Geochemistry of metabasalts from ophiolitic and adjacent distal continental margin units: Evidence from the Monte Rosa region (Swiss and Italian Alps)

Julia Kramer1, Rainer Abart1, Othmar Müntener2, Stefan M. Schmid1 and Willem-B. Stern1

Abstract

In this paper we present new whole rock analyses of amphibolites from the ophiolitic and adjacent continental tectonic units in the Monte Rosa region. Mg numbers and Ni contents indicate that these amphibolites were derived from fractionated magmas with compositions ranging from E- to N-MORB. Based on their Ni, Ti, REE and Nb systematics, the metabasalts from the ophiolitic Zermatt-Saas and Antrona units and from the continental units of the Furgg zone and the Portjengrat unit are ascribed to a common origin. They represent a coherent suite ranging from T- to N-MORB. In contrast, amphibolites from the continental Siviez-Mischabel and Monte Rosa nappes were derived from enriched MORB and/or gabbroic precursors, which are not related to the metabasalts from the ophiolites, the Furgg zone or the Portjengrat unit.

The geochemical differences between the basalts of the ophiolitic Zermatt-Saas and Antrona units and the adjacent continental Furgg zone and the Portjengrat unit are very subtle. Most mafic rocks were derived from low to moderate degrees of melting of an N-MORB type mantle source. Some compositional parameters such as (Ce/Sm)n, Zr* and (Nb/Zr)n indicate a transition from T-MORB compositions in the continental units towards less enriched compositions in the ophiolitic units. Y, Ti, V and Zr concentrations are highly correlated in the metabasalts from the Furgg zone, whereas such inter-element correlations are less well defined in the metabasalts from the ophiolitic units. This renders the previously proposed interpretation of the Furgg zone amphibolites as tectonically incorporated ophiolitic fragments unlikely. Our data rather suggest that the distal continental units (Portjengrat unit and Furgg zone) and the nearby ophiolitic units were intruded by similar magmas. Portjengrat unit and Furgg zone are interpreted as a formerly continuous tectonic unit which, based on structural grounds, represents the ocean-continent transition zone of the Briançonnais to the immediately adjacent oceanic Antrona unit. However, the ambiguity in the paleogeographic provenance of the Antrona unit (Valais vs. Piemont-Liguria ocean) cannot be resolved with the existing geochemical data.

Keywords: Metabasalt, geochemistry, continental crust, Furgg zone, Monte Rosa, Central-Western Alps.

1. Introduction

The Western Alpine Arc is characterized by the occurrence of remnants of different Mesozoic oceanic basins (e.g. Stampfli and Marchant, 1997 and references therein: Schmid and Kissling, 2000). In the Penninic nappe edifice of the Monte Rosa region, the Zermatt-Saas and the Antrona ophiolitic units represent the remnants of oceanic crust. They are sandwiched between several slivers of continental crust, which pertain to the Monte Rosa and Siviez-Mischabel nappes, and to the Portjengrat and Stockhorn units (Escher et al., 1997). The situation is illustrated in a schematic geological sketch map of the Monte Rosa region (Fig. 1) and in a simplified N–S cross-section (Fig. 2).

The paleogeographic relations were obscured in the course of polyphase Tertiary deformation. NW-directed nappe stacking started in Eocene times under eclogite facies conditions (deformation phases D1 and D2). This was immediately followed by exhumation during ongoing crustal shortening. Post-collisional SE-directed folding and oblique thrusting of the entire nappe pile (deformation phases D3 and D4) finally resulted in the complex present-day geometry (Figs. 1 and 2).

The paleotectonic reconstruction of the Monte Rosa region is still under discussion (Escher et al., 1997; Froitzheim, 2001; Keller and Schmid, 2001; Kramer, 2002). Controversies partially arise from the interpretation of mafic dykes and boudins, which occur within continental units and which possibly represent derivatives from former
Fig. 1  Sample locations in a simplified geological sketch map of the Monte Rosa region, compiled from Dubach (1998), Keller (2000), Rossler (2000), Weber (2001), Bacher (2002), Bearth (1953a, 1954a,b), Steck et al. (1999), and mapping by Kramer (2002).
Geochemistry of metabasalts from the Monte Rosa region

In the Monte Rosa region, mafic dykes and boudins are abundant in both the continental and ophiolitic tectonic units, and they occur in Paleozoic continental crystalline crust, as well as in Mesozoic cover sequences. Mafic boudins are particularly abundant in two mylonitic shear zones that overprint the nappe contacts between continental and ophiolitic tectonic units: (1) in the so-called “Furgg zone” and (2) in the “intensely strained Monte Rosa basement and cover” (Figs. 1 and 2; Kramer, 2002). Due to the abundant mafic boudins, Froitzheim et al. (2001) interpreted the Furgg zone as a tectonic mélangé with ophiolitic fragments. Other authors, however, considered the mafic boudins as dyke intrusions into continental lithosphere (e.g. Jaboyedoff et al., 1996), and the Furgg zone as an intracontinental shear zone (Escher et al., 1997; Keller and Schmid, 2001; Kramer, 2002).

In this paper we present new whole rock major and trace element data on mafic rocks collected in (1) the Furgg zone, (2) the adjacent continental Portjengrat unit and in the Monte Rosa and Siviez-Mischabel nappes as well as (3) in the ophiolitic Zermatt-Saas and Antrona units. Our own and previously published data (Becchaliuva et al., 1984; Pfeifer et al., 1989) shed light on magma sources and evolution, and on the paleogeographic relations among the tectonic units in the Monte Rosa region.

2. Geological setting

The Monte Rosa nappe forms the “backbone” of the Penninic nappe edifice west of the Lepontine dome. It is comprised of large masses of Permian granitoids and orthogneisses, which were derived from granitoid intrusions (Frey et al., 1976). These granitoids were emplaced into pre-Permian, primarily meta-pelitic paragneisses with subordinate mafic rocks (Hunziker, 1970). The present-day geometry of the Monte Rosa nappe is largely controlled by a large-scale SSE-facing D4 fold, referred to as “Vanzone backfold” by Milnes et al. (1981) and Escher et al. (1988, 1997). The ophiolitic Zermatt-Saas and Antrona units form an almost complete envelope around the continental Monte Rosa nappe, except for the area between Gornergrat and Monte della Preja, where only isolated slivers of ophiolites are present (Fig. 1).

The Furgg zone (FZ in Figs. 1 and 2) and the intensely strained Monte Rosa cover and basement (ISMR in Figs. 1 and 2) represent up to one km thick mylonitic shear zones found north and south of the Monte Rosa main crest, respectively. They overprinted basement-cover contacts of the continental tectonic units, as well as nappe contacts between ophiolitic and continental tectonic units during WNW-directed nappe stacking (deformation phases D1 and D2; Kramer, 2002). Mylonitic shearing resulted in the superposition of two phases of isoclinal and/or sheath folding affecting the nappe contacts between Zermatt-Saas unit and Monte Rosa nappe in case of the ISMR, and between Portjengrat and Stockhorn unit, Monte Rosa nappe and Antrona unit in case of the FZ, respectively (see Fig. 2; Kramer, 2002).

Subsequent reactivation of the Furgg zone during syn-D3 and syn-D4 shearing partly led to the imbrication of isoclinal D1 and D2 folds, now forming isolated fold cores that consist of a varie-
ment? base-

Several larger coherent imbricates of ultrama-

dins found in both Furgg zone and intensely

strained Monte Rosa basement and cover, howev-

er, are considered as intrusions of former dykes

and sills into continental lithosphere, that were

overprinted by mylonitic shearing later. Hence,

these mafic boudins are regarded as part of both

shear zones (FZ and ISMR) overprinting contin-

ental tectonic units. It is one of the aims of this

publication to test this structural interpretation

by adding geochemical data. Note that our struc-
tural interpretation differs from the view of

Froitzheim (2001), who considers both the large

imbricates of ultramafics and the small mafic bou-
dins as ophiolitic imbricates and defines the Furgg
zone as an ophiolitic subduction mélangé
(Froitzheim, 2001).

The intensely strained Monte Rosa basement

and cover on the southern side of the Monte Rosa

massif (ISMR) was, however, not reactivated dur-
ing D3 and D4 shearing. There, syn-D1- and D2-
shearing mainly resulted in a complex superposi-
tion of two mylonitic folding phases on basement

and cover of the Monte Rosa nappe. Because of

the abundant occurrence of mafic boudins in a

highly strained matrix, the ISMR strongly resem-
bles the Furgg zone in the field. However, the two

shear zones differ in respect to their tectonic sig-

nificance, and, as will be shown, also geochemical-

ly. Therefore, we distinguish between these two

shear zones, although some authors consider the

ISMR as part of the FZ (Dal Piaz, 1964; Froitz-
heim, 2001). In the following we will treat the

ISMR as part of the Monte Rosa nappe.

The Portjengrat unit, as well as its southern

equivalent, the Stockhorn unit, consists of contin-

ental basement and a cover series interpreted to

represent Permo-Triassic sediments. The Portjen-

grat unit is either interpreted as part of the Grand

St. Bernhard nappe system (e.g. Bearth, 1956) or

as a derivative of the Monte Rosa nappe (e.g.

Bearth, 1957; Keller and Schmid, 2001). The

Siviez-Mischabel nappe forms the central part of

the Grand St. Bernhard nappe system. Whereas

its cover comprises only Permo-Triassic rocks in

most parts of the region, a complete sedimentary

sequence of up to Eocene age is preserved in the


Since the mafic rocks that were analyzed in this

study were sampled in the Furgg zone, the ophiolitic Zermatt-Saas and Antrona units, the

continental Monte Rosa and Siviez-Mischabel

nappes, as well as in the continental Portjengrat

unit, these units will be described here in more
detail.

2.1. Furgg zone

The Furgg zone comprises the following rock
types derived from the neighbouring tectonic

units (Monte Rosa nappe and Portjengrat-Stock-

horn unit): para- and orthogneisses of Paleozoic

age, along with the adjoining meta-sedimentary

cover consisting of garnet micaschists, meta-arko-
ses, quartzites, and marbles of inferred Permo-Tri-

assic age (Bearth, 1954a,b, 1957; Klein, 1978; Ja-

boyedoff et al., 1996; Rössler, 2000; Keller and

Schmid, 2001; Bacher, 2002; Kramer, 2002). The

abundant mafic intercalations, which typically
take the form of disrupted layers and boudins are

a remarkable feature of the Furgg zone. In some

places these mafics represent more than 50% of

the rock volume on outcrop scale. In some of the

mafic boudins, eclogitic assemblages are pre-

served (Wetzel, 1972; Liati et al., 2001). As de-
scribed in the previous section, several larger co-
herent slivers comprising ultramafics and mafics

were mapped as ophiolitic imbricates derived

from the Zermatt-Saas or the Antrona ophiolitic

unit, and not as part of the Furgg zone (Keller and

Schmid, 2001; Bacher, 2002; Kramer, 2002). Be-

tween Gornergrat and Monte della Preja (Fig. 1),

the Furgg zone overprints the nappe contacts of

the Monte Rosa nappe with the Stockhorn and

Portjengrat units, respectively (Bearth, 1953a,b,

1954b, 1957; Escher and Sartori, 1991; Escher et

al., 1996; Rössler, 2000; Keller and Schmid, 2001; Bacher, 2002; Kramer, 2002). The

Within less deformed portions of the Furgg

zone rock types with a stratigraphy similar to that

of the Permo-Triassic meta-sediments in the adja-
cent Portjengrat-Stockhorn unit and Monte Rosa

nappe were mapped (Jaboyedoff et al., 1996; Kel-

ler and Schmid, 2001; Bacher, 2002; Kramer,

2002). Such a stratigraphic sequence is particular-

ly well preserved in the Passo della Preja area

(Fig. 1), where Triassic dolomite and calcite mar-
bles are associated with rauhwackes, quartzites, rauhwackes? and meta-arkoses. These Triassic marbles were in-

truded by well preserved mafic dykes (see Fig. 5 in
Jaboyedoff et al., 1996), which were collected for chemical analysis (“F4: Furgg zone marbles” in Table 1).

2.2. Zermatt-Saas ophiolitic unit

The Zermatt-Saas unit largely consists of metamorphosed ultramafic and mafic rocks (Bearth and Stern, 1971, 1979; Pfeifer et al., 1989) with a late Jurassic formation age (166–160 Ma, Gebauer, 1999). The associated meta-sediments are manganese-rich quartzites (meta-radiolarites), marbles and calcareous micaschists (“Bündner-schiefer” or “schistes lustrés”; Beach, 1976; Beach and Schwander, 1981) of probably late Jurassic to late Cretaceous age (Marthaler, 1981, 1984). The calcareous micaschists may contain meta-basalt boudins. High-pressure peak metamorphic conditions of 2.6–2.8 GPa and 590–630 °C are recorded by meta-radiolarites (Reinecke, 1991, 1998; van der Klauw et al., 1997) while conditions of 1.75–2.0 GPa and 550–600 °C are reported from the ophiolites (Barnicoat and Fry, 1986). Peak metamorphic conditions were reached during the Middle Eocene, i.e. at 44 Ma (Amato et al., 1999; Rubatto and Gebauer, 1999; Gebauer, 1999) while the retrograde greenschist facies overprint occurred during the early Oligocene (Müller, 1989; Barnicoat et al., 1995; Gebauer, 1999).

2.3. Antrona ophiolitic unit

The Antrona unit consists of metamorphosed ultramafic and mafic rocks and associated marbles and calcareous micaschists (Carrupt and Schlup, 1998; Colombi, 1989; Pfeifer et al., 1989). So far, no radiometric formation ages have been reported for the meta-basic rocks. Recently discovered eclogites (Keller, pers. comm.) probably represent the remnants of a high-pressure metamorphic event. Engi et al. (2001) related the peak metamorphic conditions found within the eastern Monte Rosa nappe to the emplacement of this nappe into the surrounding units at 35–40 Ma ago, and to the Permo-Triassic overprint occurring during the Triassic age by Dal Piaz (1966, 2001). With respect to their spectrum of rock types, boudin-rich parts of the Monte Rosa basement and its meta-sedimentary cover are rather similar to the Furgg zone and referred to as “intensely strained Monte Rosa cover and basement” (ISMR) in Fig. 1.

2.4. Monte Rosa nappe

The basement of the Monte Rosa nappe consists of pre-Carboniferous paragneisses and calc-silicate rocks (Bearth, 1952, 1954 a, b, 1957; Dal Piaz, 1966, 1971; Escher et al., 1997), which were intruded by late Carboniferous to Permian granites (310–260 Ma; Hunziker, 1970; Frey and Hunziker, 1976; Engi et al., 2001). Peak metamorphic conditions of 2.3 GPa and 520 °C were inferred from white schists within the Monte Rosa basement (Le Bayon et al., 2001) and dated at 35–40 Ma (Hunziker, 1970; Gebauer, 1999).

Meta-sedimentary strata of inferred Permo-Triassic age are rare, but partly preserved in upper Valle d’Ayas, Valle di Gressoney and Valle di Loranco (Keller, 2000; Kramer, 2002). These meta-sediments consist of garnet micaschists, metaarkoses and quartzites as well as calcite and dolomite marbles. They contain numerous mafic layers and boudins. These meta-sediments are similar to the Permo-Triassic cover of the Portjengrat unit. Yet, they were interpreted as Paleozoic in age by Dal Piaz (1966, 2001). With respect to their spectrum of rock types, boudin-rich parts of the Monte Rosa basement and its meta-sedimentary cover are rather similar to the Furgg zone and referred to as “intensely strained Monte Rosa cover and basement” (ISMR) in Fig. 1.

2.5. Siviez-Mischabel nappe

The Siviez-Mischabel nappe consists of a Paleozoic polymetamorphic basement (Bearth, 1945; Thélène et al., 1993; Escher et al., 1997) and its relatively well-preserved Permo-Mesozoic cover (i.e. Barrhorn series; Marthaler, 1984; Sartori, 1990). In contrast to all the other tectonic units described in this contribution, no eclogite facies event is documented. Nappe emplacement occurred under greenschist facies conditions, estimated at 350 °C to 450 °C and 0.4–0.6 GPa by Sartori (1990) in late Eocene times (Markley et al., 1998). The basement rocks contain numerous mafic layers and boudins (see Thélène et al., 1990; Eisele et al., 1997).

2.6. Portjengrat and Stockhorn units

The Portjengrat unit comprises basement of Paleozoic age, consisting of calc-silicates, paragneisses and orthogneisses (Huang, 1953a,b; Beach, 1945; Escher et al., 1997) and a cover of presumed Permo-Mesozoic age (Dubach, 1998). Both basement and Permo-Triassic cover contain numerous mafic layers and boudins. In Valle di Loranco, the abundance of mafic layers and boudins, as well as strain intensity, gradually increase towards the Furgg zone (Keller and Schmid, 2001). This is one of the reasons, why we regard the Furgg zone as a shear zone that overprints continental crust, in this case the Portjengrat unit.
### Table 1  Sample descriptions of the studied amphibolites, For locations see Figure 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Petrography of meta-basaltic sample</th>
<th>Host rock</th>
<th>Swiss coordinates</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1: Boudins. Furgg zone Gommergrat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99-78</td>
<td>Very fine-grained symplectite of Ab + Act; late stage large poliklitholastic, hipyidio- to idiomorphic Zo/ Czo/ Ep; Rt and Ilm rimmed by Ttn; Chl; Bl; poliklitholastic Ab</td>
<td>Garnet mica schists</td>
<td>630 425/ 92 025</td>
<td>Matttal, Gommergrat, below Stockknubel</td>
</tr>
<tr>
<td>99-85</td>
<td>Hypidio- to idiomorphic Act defining mineral lineation; Rt rimmed by Ttn; Fe-bearing carbonate; evis-shaped, deformed Zo/ Czo; Bl from Act; Chl</td>
<td>Dolomitic marbles</td>
<td>631 250/ 92 300</td>
<td>Matttal, Gommergrat, east of P. 32/3</td>
</tr>
<tr>
<td>99-86</td>
<td>Idiomorphic, poliklitholastic Grt randomly retrogressed to yellow-green Hbl and symplectite from Ab + yellow-green Act; large grains of Czo/ Zo growing on expense of symplectite; Ilm rimmed by Rt rimmed by Ttn; large grains of Ttn; WM rimmed by Czo/ Zo/ Ep; Hem</td>
<td>Quartzites</td>
<td>630 225/ 92 075</td>
<td>Matttal, Gommergrat, above Stockknubel</td>
</tr>
<tr>
<td>99-87</td>
<td>Fine-grained symplectite from Ab + yellow-green Act; large grains of Czo/ Zo growing on expense of symplectite; Ilm rimmed by Rt rimmed by Ttn; large grains of Ttn; WM rimmed by Czo/ Zo/ Ep; Hem</td>
<td>Garnet mica schists</td>
<td>630 225/ 92 075</td>
<td>Matttal, Gommergrat, above Stockknubel</td>
</tr>
<tr>
<td>F2: Boudins. Furgg zone Saastal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>99-95</td>
<td>Hypidio- to idiomorphic, zoned, yellow-green, actinolic Hbl; poliklitholastic, xenomorph Ab; Rt with reaction seams of Ttn; Hem, zoned Czo + Ep; Bl; Chl</td>
<td>Meta- arkoses</td>
<td>639 725/ 100 250</td>
<td>Saastal, below Allalin glacier</td>
</tr>
<tr>
<td>98-100</td>
<td>Latest phase: xenomorph Ab; large zoned, hypidio- to idiomorphic, unaligned Czo; Bl; partly replacing zoned Act (rim Mg-rich, core Fe-rich); Chl growing on expense of Bl; Hem; Ttn</td>
<td>Meta- arkoses</td>
<td>639 825/ 100 225</td>
<td>Saastal, below Allalin glacier</td>
</tr>
<tr>
<td>97-15</td>
<td>Latest phase: xenomorph Ab; zoned, hypidio- to idiomorphic, unaligned Czo; Bl; partly replacing zoned Act (rim Mg-rich, core Fe-rich); Chl growing on expense of Bl; Hem; Rt rimmed by Ttn</td>
<td>Meta- arkoses</td>
<td>640 350/ 100 675</td>
<td>Saastal near Mattmark</td>
</tr>
<tr>
<td>98-73</td>
<td>Latest phase: large poliklitholastic, hypidio- to idiomorphic zoned Zo/Czo; fine-grained symplectite from Ab+ Act; Act partly crystallized to larger idiomorphic grains, defining mineral lineation; Bl retrogressed to pale Chl; Ilm rimmed by Rt rimmed by Ttn; Hem, small, poliklitholastic, idiomorphic Grt, large poliklitholastic WM</td>
<td>Garnet mica schists</td>
<td>639 750/ 100 025</td>
<td>Saastal, below Allalin glacier</td>
</tr>
<tr>
<td>F3: Boudins. Furggal &amp; Valle d’Antrona</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98-77</td>
<td>Fine-grained symplectite from Ab+ Act; Act mostly recrystallized to larger hypidiorphic grains; Ab partly recrystallized to small idiomorphic grains; Bl growing at expense of Act; Rt rimmed by Ttn; Hem</td>
<td>Garnet mica schists</td>
<td>650 825/ 104 275</td>
<td>Valle d’ Antrona, W Lake Bacino dei Cavalli</td>
</tr>
<tr>
<td>98-102</td>
<td>Idiomorphic, poliklitholastic Grt randomly retrogressed to blue-green Hbl; blue-green Hbl retrogressed to symplectite from Ab + yellow-green Act; large grains of Czo/ Zo growing on expense of symplectite; Ilm rimmed by Rt rimmed by Ttn; WM; Hem</td>
<td>Garnet mica schists</td>
<td>642 550/ 101 625</td>
<td>SW-side Furggal</td>
</tr>
<tr>
<td>99-57</td>
<td>Fine-grained symplectite of Ab + Act; Act partly recrystallizing to larger grains; late stage large poliklitholastic, hypidio- to idiomorphic Zo/ Czo/ Ep; Rt rimmed by Ttn; opaque Ilm?: Chl; Bl</td>
<td>Meta- arkoses</td>
<td>644 450/ 102 075</td>
<td>NE-side Furggal</td>
</tr>
<tr>
<td>99-61</td>
<td>Very fine-grained symplectite from Ab + yellow-green Act; large grains of Czo/ Zo growing on expense of symplectite; Ilm; Rt rimmed by Ttn; WM; Hem</td>
<td>Orthogneisses</td>
<td>642 950/ 102 100</td>
<td>NE-side Furggal, Augustburgerlinne</td>
</tr>
</tbody>
</table>
Table 1  Continued.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Mineralogy</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4: Dykes &amp; sills, Furgg zone marbles, Valle di Loranco &amp; Valle di Bognanco</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98-82</td>
<td>Latest phase: poikiloblastic, hydridic to idiomorphic zoned Zr + Czo; fine-grained symplectite from Ab + Act; Act partly recrystallized to larger idiomorphic grains, defining mineral lineation; Bl retrogressed to pale Chl, Ilm rimmed by Ri rimmed by Ttn, Hmt</td>
<td>Calcitic marbles</td>
<td>652 600/ 106 875</td>
</tr>
<tr>
<td>98-68</td>
<td>Latest phase: poikiloblastic albite plagioclase, partly polysynthetic twinned, overgrowing hydridic and idiomorphic Zr + Czo; Ri rimmed by Ttn; WM; An; Kf, hypidiomorphic to idiomorphic, zoned, yellow-green, actinolitic Hbl defining mineral lineation; Hem partly retrogressed to Bl, Bl retrogressed to pale Chl</td>
<td>Calcitic marbles</td>
<td>652 075/ 106 500</td>
</tr>
<tr>
<td>99-103</td>
<td>Polikoblastic albite plagioclase, overgrowing hydridic and idiomorphic Zr + Czo; hypidiomorphic to idiomorphic, zoned, yellow-green, actinolitic Hbl; Hem partly retrogressed to Bl; Bl retrogressed to Chl; Ri rimmed by Ttn; WM</td>
<td>Calcitic &amp; dolomitic marbles</td>
<td>652 025/ 106 525</td>
</tr>
<tr>
<td>99-104</td>
<td>see 99-103</td>
<td>Calcitic &amp; dolomitic marbles</td>
<td>652 025/ 106 525</td>
</tr>
</tbody>
</table>

O1: Antrona unit |
| 98-53  | Hypidiomorphic to idiomorphic, zoned, yellow-green, actinolitic Hbl defining mineral lineation; polysynthetic twinned Pl + poikiloblastic, xenomorphic, eye-shaped, unrimmed Ab with inclusions of Ttn + Ep; zoned Czo + Ep; Rt with reaction seams of Ttn; Hem | 653 925/ 101 600 | Valle d’Antrona, near Antronapiana |
| 99-98  | see above; additionally some Fe-bearing carbonate, late-stage hypidiomorphic Ep/ Czo/ Zr | 655 450/ 108 250 | Valle di Bognanco, Alpe Vallaro |
| 99-102 | Very fine-grained symplectite of Ab + Act; Act partly recrystallized to larger grains; late-stage large poikiloblastic, hypidiop- to idiomorphic Zr/ Czo/ Ep; Rt and Ilm rimmed by Ttn; very fine-grained cubic opaques Py; Fe-poor carbonate | 652 200/ 104 300 | V. d’Antrona, NE-side Lake Bacino dei Cavalli |
| 99-105 | see 98-53, additionally large Ep/ Zr/ Czo; Chl | "Loranco amphibolite" | 649 725/ 105 200 | Valle di Loranco, path to Andolla refuge, near Alpe Campolamana |
| 98-7   | Hypidiomorphic Pl + Czo; Pl, rigid and polysynthetic twinned, saniroded; hypidiomorphic to idiomorphic, zoned, yellow-green, actinolitic Hbl defining mineral lineation; hypidiop- to xenomorphic Ttn; Chl; late carbonate sealed cracks | WM-Bi-Qz-Kfs Orthogneiss | 662 500/ 107 900 | Valle di Bognanco, 1.5 km E’ San Marco, at Simplon shear zone |

O2: Zermatt-Saas unit |
| 99-31  | Hypidiomorphic Act and also Zr/ Czo defining strong mineral lineation; Ab; Ilm rimmed by Rt and Ttn; Rt rimmed by WM; Fe-bearing carbonate | 624 675/ 84 675 | Valle d’Ayas, Mezzalama refuge |
| 99-53  | see 99-31, no pronounced mineral lineation, higher amount of idiomorphic Czo + Zr | 639 225/ 103 625 | Saastal, path from Plattjen to Britannia refuge |

C1: Sills, Siviez-Mischabel basement |
<p>| 99-14  | Poikiloblastic, hydridic to idiomorphic zoned Zr + Czo symplectically intergrown with Ab; fine-grained symplectite from Ab + Act; Act partly recrystallized to larger idiomorphic grains; Act retrogressed to Bl; Ttn, Hmt | Czo-Ep-Grt-Chl-Bi-WM-RT-Ilm-Ttn-Apt-Hem-Qz paragenesis | 624 250/ 98 350 | Matttal, NWW’ Zermatt, Luegibach |
| 99-40  | see 99-14, no symplectite, but Ab + Act; Ilm rimmed by Ttn | Para- and orthogneiss | 635 575/ 115 350 | Lower Saastal, near Zen Eisten |</p>
<table>
<thead>
<tr>
<th>C2: Boudins, Monte Rosa cover &amp; basement</th>
</tr>
</thead>
<tbody>
<tr>
<td>99-20</td>
</tr>
<tr>
<td>99-69</td>
</tr>
<tr>
<td>99-70</td>
</tr>
<tr>
<td>99-71</td>
</tr>
<tr>
<td>99-72</td>
</tr>
<tr>
<td>99-66</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C3: Sills, Portjengrat &amp; Monte Rosa cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>99-50</td>
</tr>
<tr>
<td>99-75</td>
</tr>
<tr>
<td>99-55</td>
</tr>
<tr>
<td>99-13</td>
</tr>
<tr>
<td>99-54</td>
</tr>
</tbody>
</table>
Geochemistry of metabasalts from the Monte Rosa region

3. Sample descriptions

Metabasalts sampled for geochemical analysis were taken from the Furgg zone and all adjacent units described above. Sample localities are shown in Fig. 1 and brief sample descriptions are listed in Table 1. Based on their lithologic-tectonic setting, the metabasalts are divided into three broad categories: (1) metabasalts from ophiolitic units (Antrona and Zermatt-Saas units); (2) mafic sills, dykes and boudins, found within continental basement and associated meta-sedimentary cover series (Siviez-Mischabel nappe, Portjengrat-Stockhorn unit and Monte Rosa nappe); (3) metabasalts from the Furgg zone.

3.1. Metabasalts from the Antrona ophiolitic unit (O1)

Three samples were taken from the main body of the Antrona unit (sample 99-98 near Alpe Varallo in Valle di Bognanco; sample 99-102 at Cavalli lake in Valle d’Antrona), one of them close to the contact with the Moncucco-Camughera unit (sample 98-53; Antronapiana in Valle d’Antrona). A large coherent imbricate of the Antrona unit, situated near the Simplon shear zone, was sampled at San Marco in Valle d’Antrona (sample 98-07). The “Loranco-Lappen” (Bearth, 1954b, 1957) was sampled close to Alpe Campolamana in Valle di Loranco (sample 99-105). Here the Antrona ophiolites occur within the core of an isocinal antiform (Kramer, 2002), which refolds a mappable tectonic contact between Antrona unit and Furgg zone (Keller, 2000; Bachr, 2002).

3.2. Metabasalts from the Zermatt-Saas ophiolitic unit (O2)

The Zermatt-Saas unit was sampled close to the contact with the Portjengrat-Stockhorn unit (sample 99-53 from Mittaghorn in Saastal) and with the Monte Rosa nappe (sample 99-31 from Rifugio Mezzalama in Valle d’Ayas), respectively. Sample 99-53 is from the northern limb of the D3 Mittaghorn synform, 50 m south of the contact with the calcareous micaschists. Sample 99-31 was collected ten meters west of the contact with the highly strained sedimentary cover of the Monte Rosa nappe.

3.3. Meta-basalt sills from the continental basement of the Siviez-Mischabel nappe (C1)

Samples were taken at localities in Mattertal and Saastal. The sampling sites are structurally located in the core of the D3 “Mischabel backfold”, a south-facing kilometer-scale antiform. Samples 99-14 and 99-15 (near Zermatt in Mattertal) were collected approximately 60 m north of the basement-cover contact. Samples 99-40 and 99-41 (near Zen Eisten in Saastal) were collected within basement far off any tectonic or sedimentary contact. All samples are from up to 1.5 m thick, partly boudinaged and/or isoclinally folded foliation-parallel layers. They are interpreted as early (pre-Alpine?) sills, which intruded the paragneisses of the Siviez-Mischabel nappe and were boudinaged and folded during subsequent deformation.

3.4. Isolated meta-basalt boudins from basement and cover of the southwestern Monte Rosa nappe (C2)

This group comprises samples from the intensely strained Monte Rosa cover and basement in the southwestern part of the Monte Rosa massif (ISMR), which was considered as part of the Furgg zone by some authors (i.e. Dal Piaz, 1964; Froitzheim, 2001). Meta-basalt boudins frequently occur in paragneisses whereas they are scarce in meta-granites. Since one of the metabasalt boudins was found to be intruded by a granite of supposed late Paleozoic age (Kramer, 2002) near the Mezzalama refuge in upper Valle d’Ayas, at least some of these boudins are probably Paleozoic in age. Furthermore, paragneisses occasionally con-
tain pre-Alpine sillimanite, oriented parallel to the foliation and the principal extension direction of the embedded mafic boudins (Dal Piaz, 1966, 1971). This also suggests a Paleozoic age for these metabasalts. Since mafic boudins are abundant within paragneissises of the Monte Rosa nappe, and particularly so near the tectonic contact with the Zermatt-Saas unit, field evidence does not allow us to exclude the possibility that they may represent ophiolitic imbricates incorporated during nappe stacking.

Metabasalts from this group were sampled in Valle di Gressoney at the Alpe Bettolina (sample 99-20) and at the Plateau del Lys (samples 99-66, 99-69, 99-70, 99-71, 99-72). The Bettolina sample (99-20) stems from a 0.3 m thick boudin, whereas sample 99-69 stems from a large imbricate of approximately 25 by 12 meters in size. The other samples were collected from 3 m thick boudins. Except for sample 99-66, all sampled boudins occur in a matrix of garnet micaschists, which are believed to represent Permo-Mesozoic cover. Sample 99-66 occurs in an intensely strained matrix of isoclinally folded orthogneisses, garnet micaschists and meta-arkoses. As the sample localities are structurally situated in the flat hinge region of the D4 Vanzone antiform, the distance to the nappe contact of the overlying Zermatt-Saas unit, as inferred from cross-section (Kramer, 2002), is probably less than 100 meters. Hence the boudins could also represent tectonically incorporated ophiolitic imbricates.

### 3.5. Meta-basalt sills from the Permo-Triassic cover of the Portjengrat-Stockhorn unit and northern Monte Rosa nappe (C3)

This group of samples comprises meta-basalt occurrences, which represent intrusions into Permo-Triassic country rocks, for which mélangé formation can be excluded. Metabasalts taken from the cover of the Portjengrat-Stockhorn unit were sampled in tectonically relatively undisturbed meta-arkoses and marbles below the Mittaghorn in Saastal (samples 98-75, 99-50, 99-54, 99-55). The samples were collected from 0.6 to 1 m thick, part-

---

**Fig. 3** Total alkali versus silica diagram after Le Bas et al. (1986). The symbols are generally larger than the 3 sigma error.
ly boudinaged foliation-parallel layers, interpreted as sills or parallelized dykes.

One amphibolite was collected from the Monte Rosa unit in Valle di Loranco, i.e. from an approximately 3 m thick, boudinaged foliation-parallel layer, found in carbonate-bearing metaarkoses of inferred Permo-Triassic age (sample 99-13 at Bottarello glacier).

3.6. Metabasalts from the Furgg zone at Gornergrat (F1)

Here the Furgg zone consists of an association of paragneisses and calc-silicates of supposed Paleozoic age and a cover sequence, including garnet micaschists, meta-arkoses, quartzites and calcite-dolomite marbles of inferred Permo-Triassic age. The meta-basalt samples from this part of the Furgg zone were collected in the Stockchnubel area (samples 99-78, 99-86, 99-87) and east of P. 3223 (sample 99-85; see Table 1 for exact location). Sample 99-78 was collected from an approximately 30 by 10 m large boudin, while the other samples are from smaller boudins up to 1 m in thickness. The boudins in the vicinity of the Stockchnubel are embedded in a matrix of garnet micaschists and quartzites; the sample east of P. 3223 (sample 99-85) is surrounded by a matrix of dolomite marble.

3.7. Metabasalts from the Furgg zone in Saastal (F2)

Here the Furgg zone consists of an assemblage of highly strained, fine-grained orthogneisses and the presumed Permo-Triassic cover of garnet micaschists and subordinate meta-arkoses (see Bearth, 1954b, 1957; Rössler, 2000; Weber, 2001). It contains metabasalts, which were sampled near the Allalin glacier (samples 98-73, 98-100, 99-95) and at the river Saaser Vispa (sample 97-15). Samples from the Allalin glacier area were collected from two up to 0.5 m thick boudins (samples 98-73 and 98-100) and one 3 m thick boudin (sample 99-95), all embedded in garnet micaschists and meta-arkoses. Sample 97-15 (river Saaser Vispa) was collected from a 0.8 m thick boudinaged layer embedded in meta-arkoses.

3.8. Metabasalts from the Furgg zone in Furggtal and in Valle d’Antrona (F3)

Here the Furgg zone mostly comprises the same lithologies as described for Saastal. However, in Valle d’Antrona quartzites occur less and marbles more frequently in the Furgg zone. Mafic boudins are particularly abundant, and some of them are several tens of meters long.

Metabasalts from Furggtal were collected from up to 1.5 m thick boudins embedded in a matrix of meta-arkoses (sample 99-57), garnet micaschists (sample 98-102) and orthogneisses (sample 99-61). The meta-arkoses are intercalated with garnet micaschists, at least partly due to isoclinal folding. One meta-basalt sample collected from Valle d’Antrona (sample 98-77 from west of Lake Cavalli) stems from a 1 m thick boudin in a matrix of garnet micaschists. It was collected 100 m east of and structurally below the contact to the basement of the Monte Rosa nappe.

3.9. Dykes and sills in marbles of the Furgg zone (F4)

This group of Furgg zone samples comprises metabasalts found in marbles of the Furgg zone in the Monte della Preja area. Samples stem from Alpe Preja (sample 98-82) and from the core of a synform at the Passo della Preja between Valle di Loranco and Valle di Bognanco (samples 98-68, 99-103, 99-104). Here the metabasalts may readily be interpreted as representing sills or parallelized dykes, which intruded Triassic marbles.

The post-Triassic intrusion age is particularly evident for sample 99-104, which was collected from a 0.3 m thick discordant dyke described by Jaboyedoff et al. (1996, see there Fig. 5), obviously post-dating the Triassic marbles. Samples 98-82 and 98-68 were collected from 0.8–1.5 m thick foliation-parallel boudins, sample 99-103 from a 0.6 m thick foliation-parallel layer.

4. Mineralogical composition of metabasalts

All samples are fine-grained, foliated amphibolites, with a grain size of generally less than 2 mm. Mineral parageneses (see Table 1) include yellow and green actinolitic hornblende (act), albitic plagioclase (ab), clinozoisite (cz), zoisite (zo), epidote (ep), chlorite (chl), white mica (wm) and titanite (tn) +/- biotite (bt). This assemblage is interpreted to have formed during retrograde greenschist facies overprint. Accessory minerals are rutile (rt), ilmenite (ilm), +/- hematite (hem), +/- pyrite (py), +/- zircon (zr), +/- quartz (qtz), +/- calcite (cc).

Relics of an earlier high-pressure metamorphic event could only be identified in amphibolites collected from the Permo-Mesozoic sedimentary cover of the Portjengrat-Stockhorn unit and the Monte Rosa nappe, where abundant garnet is found. This garnet is partly retrogressed to blue-green hornblende and/or chlorite. Wetzel (1972) and Liati et al. (2001) also describe relics of
### Table 2

Analytical data, Mg# number, Zr/Y ratio and Ce\_n/Yb\_n ratio. For the Ce\_n/Yb\_n ratio, the Ce and Yb values are chondrite-normalized; normalization values were taken from Boynton (1984).

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>FeO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>Mg#</th>
<th>Zr/Y</th>
<th>Ce_n/Yb_n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.75</td>
<td>61.61</td>
<td>9.62</td>
<td>9.96</td>
<td>6.57</td>
<td>9.64</td>
<td>3.73</td>
<td>3.31</td>
<td>1.02</td>
<td>0.23</td>
<td>0.003</td>
</tr>
<tr>
<td>2</td>
<td>51.82</td>
<td>61.80</td>
<td>9.64</td>
<td>9.68</td>
<td>6.48</td>
<td>9.46</td>
<td>3.67</td>
<td>3.27</td>
<td>1.03</td>
<td>0.25</td>
<td>0.003</td>
</tr>
<tr>
<td>3</td>
<td>51.72</td>
<td>61.70</td>
<td>9.65</td>
<td>9.70</td>
<td>6.50</td>
<td>9.51</td>
<td>3.71</td>
<td>3.30</td>
<td>1.03</td>
<td>0.25</td>
<td>0.003</td>
</tr>
<tr>
<td>4</td>
<td>51.77</td>
<td>61.97</td>
<td>9.61</td>
<td>9.65</td>
<td>6.50</td>
<td>9.50</td>
<td>3.72</td>
<td>3.31</td>
<td>1.03</td>
<td>0.25</td>
<td>0.003</td>
</tr>
<tr>
<td>5</td>
<td>51.62</td>
<td>61.70</td>
<td>9.62</td>
<td>9.68</td>
<td>6.48</td>
<td>9.45</td>
<td>3.66</td>
<td>3.27</td>
<td>1.03</td>
<td>0.25</td>
<td>0.003</td>
</tr>
<tr>
<td>6</td>
<td>51.63</td>
<td>61.70</td>
<td>9.62</td>
<td>9.68</td>
<td>6.48</td>
<td>9.45</td>
<td>3.66</td>
<td>3.27</td>
<td>1.03</td>
<td>0.25</td>
<td>0.003</td>
</tr>
</tbody>
</table>

---

**Note:** Mg# number, Zr/Y ratio and Ce\_n/Yb\_n ratio are provided for each sample. Normalization values were taken from Boynton (1984).
<table>
<thead>
<tr>
<th>Table 2 Continued.</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Tectonic unit</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1: Boudins, Furgg zone</td>
<td>Jk 99-78</td>
</tr>
<tr>
<td>Gornergrat</td>
<td>Jk 99-85</td>
</tr>
<tr>
<td>Jk 99-86</td>
<td>110.06</td>
</tr>
<tr>
<td>Jk 99-87</td>
<td>128.70</td>
</tr>
<tr>
<td>Jk 99-94</td>
<td>102.24</td>
</tr>
<tr>
<td>Jk 97-10</td>
<td>111.75</td>
</tr>
<tr>
<td>Jk 96-110</td>
<td>100.80</td>
</tr>
<tr>
<td>Jk 97-77</td>
<td>116.88</td>
</tr>
<tr>
<td>Jk 96-86</td>
<td>114.81</td>
</tr>
<tr>
<td>Jk 96-68</td>
<td>108.32</td>
</tr>
<tr>
<td>Jk 96-103</td>
<td>125.72</td>
</tr>
<tr>
<td>Jk 96-105</td>
<td>120.30</td>
</tr>
<tr>
<td>Jk 96-58</td>
<td>101.08</td>
</tr>
<tr>
<td>Jk 96-98</td>
<td>118.19</td>
</tr>
<tr>
<td>Jk 96-98</td>
<td>125.85</td>
</tr>
<tr>
<td>Jk 96-95</td>
<td>98.35</td>
</tr>
<tr>
<td>Jk 96-68</td>
<td>90.85</td>
</tr>
<tr>
<td>Jk 96-91</td>
<td>123.37</td>
</tr>
<tr>
<td>Jk 96-100</td>
<td>100.05</td>
</tr>
<tr>
<td>O1: Antracite unit</td>
<td>Jk 99-114</td>
</tr>
<tr>
<td>Jk 99-15</td>
<td>180.85</td>
</tr>
<tr>
<td>Jk 99-40</td>
<td>149.31</td>
</tr>
<tr>
<td>Jk 99-40</td>
<td>203.19</td>
</tr>
<tr>
<td>Jk 99-70</td>
<td>186.26</td>
</tr>
<tr>
<td>Jk 99-90</td>
<td>154.48</td>
</tr>
<tr>
<td>Jk 99-69</td>
<td>85.21</td>
</tr>
<tr>
<td>Jk 99-79</td>
<td>88.50</td>
</tr>
<tr>
<td>Jk 99-67</td>
<td>118.20</td>
</tr>
<tr>
<td>C1: Boudins, Monte Rosa cover &amp; basement</td>
<td>Jk 99-70</td>
</tr>
<tr>
<td>Jk 99-50</td>
<td>92.44</td>
</tr>
<tr>
<td>Jk 99-85</td>
<td>89.76</td>
</tr>
<tr>
<td>Jk 99-55</td>
<td>104.15</td>
</tr>
<tr>
<td>Jk 99-54</td>
<td>92.56</td>
</tr>
</tbody>
</table>

| Geochemistry of metabasalts from the Monte Rosa region | 13 |

Proofreading Geochemistry of metabasalts from the Monte Rosa region
high-pressure assemblages within amphibolites of the Furgg zone (see below). Two generations of albitic plagioclase and actinolitic hornblende are common. A first generation of plagioclase and hornblende (ab 1, act 1) forms symplectites which partly replace blue-green hornblende and, probably more commonly, former omphacite (see Kramer, 2002). These symplectites are replaced by a second generation of synkinematically grown albite and actinolitic hornblende (ab 2, act 2), or by post-kinematic clinozoisite and zoisite. The retrograde breakdown of garnet produced chlorite, zoisite/ clinozoisite and more rarely blue-green or yellow-green hornblende. Titanite is commonly the breakdown product of ilmenite and rutile, but also occurs as xenoblastic grains in the matrix.

5. Whole rock chemistry

5.1. Analytical methods

Samples were carefully selected to avoid cracks or veins, and weathered crusts were removed. The samples were crushed in a jawbreaker and ground in an agate mill to grain sizes < 60 µm. For major element analyses 300 mg of ignited powder were mixed with 4700 mg of dried Li₂B₄O₇ and fused to glass discs. The XRF analyses (SRS-3400 Bruker-AXS) were done at the geochemical laboratory of the University of Basel. The statistical uncertainty at the 3 sigma-level is less than 2 relative % for all major elements, except for K₂O (5–10 relative %) and TiO₂ (2–20 relative %). Trace elements were analyzed by ICP-MS at the CNRS in Nancy, France. For this purpose, 300 mg of sample powder were fused with LiBO₂ and dissolved in HNO₃. Detection limits range from 0.01 to 6 ppm (Table 2). Uncertainties are usually less than 10 relative % except for values close to the detection limit.

5.2. Major and trace element composition

The major and trace element compositions of the amphibolites are given in Table 2. Additional analyses from the Zermatt-Saas and Antrona ophiolitic units may be found in Pfeifer et al. (1989). The SiO₂ concentrations generally fall into a range between 46 and 52 wt%. In the total alkali versus silica (TAS) diagram after Le Bas et al. (1986), the analyses plot into the basalt and basaltic andesite fields (Fig. 3). However, all samples are amphibolites and it is therefore likely that alkali metals were affected to some degree by either ocean floor (hydrothermal) and/or regional metamorphism (Pearce, 1976; MacGeehan and

![Fig 4](image-url) Concentrations of selected major and trace elements versus Mg# (MgO/(MgO+FeOtot) in moles); symbols as in Fig. 3.
MacLean, 1980; Gelinas et al., 1982; Mottl, 1983; Rollinson, 1983; Saunders and Tearney, 1984). The same is true for other large ion lithophile elements (LILE; Cs, Rb, Ba, Pb and Sr), which is reflected by large concentration variations in the different samples (see Table 2 and Fig. 7). This makes it difficult to use major elements and especially the alkali metals to decipher the igneous history of the amphibolites. Therefore we mainly rely on trace elements in the following discussion, which are considered to be less mobile during alteration and metamorphism (Dostal and Capedri, 1979; Grauch, 1989; Gelinas et al., 1982; Humphris, 1984).

The large range of MgO (4.06–8.62 wt%) coupled with relatively low Ni contents (< 140 ppm, Table 2, see also Fig. 8) indicates that all amphibolites are derived from differentiated magmas and do not represent unmodified liquids that were in equilibrium with the mantle. This is illustrated in Fig. 4. Mg# (molar Mg/(Mg+Fe<sub>tot</sub>)) are less than 65 and decrease with increasing incompatible element contents.

Harker diagrams of selected major and trace elements (Fig. 5) show that incompatible elements (Ti, Y, V) are positively correlated with Zr. These correlations are well defined for the samples from the Furgg zone, but less clear for the

![Graph showing concentrations of selected major and trace elements versus Zr concentrations; symbols as in Fig. 3.](image-url)
ophiolitic units and the C1 and C2 units. This suggests that the Furrgg zone amphibolites were
derived form a single cogenetic magma suite, where-
as a more heterogeneous magma source and/or a
more heterogeneous magma evolution was asso-
ciated with mafic magmatism in the ophiolitic
units.

The Zr/Nb ratio in metabasalts from the
ophiolitic units is about 30 (Fig. 5). Samples from
the Furrgg zone generally plot at somewhat lower
Zr/Nb ratios indicating a higher T-type MORB af-
finitiy than the classical N-type MORB of the
ophiolitic units (Wood et al., 1979).

In MORB the REE concentrations may vary
from less than 10 times chondritic in primitive ba-
salts to about 50 times chondritic in more evolved
basalts (Schilling et al., 1983; Venturelli et al.,
1981; Pearce, 1982; Cullers and Graf, 1984; Hen-
derson, 1984; Saunders, 1984; Rollinson, 1993;
Desmurs et al., 2002). Low-pressure fractional
crystallization leads to an overall enrichment of
the incompatible elements, but does not change
the slope of the REE pattern (Schilling, 1983;
Frey et al., 1976). This is why the shape of REE
patterns observed in evolved basalts largely re-

Fig. 6 Chondrite-normalized rare earth element con-
centrations, normalization values from Boynton (1984):
La: 0.11; Ce: 0.808; Pr: 0.122; Nd: 0.60; Sm: 0.395; Eu:
0.0735; Gd: 0.259; Tb: 0.0474; Dy: 0.322; Ho: 0.0718; Er:
0.21; Tm: 0.0324; Yb: 0.209; Lu: 0.0322.
REE are particularly useful for discrimination between different MORB magma types. With respect to the relative abundance of light, intermediate and heavy REE, the investigated samples fall into two broad categories (Fig. 6).

A first group shows relatively flat REE patterns with 10 to 20 times chondritic concentrations, typical for T-type MORB, with (Ce/Yb) between 1.00 and 1.76 (Table 2). This group includes all samples from the two ophiolitic units (O1 and O2), all samples from the Furgg zone (F1–F4) and the basalts of group C3 (Fig. 6). Primitive mantle-normalized trace element patterns (Fig. 7; after Sun and McDonough, 1989) indicate a consistent positive Zr anomaly, with the exception of two samples, which probably represent former gabbro cumulates (see below). Such a trace element pattern is not uncommon in basalts and is a characteristic feature of low-degree melts generated in the spinel peridotite field (e.g. Casey, 1997). Sr (and Rb, which is not shown) is highly variable and may reflect alteration processes related to the breakdown of plagioclase.

A second group of samples comprises dykes and sills from the Siviez-Mischabel basement unit (C1) and isolated boudins found within the southwestern part of the Monte Rosa basement and
These samples have highly variable REE patterns and slopes (Fig. 6). The compatible/incompatible element ratios (Fig. 8) are different from those of the first group. As can be seen from Fig. 8, the C1 and C2 samples show different Ce/Ni ratios and highly variable Nb contents. These features indicate that the C1 and C2 samples have another origin than all the other samples.

6. Discussion and conclusions

6.1 Gabbro or basaltic precursors of the amphibolites?

It is often difficult to decide from whole rock analyses of amphibolites whether they were derived from basaltic or gabbroic precursor rocks. This problem is particularly difficult to tackle if the metamorphosed mafic rocks are differentiated, because Fe–Ti-oxide gabbros are often fine-grained and resemble metamorphosed basalts. Compatible element (Ni) versus incompatible elements (Ce, Nb) covariation trends may provide a chemical criterion for the distinction between different protoliths (see Fig. 8). If samples represent a single suite of crystallized liquids (e.g. basaltic rocks), smooth negative correlations between compatible and incompatible elements are expected. As can be seen from Fig. 8, all samples from the ophiolites, the Furgg zone (with one exception) and the Portjengrat unit (with one exception) show a smooth increase of incompatible Ce and Nb with decreasing Ni content. The samples falling off the trend most probably represent cumulates. These samples are not further considered in the discussion.

Compared to the samples from the ophiolitic units, the Furgg zone and the Portjengrat unit, the samples from the Siviez-Mischabel basement (C1) and the southwestern Monte Rosa nappe (C2) exhibit generally higher LREE contents at comparable Ni (Fig. 8) and REE spectra with higher LREE/HREE ratios (Fig. 6). In addition, in the C2 group Nb is highly variable, which probably reflects different proportions of Fe–Ti oxides.
in these samples. The smooth REE spectra from the Siviez-Mischabel basement (C1) may indicate enriched MORB (e.g. Bill et al., 2000) derived from a source with initially high incompatible element content. The samples from the southwestern Monte Rosa nappe (C2) do not show any systematics with respect to incompatible elements (Fig. 8). In addition, field relations indicate a possible Paleozoic origin for some of the amphibolites from the southwestern Monte Rosa nappe. This is why we think that the C1 and C2 amphibolites cannot be directly compared with the amphibolites from the Furgg zone and the Portjengrat unit.

6.2. Possible sources of the MORB magmatism in the Furgg zone, the Portjengrat unit and adjacent ophiolitic units

In Figure 9a, the Nb/Zr and the Ce/Sm ratios of samples from the Furgg zone, the Portjengrat unit, the Antrona ophiolites and the Zermatt-Saas ophiolites are plotted and compared to basalts from Piemont-Ligurian ophiolites from outside the study area. The Ce/Sm, and the Nb/Zr ratios of the Antrona and Zermatt-Saas ophiolites cluster in two different groups, one with Ce/Sm < 1 and Nb/Zr < 0.4, and one with Ce/Sm > 1 and Nb/Zr > 0.4, respectively (Fig. 9a). The latter are very similar to the Furgg zone metabasalts and are intermediate between T-MORB from the Gets and Platta nappe, and T-MORB from the external Ligurides and Corsica (Fig. 9b). This suggests that the Furgg zone metabasalts are T-MORB from a single homogenous magma source while in the metabasalts from the adjacent ophiolitic units the source was more heterogeneous, producing basalts of T- to N-MORB composition. All metabasalts from the Furgg zone and from the Antrona and Zermatt-Saas ophiolites show a positive anomaly in Zr (Zr*). This probably indicates a low degree of melting in the spinel field (Casey, 1997). The Zr* decreases from T- to N-MORB in Corsica and the Ligurides. This indicates that they are the products of variable degrees of partial melting (higher for N- than T-
MORB). Taken together, these data show that partial melting of a slightly enriched (lithospheric?) mantle source led to the formation of the metabasalts from the Furgg zone (group F1–F4) and Portjengrat unit (group C3), whereas partial melting of a more depleted mantle source accounted for the formation of the metabasalts of the ophiolitic units (group O1 and O2).

6.3. Tectonic implications of the geochemical data

The geochemical data discussed above suggest that the abundant small metabasaltic boudins of the Furgg zone (group F1–F4) are T-MORB type intrusives that were derived from a slightly enriched (lithospheric?) and single cogenetic magma suite. In this respect they differ from the ophiolitic units that exhibit a tendency towards a more depleted, T- to N-MORB type and towards a more heterogeneous magma source. If the Furgg zone metabasalts were derived from ophiolitic units, one would expect a complete overlap of the chemistry of the Furgg zone metabasalts with that of the metabasalts from the ophiolitic units. This is, however, not supported by our data (Figs. 8 and 9). Furthermore, the Zr, Y, V, and Ti inter-element correlations are significantly higher in the Furgg zone metabasalts than in the mafic rocks from the ophiolitic units. This excludes the possibility that the Furgg zone metabasalts were derived through tectonic incorporation of adjacent ophiolitic components. In summary, these data indicate that the Furgg zone cannot be interpreted as an ophiolitic mélangé, as proposed by Froitzheim (2001). Given the geochemical similarities of the metabasaltic boudins of the Furgg zone with those of the Portjengrat unit (group C3), the main difference between the two units seems to be the continuous increase in strain intensity towards the Furgg zone. Since the Portjengrat unit is undoubtedly a fragment of continental upper crust, the Furgg zone may conclusively be interpreted as an intracontinental shear zone that overprints both Portjengrat unit and adjacent Monte Rosa nappe. This is consistent with structural evidence indicating that the Monte Rosa nappe and the Portjengrat-Stockhorn units were originally connected to form a single Portjengrat – Stockhorn – Monte Rosa continental fragment, separating the Antrona ophiolites from the Zermatt-Saas ophiolites (Keller and Schmid, 2001; Kramer, 2002). This is again in marked contrast to the model proposed by Froitzheim (2001), who considers the Furgg zone, together with the Antrona ophiolitic unit, as representing North Penninic oceanic crust, which separates the Briançonnais microcontinent (= Portjengrat-Stockhorn unit) from the European plate (= Monte Rosa nappe). However, the geochemical data presented above do not exclude the possibility that the Antrona and Zermatt-Saas units were an originally continuous unit forming part of the Piemont-Ligurian ocean, as was proposed by Escher et al. (1997).

The different geochemical signatures of the metabasaltic boudins from the intensely strained Monte Rosa cover and basement of the southwestern Monte Rosa nappe (ISMR, group C2) preclude a direct correlation with the Furgg zone, as was proposed by Dal Piaz (1966). Furthermore, their derivation from the Zermatt-Saas ophiolitic unit can also be excluded on geochemical arguments. Hence, the chemical data presented in this study do not support the idea that the ISMR represents the prolongation of the Furgg zone in terms of an ophiolitic mélangé (Froitzheim, 2001). On the other hand, larger mappable ophiolitic slivers containing ultramafic rocks, which are surrounded by the Furgg zone, do exist. However, they demonstrably are either isoclinal D3 fold cores of the Zermatt-Saas unit (at Gornergrat) or fold cores of the Antrona unit (in the Monte della Preja region) that were fragmented during D3 overprint (Kramer, 2002) and that are not regarded as part of the Furgg zone (Keller and Schmid, 2001; Kramer, 2002).

6.4. Paleogeographic implications of the geochemical data

Based on the geochemistry of the metabasalts, two stages of mafic magmatism are inferred. An early stage is recorded by the samples of groups C1 and C2. The amphibolite boudins of group C2 are embedded in the basement of the southwestern Monte Rosa nappe (ISMR), as well as in garnet micaschists of its supposedly Permo-Triassic meta-sedimentary cover. The boudins are parallel to the foliation of the basement rocks, which is, at least in part, defined by pre-Alpine sillimanite (Dal Piaz, 1986). Hence, Dal Piaz concluded, that foliation and embedded boudins are Paleozoic in age. This view is corroborated by the observation of amphibolite boudins, which are intruded by granites of probably Permian (or Late Carboniferous) age (Kramer, 2002). Late Carboniferous to Permian igneous activity, producing MORB-type and also more differentiated magmas has been described from several regions in the Alps (e.g. von Raumer et al., 1990). A pre-Triassic age is also likely for the amphibolites of group C1 from the Siviez-Mischabel nappe, which were collected within the basement only.
In this context it is interesting to note that T-type MORB dykes have neither been reported from the sedimentary cover of the Siviez-Mischabel nappe (internal Briançonnais), nor from the southwestern part of the Monte Rosa nappe (most internal Briançonnais situated directly adjacent to undisputed Piemont-Liguran ophiolites, i.e. the Zermatt-Saas unit; see Figs. 1 and 2). Together with the fact that ophiolitic imbricates derived from the Antrona unit (Valaisian according to Keller and Schmid, 2001) can be found in the Furgg zone, these structural and field arguments may indicate that the basaltic intrusions into distal continental margin units occurred in the context of Late Jurassic to Early Cretaceous opening of the Valais ocean.

Notwithstanding the different paleotectonic interpretations, an important finding of this study is that T-type MOR basalts are not only found in ophiolitic units but also in (thinned) distal continental margin units. The volume of mafic rocks intruding the Briançonnais distal continental margin adjacent to the Valais ocean or, alternatively, to the Piemont-Liguran ocean, is distinctly higher than the volume of mafic rocks found in the Adriatic distal continental margin (e.g. Puschning, 2000; Desmurs et al., 2002). This ‘asymmetry’ in the distribution of mafic rocks along continental margins is consistent with asymmetric low angle detachment faulting during the latest stages of rifting. The finding of T-MOR basalts intruding distal parts of the continental crust is similar to the evolution of the Red Sea rifting system (e.g. Voggenreiter et al., 1988).

Acknowledgements

The authors gratefully acknowledge the contributions of all the members of the Basel, Bonn and Mainz “Monte Rosa group” (Nikolaus Froitzheim, Ronan Le Bayon, Katharina Dubach, Christiane Rössler, Lukas Keller, Andreas Weber, Corinne Bacher, Lukas Baumgartner, Sabine Pawlig). Furthermore, we benefitted from discussions with and/or reviews from Hans-Rudolf Pfeifer, Philippe Monojoie, Dieter Gebauer, and Martin Engi. J. Kramer acknowledges support from the Werenfels-Fonds, Freiwillige Akademische Gesellschaft, Basel, S. Schmid acknowledges support from NF-projects Nr. 20-61814.00 and 2000-068020/1, initiated by the late Martin Frey. The authors are grateful for Martin’s initiative and support during the initial stages of this study.

References


and geochemical variations along the Mid-Atlantic Ridge from 27°N to 73°N. *Am. J. Sci.* 283, 510–586.


Received

Accepted in revised form

Editorial handling: M. Engi