.83	99.66	100.05	99.93	99.60	99.33	99.40	99.80
trace elements [ppm]									
Ba	3	3	9	8	3	6	6	<2	4
Sr	19	<4	<4	<4	<4	17	<4	8	11
Pb	<7	<7	<7	<7	<7	8	<7	21	9
Ce	12	<6	7	15	<6	36	23	56	17
Nd	5	3	<3	<3	<3	<3	<3	5	<3
Y	9	8	10	9	9	9	9	17	11
Zr	6	10	9	10	8	11	12	10	13
V	30	23	42	41	26	28	26	56	43
Cr	1756	1919	2268	2533	2211	2314	3796	6087	2040
Ni	1738	1716	1380	1905	1992	1672	2094	1354	1644
Co	64	43	41	110	103	124	122	79	88
Cu	125	5	12	23	17	85	162	27	24
Zn	46	29	52	55	43	93	100	50	56
Ga	<3	<3	4	8	7	15	10	13	9
Sc	16	11	15	13	13	15	9	13	14
S	215	<6	175	558	<6	2208	346	97	<6

Elements analyzed but below detection limit : Rb <4, Th <2, U <8, Nb <4, La <4.

rock types: 1) meta-clinopyroxenite (di-chl±antg), 2) serpentinite (di-ol-chl-antg), 3) serpentinite (ol-chl-antg), 4) olivine-schist (tr-chl-ol ± mg-amp), 5) olivine-schist (chl-ol ± mg-amp)
mineral abbreviation: di: diopside, chl: mg-chlorite, antg: antigorite, tr: tremolite, ol: olivine, mg-amp: magnesio-amphibole

Tab.3 Rare earth elements (REE) of mafic rocks. Analytical methods: N: ICP, analyst: K. Govindaraju, Nancy; G: Neutron activation, analyst: P. Voldet, Geneva (method after Voldet, 1982). Uncertainties (2 sigma): around 10% relative for all elements but Nd (2s = 20%).

	ANTRONA				
	23-8[1)] N	17-10[1)] N	17-21[1)] N	17-4[2)] N	17-15[3)] N
La	3.21	5.69	3.67	0.69	12.87
Ce	11.77	19.75	15.41	7.15	45.85
Nd	6.42	14.69	8.77	1.41	37.13
Sm	2.52	5.19	3.17	0.96	13.13
Eu	0.93	1.74	1.37	0.49	3.32
Gd	2.63	5.47	3.07	1.09	13.33
Tb	0.00	0.00	0.00	0.00	0.00
Dy	3.29	6.60	3.67	0.95	16.06
Ho	0.00	0.00	0.00	0.00	0.00
Er	2.07	3.62	2.10	0.55	8.61
Yb	2.39	4.14	2.23	0.52	8.99
Lu	0.34	0.58	0.31	0.07	1.24
Y	24.87	49.47	26.34	6.49	111.31

	ZERMATT-SAAS /COMBIN (EAST)				ZERMATT-SAAS (WEST)			
	21-10[1)] N	21-46[1)] N	12-4[1)] G	12-12[1)] G	30-14[1)] N	30-30[1)] N	ZS168[1)] N	ZS169[1)] N
La	10.23	5.52	8.00	4.90	11.48	5.64	4.00	7.23
Ce	25.95	16.27	20.00	16.00	34.71	22.19	14.77	22.15
Nd	12.97	7.61	0.00	12.00	20.44	15.18	6.56	12.59
Sm	3.51	2.80	3.70	3.80	6.16	5.49	2.29	3.74
Eu	1.23	0.97	1.30	1.40	1.83	1.88	0.01	4.32
Gd	2.83	2.98	0.00	0.00	5.91	5.78	1.90	3.65
Tb	0.00	0.00	0.90	1.10	0.00	0.00	0.00	0.00
Dy	2.94	3.78	5.50	5.00	7.02	6.90	3.76	4.35
Ho	0.00	0.00	1.30	1.20	0.00	0.00	0.00	0.00
Er	1.52	2.19	0.00	0.00	3.80	3.77	2.95	2.53
Yb	1.60	2.41	3.00	2.20	4.36	4.23	3.39	3.08
Lu	0.22	0.35	0.52	0.36	0.59	0.56	0.47	0.43
Y	19.69	27.56	41.00	34.00	48.73	49.98	33.65	30.62

rock types: 1) meta-basalt, 2) meta-gabbro, 3) meta-ferrogabbro
analysts: N K. Govindaraju (Nancy), G P.Voldet (Genève)

Tab. 4 Trace element ratios typical for different volcanic environments after SUN et al. (1979), SAUNDERS et al. (1980; 1984), LE ROEX et al. (1983). In all three regions the values are quite uniform and are mostly in between the values of normal mid- ocean ridge basalts (N-MORB) and transitional (T-) MORB. n: normalized values (with chondrite, cf. fig. 4).

	Ba/Zr	Zr/Y	La_n/Yb_n	La_n/Sm_n	Ce_n/Yb_n	La_n/Ce_n
Antrona						
23-8	1.13	1.00	0.79	0.79	1.11	0.71
17-10	0.56	1.97	0.81	0.68	1.07	0.75
17-21	0.41	4.09	0.97	0.72	1.55	0.62
Zermatt-Saas/Combin (EAST)						
21-10	1.18	2.34	3.76	1.81	3.64	1.03
21-46	0.39	3.21	1.35	1.22	1.52	0.89
12-4	0.30	5.43	1.57	1.34	1.50	1.05
12-12	0.42	3.48	1.31	0.80	1.63	0.80
Zermatt-Saas (WEST)						
30-14	0	6.97	1.55	1.16	1.79	0.87
30-30	0	6.73	0.78	0.64	1.18	0.67
ZS168	0	6.96	0.69	1.08	0.98	0.71
ZS169	0	6.73	1.38	1.20	1.62	0.86
N-MORB	0.07	1.4-4.2	0.2-1.1	0.4-1	<1	<1
T-MORB	0.6-1	3.1-7.7	1.4-4.3	0.7-2	1-2	>1
P-MORB	1-1.2	7.1-7.9	4.8-6.9	1.1-2.6	4-5	>1
B-ARC	0.4-2.3	-	2.2-3.2	-	2.0-3.2	>1

seems slightly disturbed (too low compared to Ce), but not atypical for metamorphic mafic rocks (cf. EVANS et al. 1981), the rare earths show typical mafic volcanic and plutonic trends (fig. 4), which confirms that original bulk rock trace compositions of mafic rocks can be preserved even under upper amphibolite facies conditions.

4.4. VOLCANIC ROCKS AND DIKES

The volcanic rocks of the whole geotraverse display compositions comparable to present-day mid-ocean or marginal basin ridge basalts of constructive oceanic plate margins (MORB, fig. 5, 6, 7). However, there are a few minor but interesting differences between the Zermatt-Saas and the Antrona zone rocks. In general the scatter in the compositions of volcanic rocks of the Antrona zone is much smaller than in the Zermatt-Saas zone. Some volcanic rocks of the Zermatt-Saas zone (region no.1 and 2) have compositions outside the basalt liquid field as defined by PEARCE (1983, Al_2O_3: 13.5- 17.5, TiO_2: 1.0- 2.1), comprising mainly glaucophanites and albite-chlorite rich greenschists.The Antrona rocks do not show compositions in the spilite field as defined by MULLEN (1983, Na_2O/ CaO > 0.66), whereas about a third of the samples from the western Zermatt-Saas zone (region no. 1) fall in it and most of them are rich in glaucophane. The same tendency was observed by BEARTH and STERN (1971, 1979) for sure pillow lava samples. Mean values for K_2O are lower in the Zermatt-Saas zone than in the Antrona zone (0. 15 and 0.22 wt % respectively). For P_2O_5 one observes the contrary: the mean for the Zermatt-Saas zone is higher (0.3 wt %) than for the Antrona zone (0.2 wt %, fig. 3).

In the Zr-Y-Ti-triangle of fig. 5, the Antrona zone exhibit again much less scatter than the Zermatt-Saas zone. The meta-volcanics of the Zermatt-Saas zone are often richer in Zr and poorer in Y and show considerably more scatter in Y than the Antrona zone. Consequently half

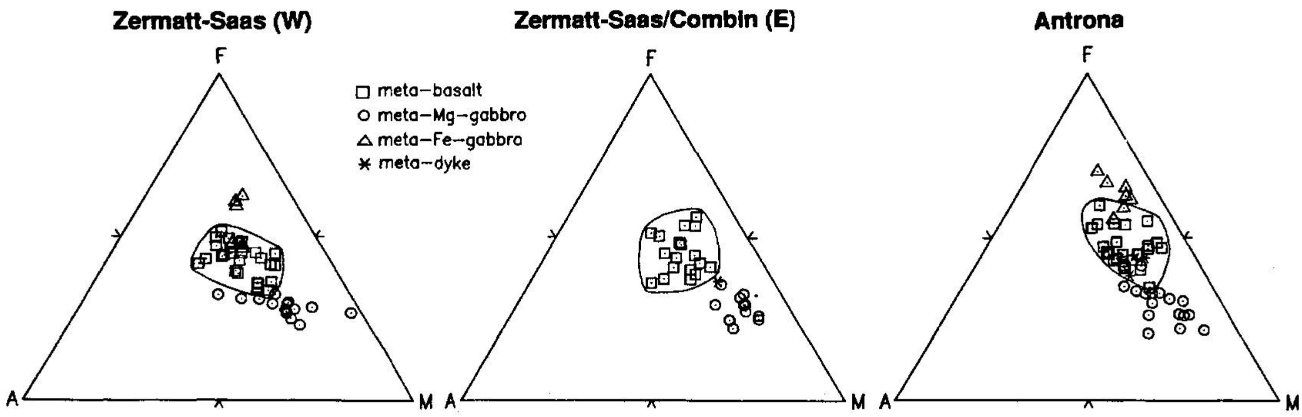

Fig. 2 Mafic rock compositions in the igneous AFM- diagram in weight % as a function of the different regions (A: K_2O+ Na_2O, M:MgO, F: FeO (tot). This diagram includes the important major elements and shows that there is little overlap between the meta-gabbros and the meta-basalts (surrounded by a line).

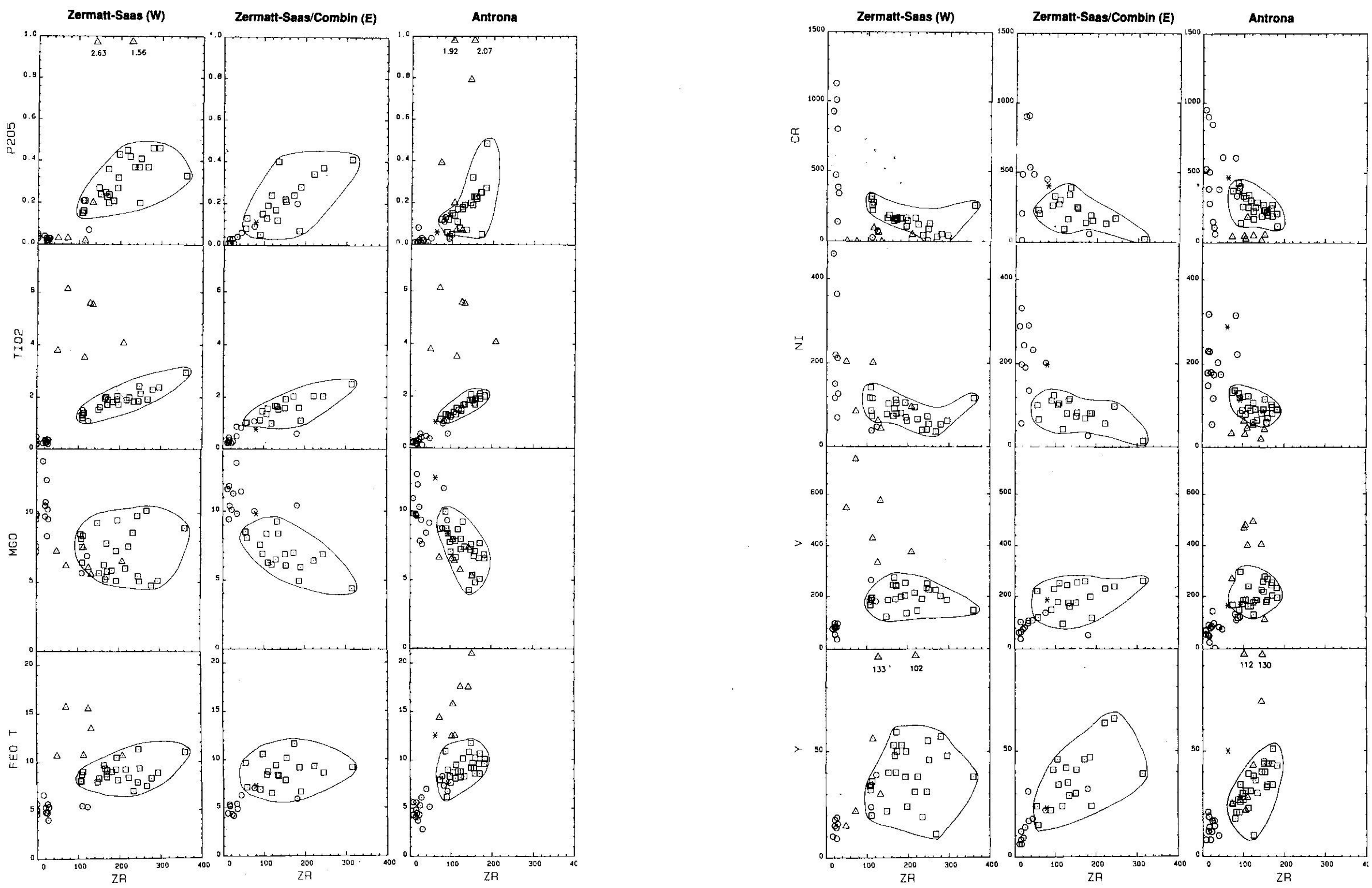

Fig. 3 Variation of some elements of mafic rocks in the three different regions. Circles: meta-magnesiogabbros, stars: meta-dikes, squares: meta-basalts, triangles: meta-ferrogabbros.
The area surrounded by a closed line in each diagram emphasizes the meta-basalts. Some extreme values are shown at the upper limit of the diagrams with an indication of the true value (P_2O_5, Y). FeO_T: total iron. The uncertainty (2 sigma) is always equal or smaller than the size of the symbols.

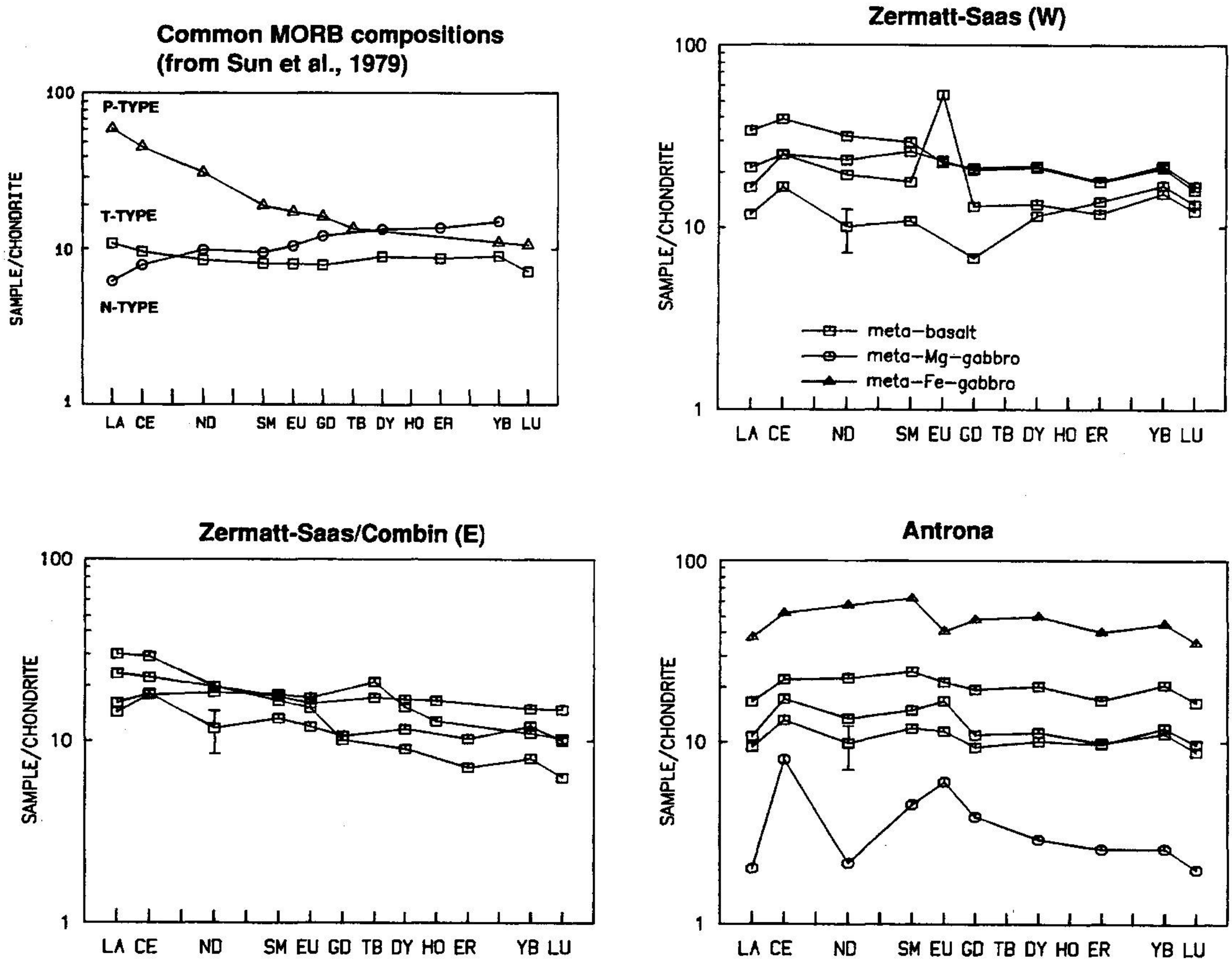

Fig. 4 Rare earth element patterns of mafic rocks of the three regions, normalized with the chondrite composition of CORYELL et al. (1963): La 0.34 ppm, Ce 0.89, Nd 0.65, Sm 0.210, Eu 0.081, Gd 0.28, Tb 0.052, Dy 0.325, Ho 0.078, Er 0.213, Yb 0.20, Lu 0.035. The Eu-anomaly of one sample seems to indicate that plagioclase has cumulus character. Uncertainties (2 sigma) correspond to to the size of the symbols, except for Nd (marked with a typical error bar). See also table 3.

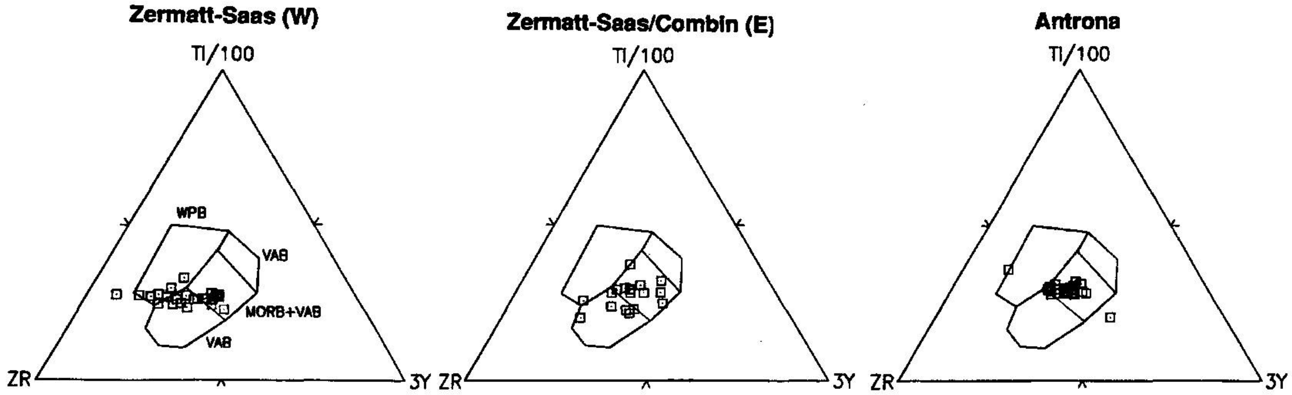

Fig. 5 Incompatible element of the meta-basalts in the Ti-Y-Zr (ppm) diagram of PEARCE and CANN (1973). VAB: modern volcanic (island) arc rocks, MORB: modern mid-ocean ridge and back arc basalts, WPB: within plate basalts.

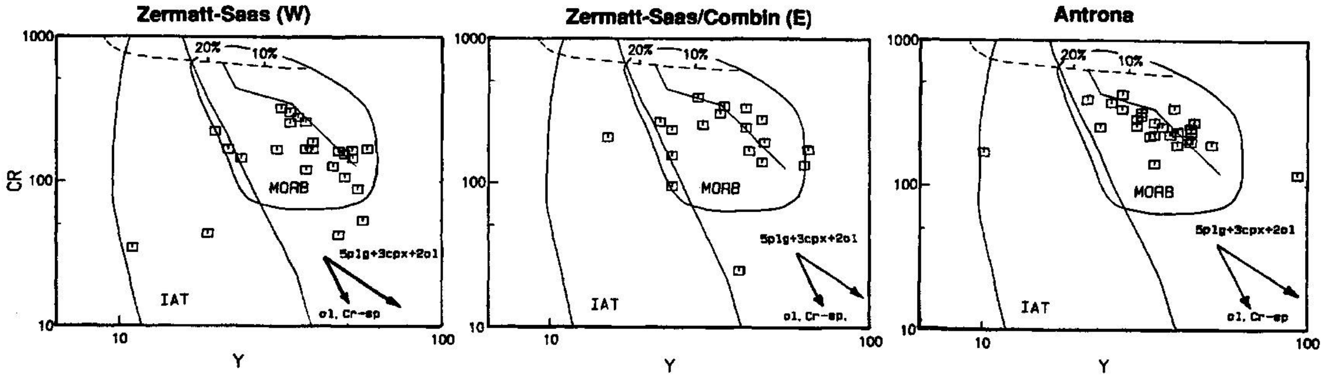

Fig. 6 Yttrium-chromium plot (ppm) to discriminate oceanic ridge basalts (MORB) from island arc tholeiites (IAT). The horizontal dashed line shows the partial melting path with the amount of mantle melting indicated in %). The subvertical line marks the fractional cristallization path for typical oceanic tholeiite systems (after PEARCE, 1983 and PEARCE and NORRY, 1979), which starts at about 17% melting. Closed system fractionation segments are subvertical, open system cristallization segments subhorizontal. Arrows indicate the evolution of melt compositions corresponding to the cristallization of particular minerals: plg: plagioclase, Ol: olivine, cpx: clinopyroxene, Cr-sp: chrome-spinel (after HÖCK and MILLER, 1987).

of the points fall into the volcanic arc (VAB) or the within plate (WPB) field of fig. 5. The same tendency has been detected by BEARTH and STERN (1979), DAL PIAZ et al. (1981), BECCALUVA et al. (1983a) and MASSON (1986). Part of this behavior is certainly due to the limited metasomatism discussed above (section 4.3). In the Y-Cr diagram of fig. 6, the Zermatt-Saas zone shows a wider range of values, but with only a few points in the island arc field (which again are glaucophanites of presumably metasomatic origin). In addition, the Zermatt-Saas zone has a significantly lower mean of Cr than the Antrona zone (around 150ppm instead of 300ppm, fig. 6). Patterns of incompatible trace and minor elements in normalized "spider" diagrams are, aside from the already discussed differences in Zr and Cr and K_2O, very similar for both zones (fig. 4 and 7). They show a slight enrichment of the elements situated on the left side of the diagram (series Sr-Ce of fig. 7), towards plume-type MORB-compositions a tendency which has been called "transitional" (T-type) by SUN et al (1979), cf. also WOOD et al. (1979a,b), PEARCE (1980; 1983), LE ROEX et al. (1983), and table 4. The same tendency was found by MASSON (1986) for samples from the Antrona zone and a few samples from Bannio/ Val Anzasca (combined Zermatt-Saas-Combin zone). In fact these data do not confirm the hypothesis of BECCALUVA et al. (1984a) of the normal (N-)type MORB-character of the Zermatt-Saas zone as opposed to the T-type character of the Antrona zone. Both have the same patterns, even with a slightly more pronounced enrichment for the Zermatt-Saas zone.

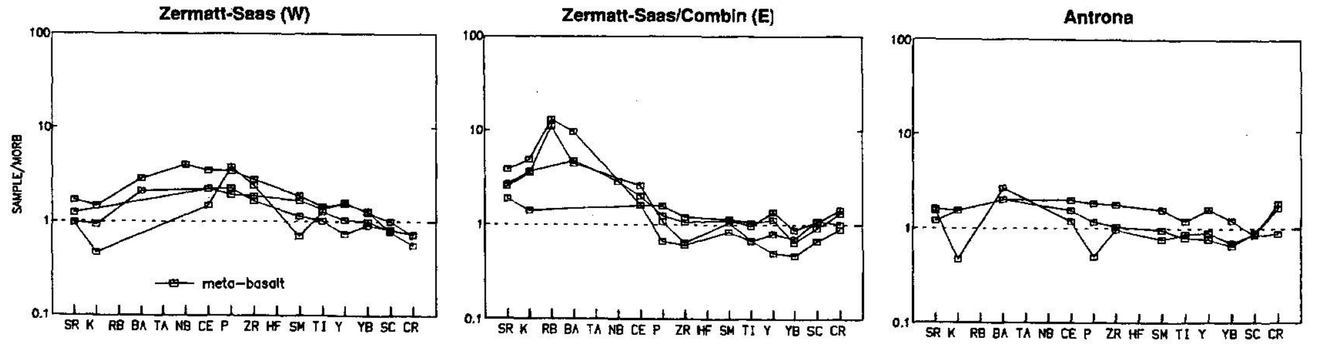

Fig. 7 Comparison of the common trace element contents (as ppm ratios) of typical basaltic rocks with the "normal MORB"-composition of PEARCE (1980, 1983). Certain samples of the eastern Zermatt-Saas/ Combin region show an enrichment in K and Rb, which we attribute to metasomatism. The samples shown are the same as in fig. 4. If an element is omitted in a line pattern, its value is below two times the detection limit, i.e. the true normalized value is lower than indicated by the line at this point.

Only a few analyses are available for dikes (star symbol in fig. 2 to fig. 8). Their composition lies typically between meta-gabbros and meta-basalts with high Cr- and MgO- and low TiO_2-values and indicate a less evolved magmatic history.

4.5. MAFIC PLUTONIC ROCKS

Because magmatic mineral phases have been preserved rarely, protoliths of metagabbroic rocks are identified either based on their coarse grained texture or on major and minor element patterns (fig. 2 and 3). For most samples chemically identified as plutonic rocks, there is also textural and mineralogical evidence for the plutonic nature of the sample in question (most of them are light green, coarse grained, epidote-rich rocks). Three groups can be recognized (fig. 8): (1) rare very Mg-rich troctolitic and olivine-gabbroic rocks with X_{Fe}-values below 0.3, (2) rocks with X_{Fe}-values between 0.3 and 0.5

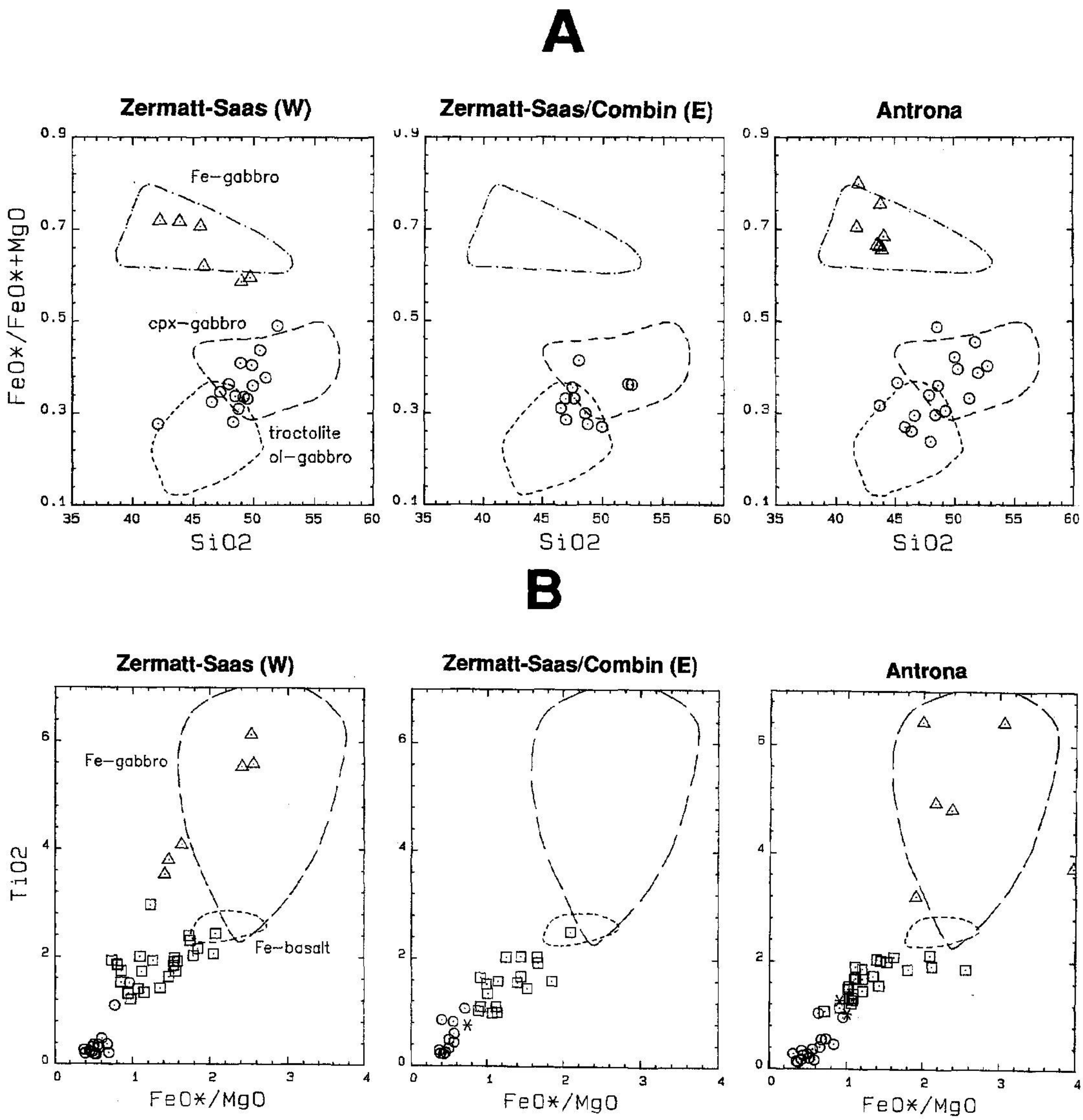

Fig. 8 Compositional variation in weight % of gabbroic rocks of the three regions investigated, compared to compositional fields of about 30 modern analogues compiled from the literature (COLOMBI, 1988). A: discrimination of magnesio- and ferrogabbros. B: discrimination of ferrogabbros from ferrobasalts (FeO*: total Fe as FeO). Circles: meta-magnesiogabbros, stars: meta-dikes, squares: meta-basalts, triangles: meta-ferrogabbros.

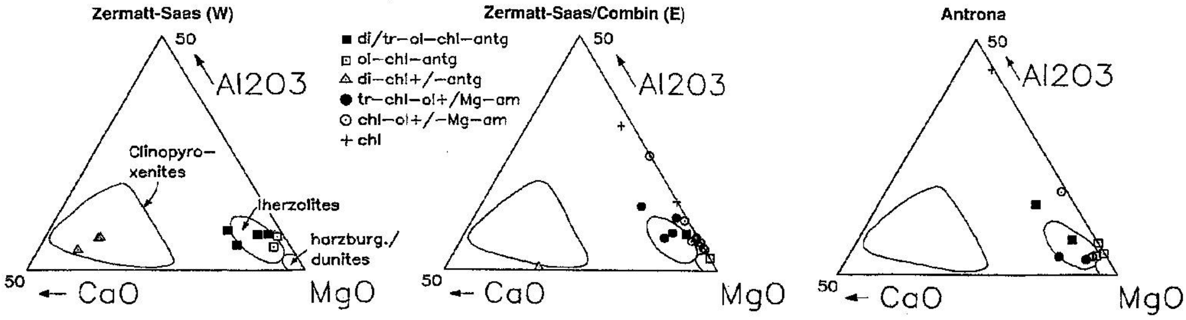

Fig. 9 Ultramafic rocks in the MgO-Al_2O_3-CaO weight % diagram of NICOLAS and JACKSON (1972), compared to peridotitic protoliths compiled from the literature (COLEMAN, 1977; ERNST and PICCARDO, 1979; BONATTI and HAMLYN, 1981). The appropriate mineral assemblages are indicated with different symbols (see legend; meaning of mineral abbreviations see table 2).

corresponding to plagioclase- pyroxene-gabbros ("gabbros" of SERRI, 1980; SERRI et al., 1985) and (3), a more Fe-rich group of ferrogabbros with X_{Fe}- values > 0.6, typical for late stage tholeiitic differentiation. The latter group could theoretically overlap with ferrobasalts or ferrodiorites, but as fig. 8B clearly shows, the twelve samples analyzed fall outside the ferrobasalt-field. Ophiolitic ferrodiorites often have increased phosphorus contents of 0.5 to 3%, due to the presence of apatite (SERRI, 1980). Two samples from the western region and one from the northeastern region fall within these limits (e.g. sample ZS 353 in table 2B). In contrast to other ophiolite regions of the Western Alps (e.g. BERTRAND et al., 1987), no plagiogranites have yet been found in the area investigated.

4.6. ULTRAMAFIC ROCKS

In all three regions, the trends observed during petrographic inspection are confirmed by the bulk rock chemistry: Al- and Ca-poor dunitic and harzburgitic compositions are limited to strongly deformed, and probably Ca-depleted serpentinites; most rocks contain typical Al_2O_3 contents of lherzolites and pyroxenites (fig. 9), comparable to other western Mediterranean ultramafics (ERNST and PICCARDO, 1979, BECCALUVA et al., 1984b; NICOLAS, 1984; POGNANTE et al., 1986; ISHIWATARI, 1985). In detail, there are some remarkable differences between the Zermatt-Saas and the Antrona zone. In the Zermatt-Saas zone some of the diopside-rich rocks have typical pyroxenite compositions resembling those of olivine-clinopyroxenites and websterites from non-metamorphic regions (as studied for example by COLEMAN, 1977; BONATTI and HAMLYN, 1981). Many ultramafic rocks of the Zermatt-Saas zone are enriched in Ti, Fe, Cr, Ni and Co with respect to similar rock types of the Antrona zone (fig. 10). In the very eastern part of the Zermatt-Saas/Combin zone, E of Malesco/Valle Vigezzo, iron-, titanium and phosphorous-rich, nickel-poor rocks occur (fig. 10).

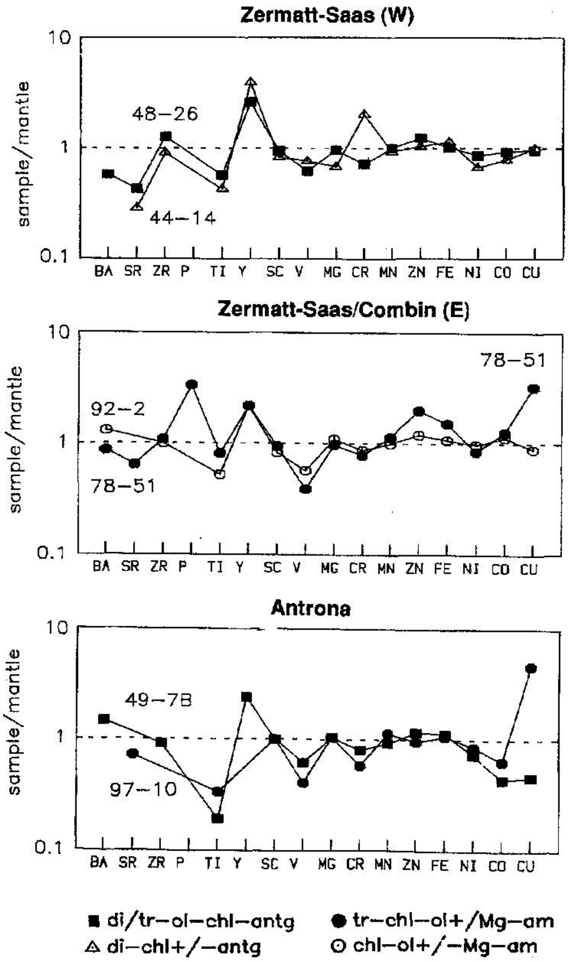

Fig.10 Comparison of a series of elements of ultramafic rocks with the lherzolitic mantle rock composition of JAGOUTZ et al. (1979). All analyses are normalized to water free compositions. Elements expressed as molecular weight %: Fe: FeO, Mn: MnO, Mg: MgO, Ti: TiO_2, P: P_2O_5; all others as elemental ppm. Meaning of mineral abbreviations: table 2.

5. Discussion

5.1. VOLCANISM AND SEDIMENTARY ENVIRONMENT

The present study confirms with statistically representative populations that metabasalts from this part of the Mesozoic Piemonte-Ligurian ophiolites are comparable to tholeiitic basalts erupted at mid-oceanic or marginal basin ridges during the last 30 million years (MORB). Although major and minor element contents vary considerably beween the different regions, their rare earth patterns (REE) are practically identical. Their "transitional" character with slight enrichment in the light REE is comparable with present day ridge segments which are influenced by a deep or continental light REE enriched mantle (either hot spots, a young ocean developed from continental rifts or in back arc marginal basins, cf. MENZIES and HAWKESWORTH, 1987; SAUNDERS and TARNEY, 1984). Preliminary results on metabasalts from the Tsaté nappe overlying the Zermatt-Saas zone show the same trace element patterns, confirming the general "transitional" character for the whole Piemonte-Liguria metabasalts of the West-Central Alps.

The major compositional differences between the Zermatt-Saas and the Antrona zone concern the much greater variance and the often spilitic character of the former. The higher Zr and lower Cr contents of the Zermatt-Saas volcanics indicate a somewhat more evolved magmatic evolution of these rocks than those of the Antrona-zone (possibly olivine-Cr-spinel fractionation, cf. fig. 6). The presence of pillow structures, the metalliferous sediments and the known massive sulfide deposits in the Zermatt-Saas zone at large (CASTELLO, 1981) implies the presence of pillow volcanoes (SCHMINCKE, 1986) and an intense syn- and posteruptive interaction with seawater, as it is typical for the slowly spreading North-Atlantic ridge. However, the homogeneous thick masses of basaltic material of the Antrona zone correspond most likely to massive and repeated sheet flows, as they are typical for present day fast spreading ridge segments, as the East Pacific rise (MACDONALD, 1982). Apart from the manganiferous quartzites which are missing in the Antrona zone, the actual knowledge about the overlying carbonate-dominated sediments does not allow a detailed comparison and subsequent conclusions.

5.2. LOWER OCEANIC CRUST AND UPPER MANTLE

At this level of the oceanic lithosphere the two zones investigated are rather similar. Dikes occur mainly in ultramafic rocks and magnesiogabbros and do not form a proper sheeted dike complex, a feature that could indicate a rather modest ridge system for both zones. Similarly, the relative presence of ferrogabbros and the absence of plagiogranites is shared by both zones. In both zones relatively undepleted mantle fragments (lherzolites and pyroxenites) dominate. In addition, in both zones considerable volumes seem to have escaped oceanic serpentinization prior to the alpine orogeny. However, their trace element content is sufficiently different to reject a close relationship between the two mantle regions involved.

5.3. POSSIBLE PALEOGEOGRAPHIC SITUATIONS

The fact that the two ophiolites zones of Zermatt-Saas and Antrona surround the continental Monte Rosa nappe almost completely (fig. 1), suggest a common paleogeographic origin for them. However, 3 km are missing to make the envelope complete. The geochemical data presented above reveal minor, but systematic differences between the two zones, which supports a separate magmatic history for them. On the other hand the relatively large differences of MOR- basalts on several present day ridges (WOOD et al., 1979b, LE ROEX et al., 1983); shows that considerably different rocks can originate from the same ridge system. Therefore, it seems, based on the present day knowledge, that the problem of a possible cogenetic nature of the two zones cannot be solved unambiguously. Instead, the following two models are equally probable (fig. 11):

– *Model (1):* the two zones correspond to two ocean basins of maximum 20 to 50km width, separated by a suboceanic or emerged platform, which is underlain by continental crust (possibly made up of what is presently the Monte Rosa nappe and the Furgg zone as defined by MARTIN, 1982, in the west and the Margna nappe in the east, cf. TRÜMPY, 1975). The Zermatt-Saas zone would then correspond to the southern, slowly spreading part of the main Piemonte-Liguria ocean, which was characterized by abundant pillow volcanoes with important seawater interaction and hydrothermal activity. The present day Arosa-Platta nappe and the Viso ophiolites are possible continuations to the east and to the west respectively (WEISSERT and BERNOULLI, 1985; LAGABRIELLE, 1987; LEMOINE and TRÜMPY, 1987). In this model the Antrona zone would lie farther to the north, adjacent to the Briançon-

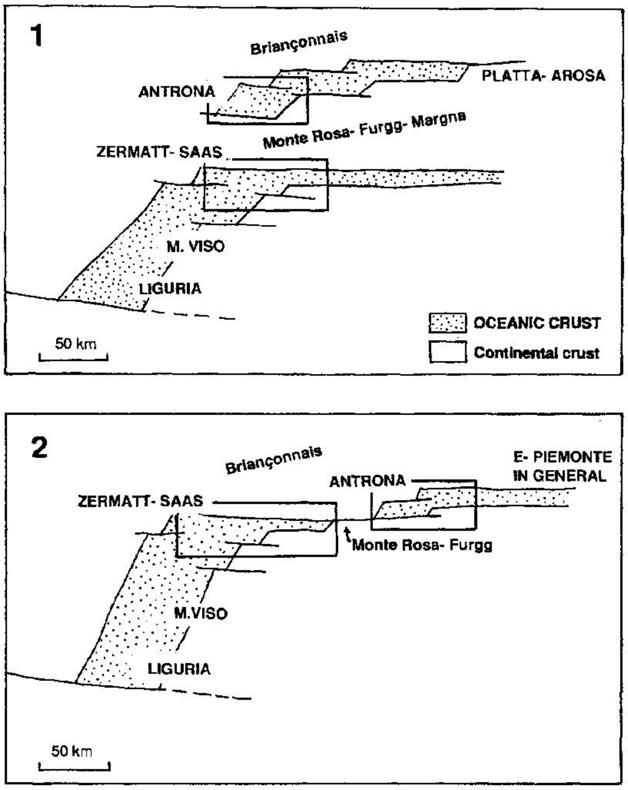

Fig. 11 Possible paleogeographic relations between the Zermatt-Saas and the Antrona zone during the upper Jurassic. The general shape of the Piemonte basin is inspired by LAGABRIELLE (1987). 1: two basin model. 2: one basin model.

nais platform (today Siviez-Mischabel nappe; cf. ESCHER, 1988), possibly forming the western end of a oceanic basin that comprised once the present-day Val Malenco-Monte del Forno ophiolites in the east (PERETTI and KÖPPEL, 1986). In this faster spreading environment, massive sheet flows seem to have been formed within a relatively short time period.

– *Model (2):* The two zones have been part of the same Piemonte-Liguria ridge system, but formed different sectors, separated by transform faults or continental rifts, involving the present day Monte Rosa nappe and the Furgg zone. Conceivably different degrees of crystal fractionation and regional mantle heterogenities produced the differences in the geochemical patterns of the two zones. It is to hope that close-up looks at actual examples of continental rifting and subsequent spreading or faulting (KELTS, 1981; STAMPFLI and MARTHALER, 1989) together with very detailed field data will one day allow to determine the most likely of the two models.

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