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Dedicated to the memory of Werner Hansmann

Mesozoic ophiolite relics in the Southern Steep Belt of the Central Alps

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Abstract

SHRIMP U/Pb age determinations on plagiogranite zircons in the Zone of Bellinzona-Dascio ophiolites yield late Jurassic ages of 149 ± 3 Ma and 142 ± 5 Ma. The plagiogranites are part of a rodingitized and metamorphosed yet well preserved igneous oceanic suite including Mg-gabbros, Fe-Ti-rich gabbros and basalts that is a common feature of the Jurassic Piemont-Ligurian ophiolites. These magmatic ages are among the youngest in this domain and fit well with the observed N-MORB signature of the basalts. The data are indicative of formation in a relatively mature Piemont-Ligurian ocean rather than in an early, embryonic Valaisan ocean.

Keywords: Ophiolites, U/Pb dating, zircon, plagiogranites, Zone of Bellinzona-Dascio, Southern Steep Belt, Piemont-Ligurian ocean, Central Alps.

Introduction

Dispersed ultramafic bodies of meter to kilometer size are found in the Zone of Bellinzona-Dascio (abbreviated in the following to ZBD), a verticalized East-West striking unit in the southern Central Alps (Fig. 1). To date, the origin of both the ultramafic rocks and the entire zone have not been well constrained, mostly because Alpine metamorphism and deformation have reached high grades in this particular section of the Central Alps. Retracing the pre-Alpine history of the ZBD ultramafic rocks and thus linking them with ophiolitic units in the Alps may provide clues for positioning the entire ZBD in the Alpine edifice. In addition, the question whether ZBD ultramafic rocks are related to the ophiolite complexes of the Valaisan or the Piemont-Ligurian domain to the East and West, or if they originate from an altogether different, i.e. previously unknown oceanic domain, needs to be resolved. If the ZBD ophiolitic rocks are part of the Piemont-Ligurian domain, they would represent the missing link between the major ophiolitic complexes of the Western Alps, such as Aosta and Zermatt-Saas Fee (e.g. Bearth, 1967; Dal Piaz, 1969; Pfeifer et al., 1989; Rubatto et al., 1998), and those in the Eastern Alps, such as Platta (e.g. Dietrich, 1969; Schaltegger et al., 2002) and Malenco (Trommsdorff et al., 1993). This addition would complete the picture of this oceanic domain.

Geological context and field aspects

The ZBD extends for about 50 km and is up to 4 km wide (Knoblauch, 1939; Moticska, 1970; Fumasoli, 1974; Bächlin et al., 1974; Heitzmann, 1975; Evans et al., 1981; Schmidt, 1989). In general, this unit is a very heterogeneous mixture of different types of gneisses, minor marble lenses and layers, amphibolites and ophiolitic rocks. It is considered a "lithospheric mélange" zone (Schmid et al., 1996; Engi et al., 2001) not unlike the north penninic Adula-Cima Lunga Nappe (Trommsdorff, 1990). All rock types in the ZBD are of high metamorphic grade i.e. uppermost amphibolite facies with temperatures between 650 and 750 °C at moderate pressures of probably less than 0.7 GPa (Heitzmann, 1975; Schmidt, 1989; Engi et al., 1995; Todd and Engi, 1997; Stucki, 2001; Stucki et al., 2001). A possible origin for both its lithological heterogenity as well as the particular pattern of metamorphic grade is provided by Engi et al. (2001). Contacts to the south (Tonale Series) as well as to the north (Adula Nappe) are both tectonic in nature. Together with the Iorio Tonalite adjacent to the south (Weber, 1957; von Blanckenburg, 1992) and the Tonale Series (Staub, 1924), the ZBD is part of the "Southern Steep Belt" or "Central Alpine Steep Belt" (Milnes, 1974).

The ophiolitic rocks occur at 15 localities as boudins of metaperidotite with associated mafic rocks within the country rocks. The largest ophio-

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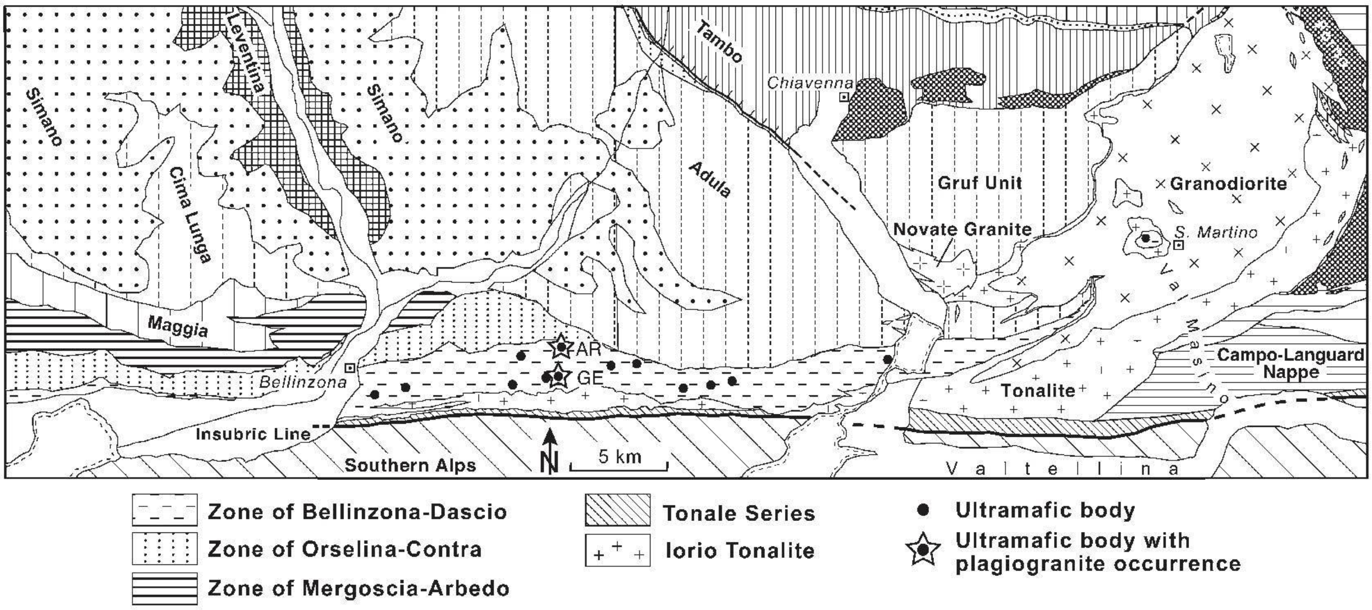


Fig. 1 Tectonic map of the Zone of Bellinzona-Dascio, modified after Pfiffner (1999). Note the re-introduction of the Zone of Orselina-Contra as originally proposed by Knoblauch (1939) and adapted by Bächlin et al. (1974). Dots indicate major mafic-ultramafic bodies, stars indicate those containing plagiogranites that were dated. GE—Alpe d'Albion (Swiss coordinates or kilometric grid: 731'150 / 116'200), AR—Intersection Albionasca and Roggiasca Valleys (Swiss coordinates: 732'750 / 118'575).

litic fragment, the Gana Rossa metaperidotite, was studied by Fumasoli (1974) and Schmidt (1989). The ultramafic body at Alpe d'Albion is the most thoroughly studied outcrop in the ZBD (Trommsdorff and Evans, 1979; Evans et al., 1981). To the east, amongst numerous small bodies, another relatively large lens is found near the town of Dascio (Heitzmann, 1975). The xenolithic ultramafic body within the Masino window (near S. Martino in Fig. 1; Crespi, 1965; Hansmann, 1981) in the Bregaglia-Masino granitoid intrusion is also regarded as being part of the ophiolitic rocks of the ZBD (Stucki, 2001).

All ophiolitic bodies within the ZBD share the same properties: The ultramafic lenses are predominantly peridotitic and aligned parallel to the strong Alpine foliation that strikes east-west. A rim of amphibolite often surrounds them. Ophiolitic mafic rocks are very common and found as boudinaged, mostly rodingitized dikes within the metaperidotites. The assemblages of the rodingitized mafic rocks are entirely metamorphic (Trommsdorff and Evans, 1979; Schmidt, 1989). Despite rodingitization, Alpine deformation and metamorphism, the majority can be readily recognized in the field as having been formerly gabbroic: the pre-Alpine flaser texture is remarkably well preserved in many instances. In addition, gabbros rich in iron-titanium-oxides (former Fe-Ti-gabbros) are common throughout all the ophiolitic bodies. Apart from the formerly gabbroic rocks, four minute plagiogranite dikes were identified.

Formerly basaltic rocks are relatively scarce. They are easily distinguished in the field from the gabbroic rocks by being relatively homogeneous on a cm-scale. They have not been found crosscutting the gabbroic rocks.

The fairly systematic occurrence of formerly intrusive rocks, notably the Fe-Ti-gabbros throughout the entire ZBD leaves little doubt that the dispersed ophiolitic bodies represent remnants of one single ophiolite suite (see also discussion).

For geochemical investigations, zircon separation and subsequent age determinations two of the plagiogranite dikes were examined more closely: one (AR5b) was found at the intersection between the Albionasca and Roggiasca valleys. Another occurrence (GE35P1.1) is found in the well-known Alpe d'Albion ultramafic body (Fig. 1) and cuts across a rodingitized gabbro dike. Both samples contain abundant zircon of magmatic origin.

Methods

Whole rock chemical analysis

X-ray fluorescence (XRF)

The bulk composition of mafic and ultramafic rocks was determined by X-ray fluorescence analysis at the Swiss Federal Laboratories for Material Testing and Research (EMPA) in Dübendorf with a sequential spectrometer (Philipps PW 1404) using natural USGS reference rocks for calibration. Ultramafic rocks were ground in an agate mill in order to minimize possible contamination from the mill, all other rock types in a tungsten carbide mill. Major elements were determined using glass beads which were fused from ignited (at 1050 °C) rock powders mixed with $Li_2B_4O_7$ (ratio of 5x $Li_2B_4O_7$ and 1x rock powder) in gold platinum pans at 1150 °C. Intensities were corrected for instrumental drift, background and matrix effects. Trace elements were determined by XRF analysis of approx. 10 g rock powder samples using the synthetic background method that require knowledge of the major element contents (Nisbet et al., 1979).

Inductively coupled plasma mass spectrometry (ICP-MS)

80–200 mg of sample-powders were dissolved in a mixture of HNO_3 and HF Suprapur Merck acids in different concentrations using Teflon beakers of 160 ml volume. This mixture of powder and acids was placed in a microwave oven (MLS1200, ML GmbH) where the elevated pressure and temperature allow the acid to attack and dissolve the rock-powder. Contemporarily with the same procedure blank and standard rock-powder samples were prepared. The dissolved mixtures were then diluted with deionised water at 50 ml (ultramafic rocks) or at 100 ml (mafic rocks).

Solutions were measured with an ELAN 6000 (Perkin Elmer Sciex) at EMPA in Dübendorf. Data correction related to drift-effects was made using the ^{111}Cd correction factor for Ga, Ge, Rb, Sr, Y, Zr, Nb, Ba and La to Gd and the ^{185}Re correction factor for Hf, Th, U and Tb to Lu as internal standards. To avoid existing incompatibilities between the computed data and published standard data, due to artifacts introduced with the correction procedure, a linear interpolation was made between the two standards. The formula used for the linear interpolation is:

$c(x) = c_{Cd}(x) \times m/b + c_{Re}(x) \times (b-m)/b$

where: c = concentration of element x, m = mass of element x and b = 74 = $(m_{Re}-m_{Cd})$. Detailed information on the procedure may be found in Müntener (1997).

Age determinations: SHRIMP

Zircons were separated in the laboratory at the ETH by routine crushing and sieving, followed by gravimetric separation with methylene iodide. Crushing was processed down to a minimum grain size of 1 mm and 0.5 mm. Final separation was done by hand picking. Zircon crystals were then mounted in epoxy and polished down to expose the grain centres. Cathodoluminescence investigation was carried out at the Electron Microscope Unit, Australian National University, with an HITACHI S2250-N scanning electron microscope working at 15 kV, ~60 µA, and ~20 mm working distance.

U–Th–Pb analyses were performed using a sensitive, high-resolution ion microprobe (SHRIMP II). Instrumental conditions and data acquisition were generally as described by Compston et al. (1992). The data were collected in sets of seven scans throughout the masses. The measured $^{206}Pb/^{238}U$ ratio was corrected using reference zircon from a gabbro of the Duluth Complex in Minnesota (AS3, 1099 Ma, Paces and Miller, 1993), whereas zircon of known composition (SL 13) has been used to determine the U content of the target. The data were corrected for common Pb on the basis of the measured $^{207}Pb/^{206}Pb$, as described in Compston et al. (1992). Owing to the young age and the low U content of the samples, some analyses have a high proportion of common Pb. However, in absolute amount, the common Pb content of the samples is similar to that of the common Pb-free standard. This indicates that the common Pb is mainly surface and instrumental background, the composition of which is known to be that of Broken Hill Pb ($^{204}Pb/^{206}Pb$ = 0.06250, $^{207}Pb/^{206}Pb$ = 0.96180, $^{208}Pb/^{206}Pb$ = 2.22850). None of the mean ages calculated would change significantly if a different common Pb composition was used. Age calculations were done using the software Isoplot/Ex (Ludwig, 2000). Isotopic ratios and ages in text and Tables are reported at the 95% confidence level.

Age determinations: Isotope dilution

Conventional isotope dilution analysis was carried out at the Institut für Isotopengeologie und Mineralische Rohstoffe (ETH) with a Finnigan MAT 262 mass spectrometer equipped with an ion counting system. Chemical dissolution of the zircon, measurements and data treatment were according to Hansmann et al. (2001).

Petrographic and geochemical characteristics

The host ultramafic rock

The ultramafic rocks are entirely metamorphic, schistose to massive olivine–enstatite–spinel–chlorite rocks. Trommsdorff and Evans (1974) showed that this assemblage defines the high temperature extreme of the amphibolite facies. Neither garnet nor any other relics of a former high-

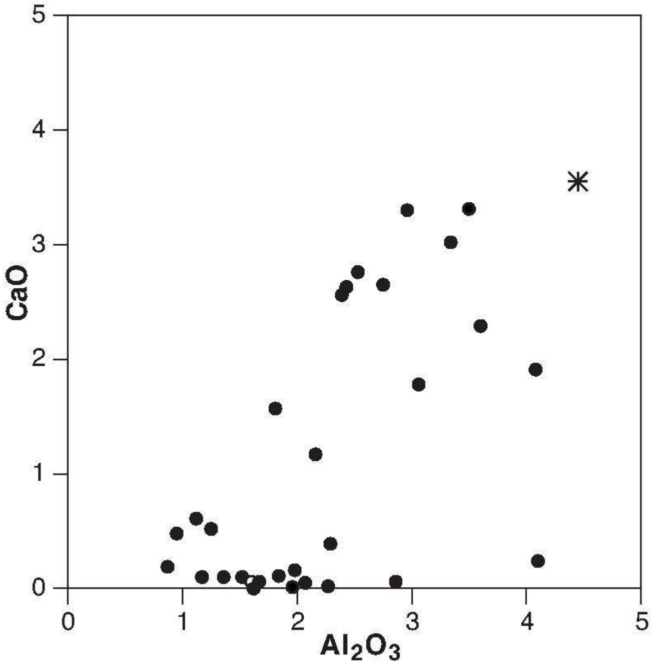


Fig. 2 CaO versus Al_2O_3 content in the Zone of Bellinzona-Dascio (ZBD) metaperidotites. Apart from the wide range from Ca-Al-poor compositions to those approaching primitive mantle values (star symbol: estimate by McDonough and Sun, 1995), a group of almost Ca-free samples is quite conspicuous. This particular composition is attributed to a serpentinization event during exposure on the Piemont-Ligurian ocean floor.

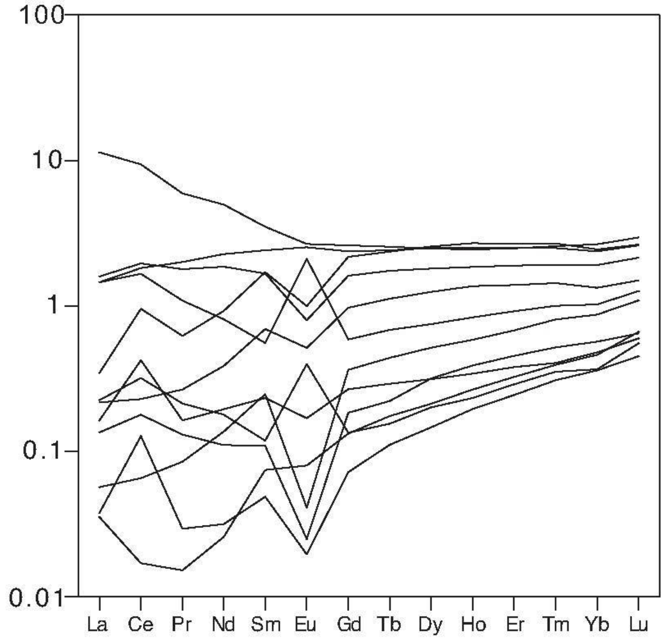


Fig. 3 Rare Earth Element (REE) patterns (normalization on a CI-chondrite, Sun and McDonough, 1989) of the ZBD metaperidotites. Despite considerable scatter in the Light REE (LREE), the range from fairly depleted patterns to nearly undepleted patterns resembling a primitive mantle pattern is obvious and typical of formerly subcontinental mantle rather than asthenospheric mantle.

Table 1 Representative bulk chemistry XRF analyses of mafic rocks in the ZBD ophiolites. (A) refers to Mg-gabbros, (B) to intermediate gabbros, (C) to Fe-Ti-gabbros, (D) to plagiogranites and (E) to basalts. (R) refers to rodingitized samples. Source of Mg 6.6.3 R: Evans et al. (1981).

	A				B	C			D		E	
	MA5	GE40.2	GR13 R	GR34 R	MA4	DA2.3	GR18 R	GR45 R	GE35 P1.1R	AR5b	AR9	Mg 6.6.3 R
SiO_2	48.17	47.43	38.02	41.37	38.16	43.47	33.65	33.48	39.95	41.64	48.03	39.17
TiO_2	0.19	0.29	0.68	0.16	2.77	4.41	5.61	4.08	2.06	1.08	1.24	0.98
Al_2O_3	19.12	16.79	17.15	14.49	14.47	13.22	11.18	10.70	15.93	16.76	16.16	12.55
Fe_2O_3	4.44	6.81	4.96	3.83	9.62	13.98	14.84	15.12	10.90	6.98	8.64	7.26
MnO	0.06	0.12	0.07	0.13	0.47	0.23	0.34	0.25	0.15	0.09	0.14	0.13
MgO	10.48	11.14	12.97	10.07	11.62	7.25	8.60	6.98	8.62	15.25	8.64	7.49
CaO	13.04	13.08	23.04	27.30	20.89	12.18	23.06	27.27	21.70	13.48	11.72	29.00
Na_2O	1.84	1.92	0.00	0.01	0.00	1.17	0.00	0.04	0.17	0.99	2.92	0.00
K_2O	0.16	0.22	0.00	0.00	0.00	2.32	0.00	0.00	0.01	0.24	0.35	0.09
P_2O_5	0.02	0.02	0.02	0.01	0.10	0.02	0.05	0.12	0.02	0.43	0.28	0.13
H_2O	2.18	1.15	2.47	2.70	1.84	1.29	1.38	1.80	0.31	2.60	0.72	2.50
Total	99.70	98.97	99.38	100.07	99.94	99.54	98.71	99.84	99.82	99.54	98.84	99.30
Rb	7.5	1.6	0.3	11.5	1.1	63.4	0.1	14	0.2	3.3	4.9	
Sr	177.4	231	7.8	22.7	65	198.5	2.8	28	1160	239	166.6	
Y	4	10.6	4.9	33	25.6	12.1	31	75	21.1	92	23	
Zr	7.3	13.6	10.5	34	62.5	32.1	76	161	609	1290	78	85
V	83	109	114	132	429	888	567	679	209	45	149	186
Cr	450	194	100	505	138	1	*	*	6	70	173	359
Ni	250	169	83	301	319	144	130	88	129	349	93	98
Zn	31	43	34	33	47	90	53	64	63	29	47	18
Sc	14	22	2	12	42	64	32	37	42	17	28	28

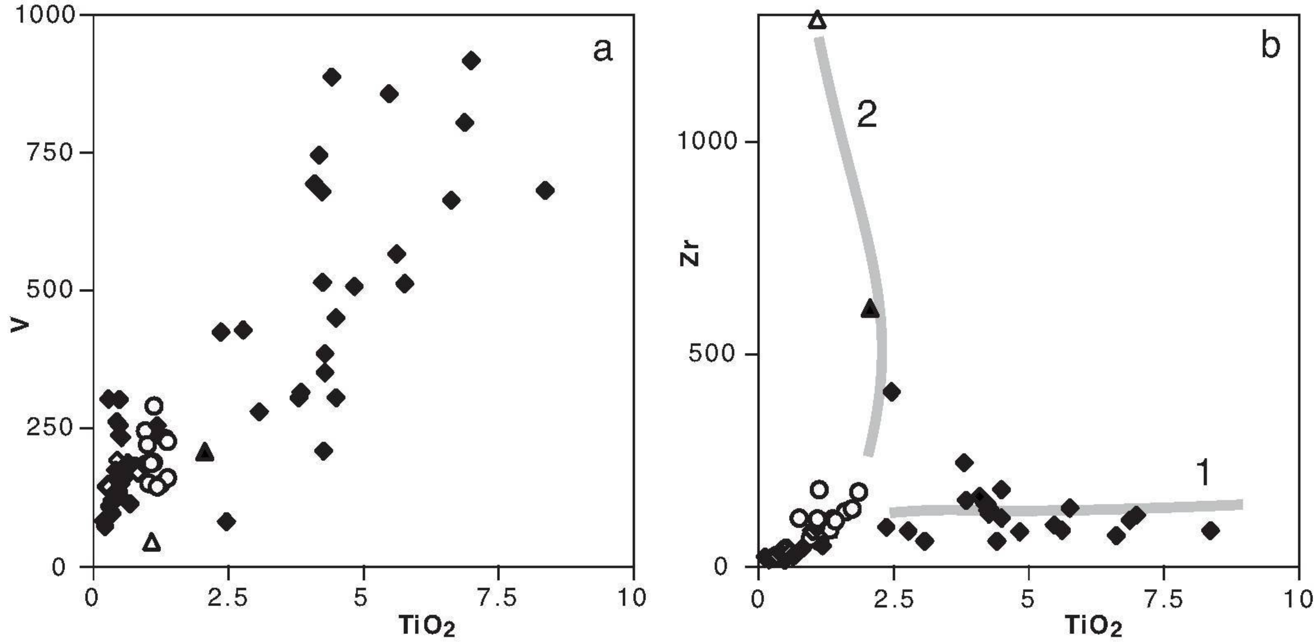


Fig. 4 V, Ti and Zr contents of the oceanic igneous rocks in the ZBD ophiolites, including both gabbros (diamonds), plagiogranites (GE35P1.1–full triangle, AR5b–open triangle) and basalts (open circles). Note the steady V- and Ti-enrichment in the evolved gabbroic rocks in (a) and the split enrichment trends in gabbros ("Zr-poor, Ti-rich" trend 1) and plagiogranites ("Zr-rich, Ti-poor" trend 2) in (b).

pressure metamorphic stage are present in the metaperidotites of the ZBD. They most likely represent metamorphosed serpentinites (Trommsdorff and Evans, 1979), as suggested by the occurrence of associated rodingitized dikes and the particular chemical composition of the ultramafics. For instance, many of the ultramafic rocks are virtually Ca-free yet still Al-bearing (Fig. 2). This implies a metasomatic rather than an igneous (i.e. partial melting) origin of the Ca depletion, most likely concomitant with rodingitization of the enclosed mafic rocks.

Regarding Ca-, Al- and REE contents (Figs. 2 and 3), the metaperidotites cover the entire range from fertile to moderately depleted lherzolites and are thus regarded as former subcontinental mantle material (Fig. 3). This finding agrees well with observations on other Alpine ophiolites (Trommsdorff et al., 1993; Rampone et al., 1998), regardless of their present tectonic setting.

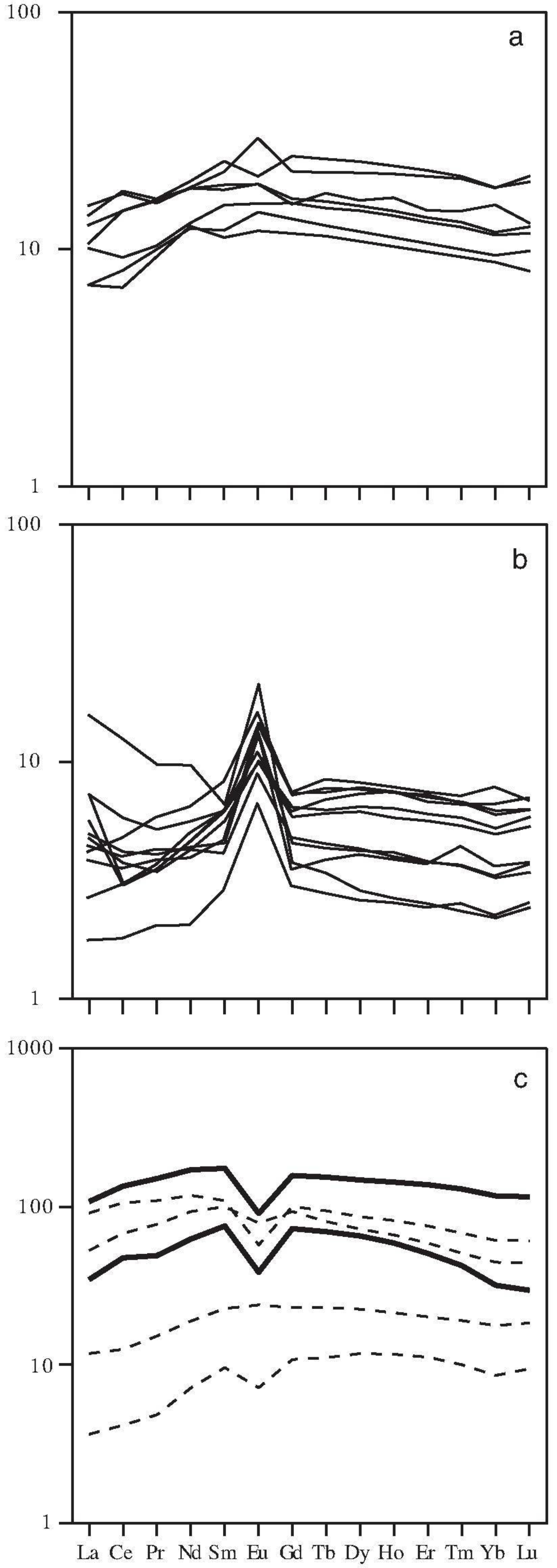
Oceanic magmatic rocks

Intrusive rocks (gabbros and plagiogranites)

The metamorphosed and rodingitized oceanic intrusive rocks throughout the ZBD display very complex mineralogical compositions, owing to the varying degree of rodingitization and the former igneous domain (former plagioclase, pyroxene and ilmenite). In strongly rodingitized former gabbros, the assemblages grossular–clinozoisite / epidote ± clintonite ± chlorite, or vesuvianite–clintonite ± grossular replace former igneous plagioclase. At S. Martino (Val Masino, Fig. 1), former igneous plagioclase may also be replaced by anorthite–clinopyroxene–spinel (Hansmann, 1981; Stucki, 2001). Fassaitic diopside ± clintonite ± chlorite ± grossular/andradite replace former igneous augite. The former Fe-Ti-oxide domains are generally composed of magnetite, perovskite, titanite and titanian garnet. The more weakly rodingitized gabbros show anorthite–clinozoisite/epidote in place of igneous plagioclase and clinopyroxene–amphibole in place of igneous augite. In these rocks, the former Fe-Ti-oxide domains contain ilmenite–ulvospinel ± perovskite, titanite and Al-Ti-rich clinopyroxene.

With the exception of relic igneous zircon, the mineralogy of the cm-thick plagiogranites largely reflects that of the host rock they occur in. AR5b is composed mainly of hornblende, anorthite and clinopyroxene; GE35P1.1 consists of Al-rich clinopyroxene and minor spinel and titanite.

Strongly rodingitized former basalts are characterized by the assemblage grossular–vesuvianite–diopside ± clintonite ± chlorite. The moderately rodingitized types contain clinopyroxene–clinozoisite/epidote–spinel ± chlorite ± clintonite. The mineral assemblages of non-rodingitized basalts and gabbros are nearly identical: they are composed of plagioclase and hornblende with varying amounts of clinopyroxene and clinozoisite.



In terms of whole rock chemical composition, the intrusive suite in the ZBD ophiolitic rocks displays all the typical features found in Piemont-Ligurian ophiolites (Table 1). The evolution from primitive Mg-gabbro to evolved Fe-Ti-gabbro is first reflected by an increase in Fe_2O_3, TiO_2 and V contents (Fig. 4a). Zr increases slightly in the course of gabbro differentiation (trend 1) and is drastically enriched in plagiogranite (trend 2) leading to a distinct, split trend on a Ti–Zr-diagram (Fig 4b). This phenomenon is well known from fresh oceanic intrusive suites (e.g. Engel and Fischer, 1975) and several Alpine ophiolites (Beccaluva et al., 1977; Pognante et al., 1982; Bertrand et al., 1987; Borsi, 1995) that belong to the Piemont-Ligurian domain. So far, no plagiogranites have been reported from Valaisan ophiolites. The REE contents (Fig. 5) of the intrusive rocks compare favorably with those of other Alpine ophiolites: REE patterns normalized to a CI-chondrite (Sun and McDonough, 1989) show a slightly upward convex shape. The Mg-gabbros are characterized by a distinct positive Eu anomaly (indicative of cumulus plagioclase) which gives way to a negative Eu-anomaly in the Fe-Ti-gabbros and plagiogranites, confirming their residual character (Fig. 5). The latter two also show distinctly LREE depleted patterns, a feature observed in other plagiogranites (Alpine: Borsi et al., 1996; worldwide: e.g. Coleman and Peterman, 1975; Gerlach et al., 1981; Luchitskaya, 1996). Furthermore, the very similar shape of the REE patterns indicates a cogenetic relationship between plagiogranites and Fe-Ti-gabbros. Total REE enrichment varies strongly; it is highest in the plagiogranites and some apatite-rich Fe-Ti-gabbros.

In the former basalts, the concentration of the trace elements Ti, Zr and V is in the range of most other Alpine ophiolitic (both Valaisan and Piemont-Ligurian) and fresh tholeiitic basalts. The diagnostic REE patterns (Fig. 5) are highly typical of normal Mid-Ocean-Ridge basalts (N-MORB, Sun and McDonough, 1989). The marked LREE depletion ($La_N/Sm_N<0.7$) shown by ZBD basalts appears to be among the most pronounced in the entire Alpine chain.

Fig. 5 Chondrite-normalized REE patterns of the oceanic igneous rocks in the ZBD ophiolites. (a) Basalts, showing a rather classical N-MORB pattern with a distinct LREE depletion. (b) Mg-gabbros, relatively REE-poor, all show a strong positive Eu-anomaly, indicative of cumulus plagioclase. (c) Evolved intrusive rocks (plagiogranites: solid line, Fe-Ti-gabbros: dashed line), mostly characterized by a negative Eu-anomaly yet differing total REE-enrichment (strong in the plagiogranites, varying in the Fe-Ti-gabbros).

Note that despite the strongly dismembered character of the ZBD ophiolites (which could lead one to the assumption that these possibly belong to more than one domain), the above described, distinct chemical composition of both gabbroic and basaltic rocks is a diagnostic feature throughout the entire ZBD (Stucki, 2001).

Zircon characteristics

Morphology

Zircons were separated from the former granitic differentiates GE35P1.1, AR5b and GE21.2. The zircon crystals are, apart from inclusions and cracks, quite transparent and slightly pink to tan colored to almost colorless. Their surface is strongly etched and pitted (see Fig. 6) indicating alteration and corrosion. Still, the original magmatic typology is mostly preserved and clearly distinguishable in complete crystals. In general, they are moderately prismatic with an elongation ratio of approximately 2:1 to 3:1. Average length is 200 µm to 1 mm. The fact alone that zircon is euhedral signifies that it was an early crystallizing phase in the leucogranitic melt. By contrast, zircons from primitive gabbros tend to be anhedral as Zr-saturation is reached in the interstices during the very last stages of crystallization (e.g. Rubatto et al., 1998).

According to the diagram established by Pupin and Turco (1972) and Pupin (1980), based on the relative growth of prismatic and pyramidal faces, 90% of all zircons fall into the fields D and J5. One such example is represented by the crystal in the upper right in Fig. 6. Such typology indicates high temperature (approx. 900 °C) of formation in a highly agpaitic, i.e. high Na/Al environment (Pupin, 1980). This finding is in good agreement with the conditions of crystallization and the general chemical composition of plagiogranites. It also matches very well with that of zircons previously described from better-preserved Alpine plagiogranites (e.g. Ohnenstetter et al., 1981; Borsi et al., 1996).

Cathodoluminescence (CL) investigation

In order to obtain information on the zoning patterns as well as to select inclusion- and alteration-

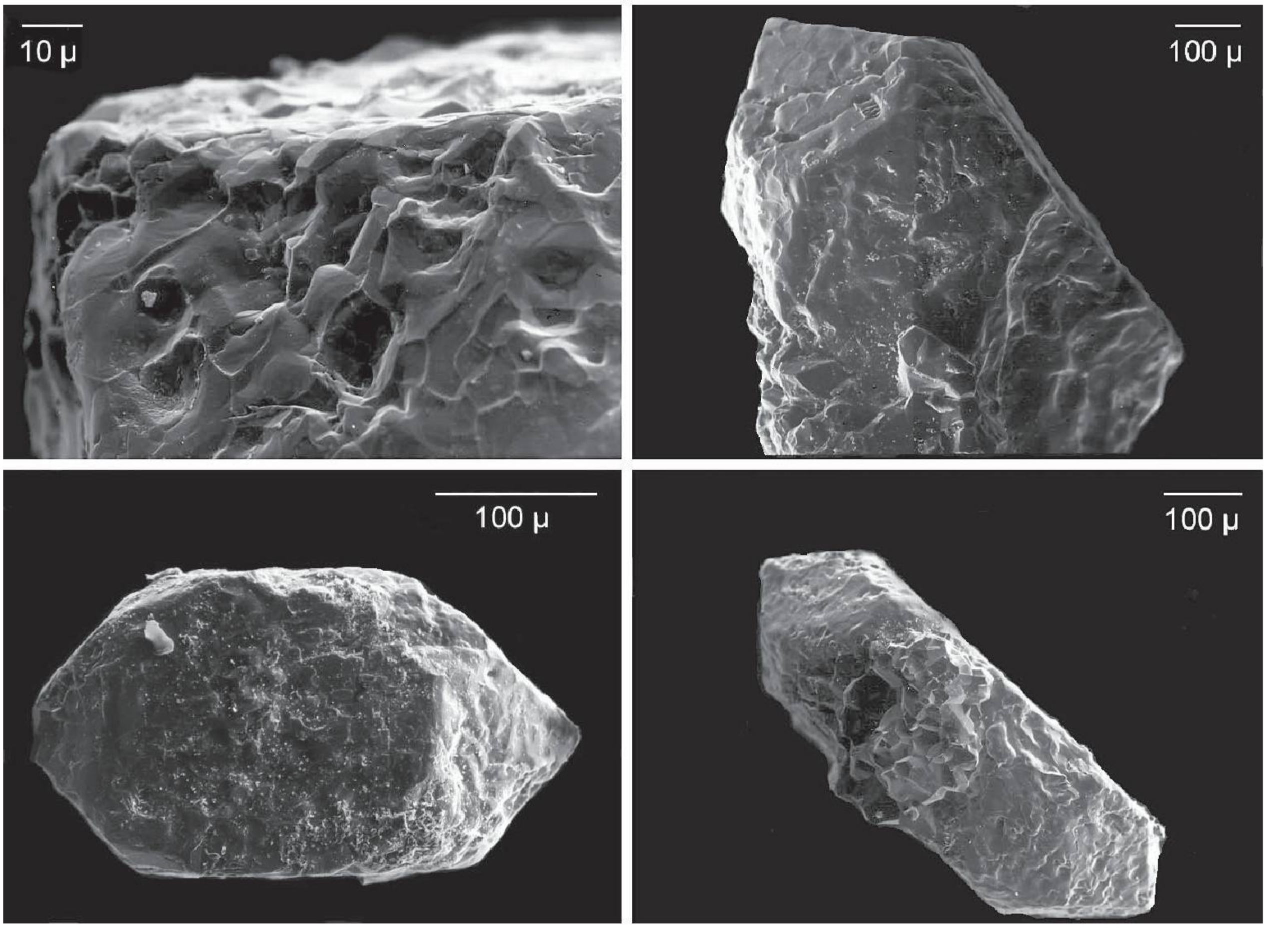


Fig. 6 SEM images of separated zircon crystals from GE35P1.1. Note the etched and pitted surface on the close up view top left but the still preserved typological features of the crystals, showing them to be D to J5 type according to the classification by Pupin (1980), indicating formation in an evolved tholeiitic rock.

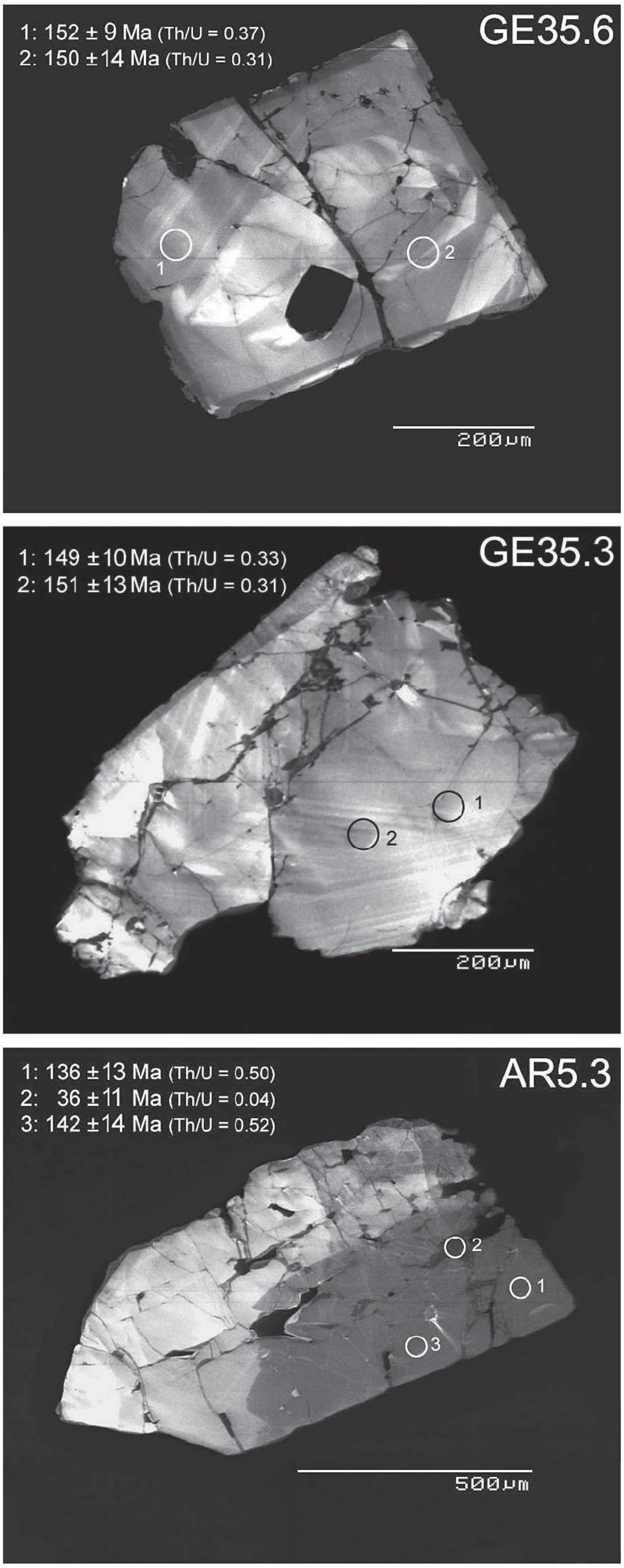


Fig. 7 Selected cathod luminescence images including results of SHRIMP dating. Note faint but intense zoning in the zircon crystals from GE35, particularly in GE35.3. Intense cracking is common to all crystals and coupled with recrystallization veins (dark CL, e.g. in AR5.3). The darkest veins "filling" cracks yield apparent Alpine ages of approx. 35 Ma (95% confidence level). Static recrystallization resulting in zones of bright luminescence are common and best seen in GE35.2 and AR5.3.

free areas for SHRIMP analyses, a cathodoluminescence (CL) investigation was performed on several zircon crystals.

The CL images reveal magmatic zoning crosscut by cracking as well as recrystallization along the cracks. This has been observed in virtually every crystal examined. A very typical example is represented by zircons AR5.3 and GE35.2 (Fig. 7).

Magmatic patterns: Zircons are characterized by weak oscillatory zoning and growth banding of varying width. GE35.2 in Fig. 7 shows oscillatory zoning with relatively fine growth bands. In some areas, no zoning is visible (Fig. 7c), but this might be an artifact of the resolution of the imaging in zircon where the contrast in emission between the zones is weak. To date, unfortunately, no CL images are available from zircons in non-metamorphic plagiogranites for comparison. No inherited cores have been found in the zircons studied.

Metamorphic imprint: The magmatic zoning is cut by dark veins, and in extreme cases zircons appear brecciated. Virtually all crystals display dark fractures and veins in the interior parts as well as along the outer rims. In these areas, zircon is lacking a magmatic zoning pattern and displays a cloudy, generally darker zoning (e.g. AR5.3 and GE35.2 in Fig. 7). These domains are interpreted as zircon recrystallized under metamorphic conditions, as previously described (e.g. Rubatto et al., 1998; Lombardo et al., 2002). Such secondary features are not surprising considering the degree of Alpine metamorphism and deformation experienced by the formerly igneous rocks.

U/Pb dating

SHRIMP

Zircons from AR5b and GE35P1.1 were analyzed for U, Th and Pb with the Sensitive High Resolution Ion MicroProbe (SHRIMP) at the Australian National University. The major advantage of SHRIMP over the conventional isotope dilution technique is the ability to measure relatively small areas (down to approx. 20 µm). Combined with CL imaging, this allows analyzing specific growth domains while avoiding alteration zones, cracks and inclusions. This proved to be crucial for zircons analyzed in this study.

The results of SHRIMP analyses are presented in Table 2. The studied zircons are poor in Th and U: average U contents are less than 20 ppm and Th less than 10 ppm. These values are typical of zircon from plagiogranites, yet they are among the lowest reported (e.g. Ohnenstetter et al. 1981; Borsi et al. 1996; Rubatto et al., 1998) and make age determinations a challenging task.

The crystal domains preserving magmatic oscillatory zoning have average Th/U ratios between 0.42 and 0.48 which is in the range previously reported for similar igneous zircon (e.g. Rubatto et al., 1998; Hansmann et al., 2001; Lombardo et al., 2002). The main zircon generation yields ages that define a well sorted population for each sample. On a Tera–Wasserburg diagram (Fig. 8), the uncorrected analyses define a regression line to common Pb, which intercepts with the concordia curve and constrains the age of the population. Nine analyses from GE35P1.1 yield a weighted mean age of 148.7 ± 3.3 Ma (95% confidence level). From the AR5b zircons, a weighted mean age of 141.7 ± 4.76 Ma (95% confidence level) was obtained from nine analyses.

In sample AR5b, nine analyses yielded younger ages scattering between 36 ± 13 and 112 ± 11 Ma. Th/U loosely decreases with younger apparent age (Table 2 and Fig. 7). The youngest apparent ages (ca. 36 Ma) correspond to dark veins crosscutting the zircon (Fig. 7c) and have the lowest Th/U ratio (0.04–0.08). In sample GE35P1.1, three analyses yield scattering Cretaceous ages, significantly younger than the main group. Unlike sample AR5b, these analyses do not have lower Th/U and do not necessarily correspond to cracks and recrystallized zircon domains.

The late Jurassic age of the zircon domains preserving magmatic oscillatory zoning and relatively high Th/U is indistinguishable in the two samples. Given the zircon characteristics, these ages are interpreted as the time of crystallization of the plagiogranites.

The younger ages are interpreted as affected by Pb loss due to Alpine metamorphic overprint. Because of the relatively low metamorphic temperature, Pb loss did not occur by lattice diffusion, but was rather produced by fracturing, fluid infiltration and sub-solidus recrystallization. There is no evidence for new growth of metamorphic zircon on the original magmatic cores. New growth is not expected at these metamorphic temperatures and in the absence of melt (e.g. Rubatto et al., 2001; Williams, 2001). Most of the young ages were measured in areas where the cloudy zoning occurs, which is attributed to sub-solidus recrystallization. The fact that a few of the young ages were measured in apparently pristine magmatic domains suggests that some loss of Pb occurred in these areas even without apparent damage to the magmatic zoning.

The question whether some of the AR5 zircons reflect a Cretaceous metamorphic overprint, as observed in the Malenco Unit (Müntener et al., 2000), cannot be answered. The rather gradual decrease of both Th/U and age ranging from 112 ± 11 to 59 ± 13 Ma does not support a discrete metamorphic event during late Cretaceous (Villa et al., 2000). If recent Pb loss is excluded, the two youngest ages of approximately 36 Ma can be taken as a maximum age for the Alpine metamorphism.

Isotope dilution

For the convenional isotope dilution technique, some of the largest grains (approx. 1 mg) were selected. Heavily fractured crystals were avoided as metamorphic phases (such as ilmenite, fassaite or chlorite) are fairly common within the cracks. The selected crystals were abraded using crushed pyrite in order to minimize the effect of possible alteration zones or metamorphic overgrowth along the rims. Yet despite this precaution, results are of limited significance due to the low U (and hence radiogenic Pb) contents.

The isotopic composition of the four single zircons analyzed are presented in Table 2. Analyses of the three grains from Alpe d'Albion weakly define a regression line on a concordia diagram which intersects the concordia at 157 –16 + 65 Ma (Fig. 9). Although precision is limited, this result is in agreement with the SHRIMP age of 148.6 ± 3.3 Ma which is interpreted as the best constraint on the crystallization of this plagiogranite. The result of the single zircon analyzed from AR5b is discordant and yields a minimum apparent $^{206}Pb/^{238}U$ age of approx. 142 Ma. Given the low amount of U in the zircon and the common cracks apparent in the CL images (Fig. 7), this poor result is not surprising. Again, the SHRIMP age of 141.7 ± 4.7 Ma is our best estimate on the intrusion of this second plagiogranite.

Discussion and conclusions

Geochemical characterization of the ZBD ophiolites

The ZBD ophiolites are characterized by the occurrence of metamorphic and frequently rodingitized equivalents of gabbros, plagiogranites and basalts derived from a formerly subcontinental mantle. This peculiarity is common to most "ophiolite complexes" throughout the Alps (e.g. Rampone et al., 1998; Trommsdorff et al., 1993, 2000) and raises doubts as to whether the term "ophiolite" in its strict sense (Anonymous, 1972) is applicable to this association. However, in order to emphasize the oceanic origin of both intrusive and volcanic rocks as well as the imprint left on all rock types (rodingitization, serpentinization), the

Table 2a Isotopic characteristics of zircon from GE35P1.1 and AR5b analyzed by SHRIMP.

Labels	ppm U	ppm Th	Th/U	% comm Pb	Unc $^{238}U/^{206}Pb \pm 2\sigma$		Unc $^{207}Pb/^{206}Pb \pm 2\sigma$		Age $^{206}Pb/^{238}U \pm 2\sigma$	
Sample AR5b										
AR5-1.1*	6.7	3.7	0.55	13.6	38.76	5.06	0.1730	0.0355	142.2	19.4
AR5-1.2*	7.0	3.4	0.49	13.5	37.48	4.08	0.1725	0.0282	147.0	16.7
AR5-2.2*	4.0	1.3	0.32	14.4	34.70	5.00	0.1805	0.0451	157.1	24.1
AR5-3.1*	8.0	4.0	0.50	6.2	44.15	4.20	0.1053	0.0174	135.6	13.1
AR5-4.1*	8.3	4.3	0.51	12.7	41.45	3.10	0.1652	0.0262	134.3	10.9
AR5-4.3*	7.6	3.6	0.48	17.0	39.66	3.12	0.2040	0.0190	133.6	10.9
AR5-7.1*	5.6	2.2	0.39	10.1	39.31	3.73	0.1409	0.0216	145.8	14.2
AR5-4.4*	6.9	3.8	0.55	19.1	33.47	2.87	0.2230	0.0337	154.1	14.8
AR5-3.3*	7.6	4.0	0.52	11.4	39.92	3.75	0.1528	0.0247	141.6	13.8
AR5-1.3	4.7	0.7	0.16	29.8	77.99	10.79	0.3206	0.0636	57.8	9.8
AR5-2.1	2.1	0.2	0.08	56.2	79.35	17.64	0.5620	0.1212	35.5	13.3
AR5-2.3	4.4	1.0	0.22	39.6	65.87	9.63	0.4106	0.0872	58.8	12.6
AR5-3.2	3.0	0.1	0.04	39.9	107.67	24.06	0.4128	0.1217	35.9	11.3
AR5-6.1	20.4	6.4	0.31	11.6	77.19	5.54	0.1545	0.0145	73.4	5.4
AR5-7.2	18.8	4.3	0.23	15.7	81.84	4.53	0.1921	0.0192	66.1	4.0
AR5-4.5	10.8	4.2	0.39	17.7	47.04	4.50	0.2103	0.0211	111.9	11.1
AR5-1.4	8.6	2.6	0.30	24.3	66.54	6.18	0.2713	0.0444	72.9	8.2
Sample GE35P1.1										
GE35-1.1*	40.6	24.2	0.60	1.9	42.89	2.03	0.0659	0.0047	145.8	6.9
GE35-3.1*	10.6	3.6	0.33	9.8	38.62	2.45	0.1389	0.0137	148.8	9.6
GE35-3.2*	10.1	3.1	0.31	9.5	38.16	3.21	0.1362	0.0184	151.0	13.0
GE35-4.1*	10.7	4.9	0.46	11.6	37.80	3.24	0.1547	0.0202	149.1	13.2
GE35-6.1*	12.3	4.5	0.37	10.3	37.66	2.29	0.1430	0.0140	151.8	9.5
GE35-6.2*	8.9	2.8	0.31	13.9	36.67	3.08	0.1755	0.0231	149.7	13.2
GE35-7.1*	11.7	5.6	0.47	12.2	36.02	2.97	0.1607	0.0142	155.2	13.0
GE35-8.1*	14.4	6.8	0.47	5.7	41.68	2.10	0.1014	0.0093	144.2	7.4
GE35-9.1*	13.9	6.6	0.48	6.6	39.11	3.27	0.1089	0.0098	152.2	12.7
GE35-1.2	10.2	2.8	0.27	11.8	55.60	3.98	0.1569	0.0172	101.4	7.5
GE35-2.1	10.7	4.8	0.45	19.2	62.64	4.51	0.2247	0.0267	82.6	6.6
GE35-5.1	9.5	3.3	0.35	12.7	43.31	3.28	0.1651	0.0160	128.6	10.0

* analysis on magamtic zircon used for mean age calculation
Unc — measured ratio uncorrected for common Pb

Table 2b Isotopic characteristics of zircon from GE35P1.1 and AR5b analyzed by the single grain conventional isotope dilution method.

	U (ppm)	Weight (mg)	%com Pb	$^{207}Pb/^{206}Pb \pm 2\sigma$	$^{208}Pb/^{206}Pb \pm 2\sigma$	$^{206}Pb/^{238}U \pm 2\sigma$	$^{207}Pb/^{235}U \pm 2\sigma$
GE35P: GE-1	7.35	0.615	44	0.04930 ± 56	0.1457 ± 20	0.021660 ± 82	0.14723 ± 186
GE35P: GE-2	6.63	0.98	45.7	0.04960 ± 194	0.1318 ± 52	0.017690 ± 82	0.12100 ± 76
GE35P: GE-3	8.8	0.97	32.6	0.04925 ± 66	0.1619 ± 18	0.020041 ± 132	0.13610 ± 22
AR5b: AR-56	4.86	0.773	8.6	0.04943 ± 72	0.1650 ± 24	0.022230 ± 114	0.15150 ± 24

term "ophiolite" is still used here even if it is not fully satisfactory.

With respect to chemical composition, the intrusive rocks exhibit very strong variability and include Mg-rich, primitive gabbros, intermediate gabbros, highly evolved Fe-Ti-rich gabbros as well as plagiogranites. The basalts, the intermediate and evolved gabbroic rocks and the plagiogranites are characterized by a marked LREE depletion. The REE patterns of the basalts are remarkably constant and very similar to those of classical N-MORBs. These findings imply that the magmatic rocks formed in a relatively mature oceanic setting as their LREE depletion indicates an asthenospheric mantle source having undergone a considerable degree of partial melting.

Age constraints on oceanic magmatic activity in the ZBD ophiolites

A difference in age between gabbros on the one hand and plagiogranites plus basalts on the other

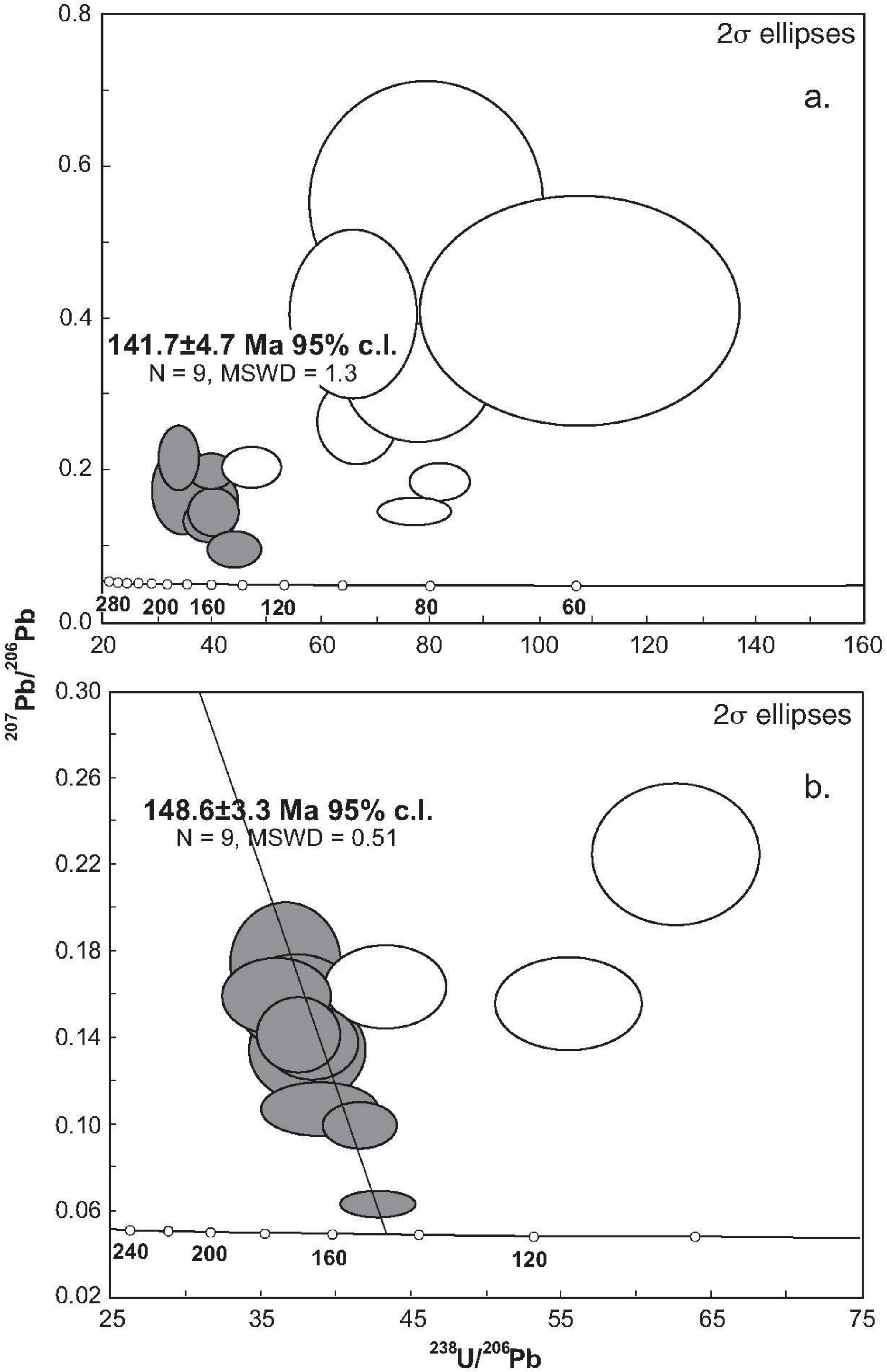


Fig. 8 Tera–Wasserburg age diagrams (including 2σ errors) on zircons from (a) AR5 and (b) GE35P1.1 analyzed by SHRIMP.

appears to be present in several Western Alpine and Ligurian ophiolite units, such as Corsica, Internal Ligurides, Montgenèvre, Monviso and Voltri Group (Costa and Caby, 2001; Ohnenstetter et al., 1981; Rampone et al., 1998; Bortolotti et al., 1995; Lombardo et al., 2002). However, caution must be used when comparing ages obtained by different methods (in this case mostly gabbro Sm/Nd ages with plagiogranite U/Pb ages). In the Platta ophiolites, where U/Pb ages are available for both gabbroic and granitic rocks, no such temporal gap has been observed (Schaltegger et al., 2002). A large temporal gap between the intrusion of gabbros and plagiogranites in the ZBD ophiolites is neither supported by field evidence nor by the chemical composition: the REE patterns of the ZBD plagiogranites suggest a comagmatic origin of gabbros and plagiogranites. Partial melting of mafic rocks which produces considerably LREE-enriched patterns (Costa and Caby, 2001) can be excluded as a possible origin for the plagiogranites. We thus suggest that the plagiogranite ages obtained here can be considered as the general age for oceanic magmatic activity in the ZBD ophiolites.

Origin of the ZBD ophiolites

Reliable age determinations from Alpine ophiolite units have been quite limited until recently and are available for Piemont-Ligurian ophiolites only: considering U/Pb zircon ages only, the temporal range is small and scatters between 166 ± 1 Ma and 148 ± 2 Ma (Bill et al, 1997; Rubatto et al., 1998; Borsi et al., 1996; Desmurs et al., 1999; Ohnenstetter et al., 1981; Costa and Caby, 2001; Rubatto and Hermann, 2003). According to the lithostratigraphy and paleogeographic reconstruction (e.g. Stampfli et al., 1998), the opening of the Valaisan ocean can be placed at around 116 Ma. Liati et al. (2003) reported magmatic activity in the Chiavenna unit at 93 Ma, an age interpreted as the late stage of spreading in the Valaisan ocean.

Crystallization ages of 149 ± 3 Ma and 142 ± 5 Ma for the two ZBD plagiogranites are late Jurassic and clearly exclude the possibility that the ZBD ophiolites are part of a distinct, i.e. pre-Mesozoic (Schmidt, 1989) ophiolite suite. They also indicate that the ZBD was part of the Jurassic Piemont-Ligurian domain or the Cretaceous Valaisan ocean.

The age of 149 ± 3 Ma falls into the same range of plagiogranite ages that were obtained by Costa and Caby (2001) in the Montgenèvre ophiolite (148 ± 2 Ma), by Lombardo et al. (2002) in the Monviso (152 ± 2 Ma) and by Borsi et al. (1996) in the Voltri Massif (150 ± 2 Ma), all part of the Piemont-Ligurian domain. The crystallization age of 142 ± 5 Ma, is, however, younger than any previously reported ages from Piemont-Ligurian ophiolites.

The ZBD ophiolites are considered to be part of the Piemont-Ligurian domain on the following grounds: (i) Their intrusion age is on the younger end of Piedmont-Ligurian activity, but too old for being part of the Cretaceous Valaisan ocean. (ii) The particular geochemical signature (distinct LREE-depleted N-MORB) is observed in all oceanic magmatic rocks in the ophiolite bodies throughout the ZBD. This homogeneity, in chemical composition as well as in general field appearance, suggests that the strongly dismembered ZBD ophiolites originate from one single ophiolite "unit" rather than being a mixture of Valaisan and Piemont-Ligurian ophiolites. (iii) All the Valaisan ophiolitic remnants so far identified contain very few or no gabbroic rocks at all (Florineth and Froitzheim, 1994; Steinmann, 1994; Cannic et al.,

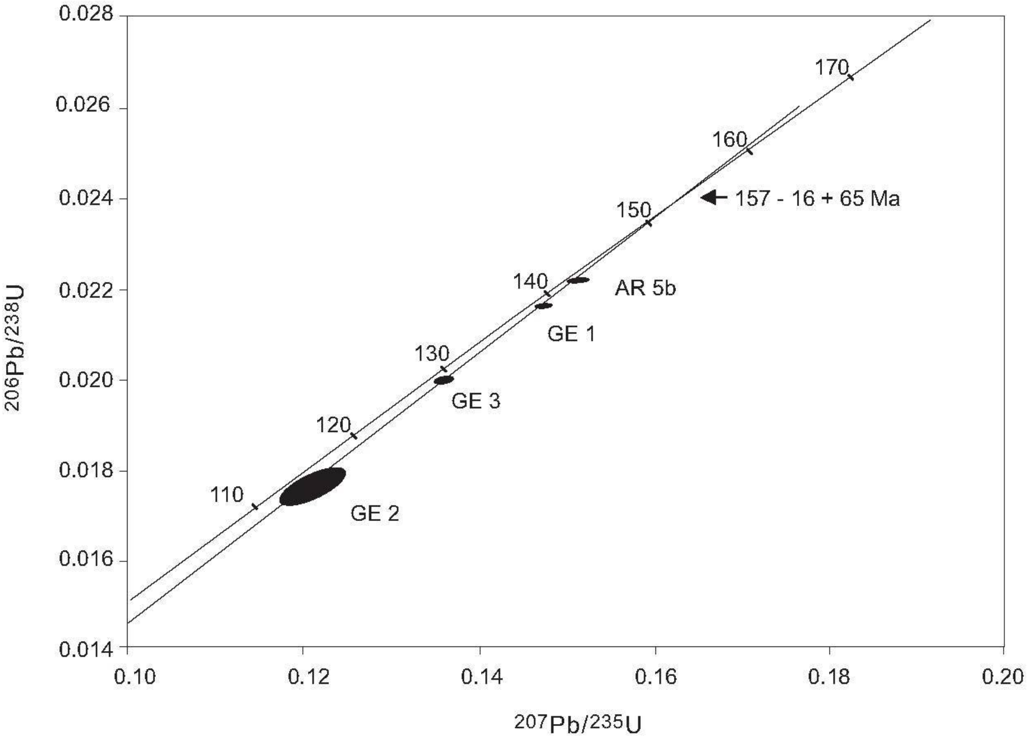


Fig. 9 Concordia diagram on zircons analyzed with the single grain conventional method. Sample numbers: GE: GE35P1.1, AR: AR5b. Error ellipses represent 2σ

1996; Pfiffner, 1999; Talerico, 2001), while such rocks are relatively abundant in most Piemont-Ligurian ophiolites. The dominance of gabbroic rocks in the ZBD ophiolites appears to support a Piemont-Ligurian origin, albeit fairly circumstantially so. (iv) So far, basaltic rocks of LREE-depleted N-MORB character have only been reported from Piemont-Ligurian ophiolites, e.g. in the Internal Ligurides (Venturelli et al., 1981), Corsica (Venturelli et al., 1981; Saccani et al., 2000), Platta (Frisch et al., 1994; Schaltegger et al., 2002) and the Forno metabasalts (Puschnig, 1998). Valaisan basalts appear to be only of T-MORB to E-MORB type (e.g. Evans et al., 1981; Talerico, 2001) and may indicate that the Valaisan ocean never attained the stage of evolution recorded by N-MORB basalts of the Piemont-Ligurian ocean. The smaller number of available outcrops and analyses of basalts from Valaisan ophiolites, however, may also to some extent explain the lack of N-MORB basalts in this domain. (v) According to Bill et al. (2000), LREE depleted (i.e. N-MORB) basalts in the Piemont-Ligurian domain represent a relatively mature oceanic stage characterized by an asthenospheric mantle source of the magmatic rocks and considerable degrees of partial melting in that mantle source. These basalts are generally younger than more LREE enriched varieties of T to E-MORB type found in other Piemont-Ligurian ophiolite bodies, e.g. the Zermatt-Saas Fee ophiolites (Pfeifer et al., 1989) or the Gets Nappe ophiolites (Bill et al., 2000). The latter suggest sources not depleted in LREE or small degrees of partial melting, compatible with formation in an embryonic ocean. The basalts as well as the bulk of all gabbros in the ZBD ophiolites are characterized by a LREE-depletion which is among the most pronounced of all Alpine ophiolites. Consequently, their chemical signature suggests a fairly evolved stage of oceanic magmatic activity. This is in line with the relatively young age, with respect to the other Piemont-Ligurian ophiolites, of magmatism in the ZBD ophiolites, and rather incompatible with formation in an ocean basin that is yet to open. According to the estimates of Steinmann (1994) and Florineth and Froitzheim (1994), one would expect evolved stages of oceanic magmatism producing N-MOR basalts in the Valaisan ocean to have happened roughly 100 Ma ago, i.e. much later than the age of magmatism in the ZBD ophiolites.

We therefore propose the ZBD ophiolites to have been part of the Piemont-Ligurian ocean in which case they represent so far the youngest preserved fragments observed in this domain.

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